The First Cardiac CT Scanners (16-s and 64-s CT)

Imaging of the heart demands spatial, temporal and contrast resolutions greater than for any other organ system of the body.

Excellent spatial resolution is necessary to evaluate the fine anatomical details of the coronary arteries, while temporal resolution is necessary to evaluate coronary arteries without motion heartbeat artifacts; contrast resolution is critical for determining coronary plaque composition.

For these reasons, using the first-generation single-slice conventional CT system (SSCT), developed in the 1980s, and a cross-sectional scanner with a gantry rotation time of 4.5 seconds and a slice thickness of 10 mm, the cardiac and coronary images were severely degraded by motion and heartbeat artefacts as well as the volume average artifact.

Electron beam CT (EBCT), developed in the early 1980s, is the origin of CT cardiac imaging by combining high temporal resolution and electrocardiographic prospective triggering, allowing to “freeze” the heart. It is a cross-sectional imaging technique developed specifically for cardiac imaging, based on the production of x-rays from a tungsten arc ring target below the patient by an electron beam that is swept by an electromagnetic field. Unlike in conventional CT, there are no moving parts; thus, scanning times are as fast as 50-100 ms per slice. In addition, scanning can be triggered by the patient’s electrocardiogram, allowing the visualisation of the cardiac structures, coronary arteries and coronary walls as well as the detection and evaluation of calcification, called “calcium scoring”. However, because of limitations in spatial resolution, a 1.5-mm long z-axis and contrast resolution, EBCT systems have largely been replaced by multi-slice CT systems.
In the late 1980s, significant progress has been made in using SSCT by the slip-ring technology, which allows the gantry to rotate continuously around the patient while the table is advanced, leading to a helical scanner era. Thanks to this new technology, it was possible to acquire not only a single slice, but the entire body volume. The collimation of the table and the feed speed in spiral CT can be changed independently. The pitch defines the relationship between the speed of the advancement of the table and detector collimation; the higher the pitch, the lower the exposure of the patient and the more extensive volume affected by the scan. With these characteristics and considering the shorter scan times, it is therefore possible to study a large body volume in a single breath-hold, greatly reducing movement artifacts. Volume data could also be acquired without the risk of mis-registrations or double registrations of anatomical details. Images could be reconstructed at any position along the patient axis (z-axis) and overlapping image reconstruction could be used to improve the longitudinal resolution. This led to the development of image processing techniques such as multiplanar reformation (MPR), maximum intensity projection (MIP) and the volume rendering technique (VRT). Soon after their introduction, the slip-ring technique and spiral CT scanners were rapidly adopted.

Despite its great use in clinical practice, single spiral CT has considerable limitations. It is not yet possible to evaluate large study volumes with thin collimation in a short time, and in spatial resolution in the transverse plane (axial resolution) and in the longitudinal plane (longitudinal resolutions), it is not possible to obtain isotropic voxels reduced in this way the quality and therefore the utility of off-axis reconstruction. In 1998, the introduction of MSCT scanners, with multi-row detectors along the z-axis, represented a significant technical improvement in CT imaging.

The primary difference between single-slice CT (SSCT) and MSCT is the design of the detector arrays. The SSCT has a large number of detector elements in a single row across the irradiated slice to intercept the x-ray fan beam. The single detector element is typically about 20 mm along the Z-axis. The slice thickness in the SSCT is determined by detector size and the x-ray beam collimator (usually 10-mm wide x-ray beam). The MSCT has a large number of detector elements per row in multiple rows, and each individual detector is divided into several smaller detector elements. In the earlier CT scanners, the single detector was based on 16 rows of 1.25-mm detector elements. Those elements could be electronically linked to function as a single detector or could be used individually.

Subsequently, manufacturers developed different geometries in the detectors. Fixed-matrix detectors are formed by detector elements of equal size, while in adaptive-matrix detectors, all elements of the matrix away from the centre have larger dimensions. In hybrid-type detectors, all elements of the matrix have the same dimensions, with the exception of a number of elements that are thinner.

In the SSCT, thickness is determined solely by the collimation of the radiation beam, while in the MSCT, it is defined by the dimensions of the detectors along the z-axis. The detectors will generate a signal produced at the coupling of multiple detectors or by individual detectors, depending on the geometry set in the scan protocol.

A group of two 1.25 mm elements could be linked to act as a 2.5-mm wide detector group. Similarly, a 2.5-mm group can be combined to form 4 detector 5 mm group with 20 mm coverage.

By collimating a 1.25-mm x ray beam in the z-axis, the beam aligned to the partially irradiated two innermost detector elements can be obtained with a slice thickness of 0.625 mm.

This way, in the MSCT, the slice thickness is determined by detector configuration rather than x-ray collimation.

Based on the clinical needs, it is then possible to set a scan with high spatial, longitudinal resolution, although with an increase in total scan time, which is useful
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in the study of the brain parenchyma. Alternatively, a scan with lower longitudinal resolution, but with a faster scan time, is useful for the study of large body segments such as the chest or abdomen, often susceptible to motion artifacts.

Another detector array design has innermost 1-mm detector elements, representing another possibility to use only the ultrathin detector elements by collimated x-ray beam obtained submillimetre slice.

Submillimetre slices represent a great step forward in CT; when images are reformatted, the spatial resolution along the z axis is equal in the other direction generated via isotropic imaging.

Thin and submillimetre slices eliminate partial volume effects and allow the reconstruction of the high-quality off-axis (sagittal coronal or oblique axis) or three-dimensional reconstruction.

Another substantial difference between SSCT and MSCT is the number of detector rows.

Multislice CT technology has led to a simultaneous acquisition of more than one slice at a time, improving volume coverage within a shorter scan time and longitudinal resolution (z-axis).

This increased performance of multi-detector row CT, relative to single-section CT, allowed the optimisation of a variety of clinical protocols. The scan time for standard protocols could be substantially reduced, which proved to be of immediate clinical benefit for the quick and comprehensive assessment of trauma patients and uncooperative patients. Alternatively, the scan range that could be covered within a certain time was extended, which is relevant for oncologic staging or for CT angiography with extended coverage, such as the lower extremities.

An important clinical benefit, based on the ability to scan a given anatomic volume within a given scan time with a substantially reduced section and increased longitudinal resolution, is the presence of almost isotropic voxel sizes, and the isotropic resolution was within reach for many clinical applications.

In addition to the new detectors and the possibility of obtaining the simultaneous acquisition of more slices of the body, at the same time great benefits are data from the increase of tube rotation time that 1 second of SSCT reduces up to 0.5 seconds in MSCT. The low rotation time, associated with the increase in coverage, leads to a significant overall reduction of scan time and the possibility of studying large body volumes with high longitudinal resolution.

The overall reduction of the scan time has led, in addition to increased feasibility, to an optimisation of the contrast medium injection protocols, leading to the reduction of the contrast volume and to the possibility of also obtaining an angiographic phase.

Multi-detector row CT technology has benefitted clinical applications in several ways. A shorter scan time is important for trauma patients, paediatric patients, and CT angiography, while an extended scan range is important for CT angiography and combined chest-abdomen scans, such as in oncologic staging. The improved longitudinal resolution is beneficial for all reconstructions, particularly when 3D postprocessing is part of the clinical protocol. In this way, CT imaging has become a vital component of medical imaging.

Consequently, all vendors pushed towards more and more slices, making the number of slices one of the most important performance characteristics of a CT scanner.

The technological innovations that have made the fundamental MSCT to 4 and 8 in clinical practice have laid the foundations for the use of CT also in the evaluation of the cardiac district.

With a gantry rotation time of 0.5 s and dedicated image-reconstruction approaches, the temporal resolution for acquisition of an image was improved to 250 ms and less, which
proved to be sufficient for motion-free imaging of the heart in the mid- to end-diastolic phase when the patient had a slow to moderate heart rate (up to 65 beats per minute).

With four simultaneously acquired sections, coverage of the entire heart volume with thin sections (1.0- or 1.25-mm collimation) within a single breath-hold became feasible.

Initial clinical studies showed the potential of multi-detector row CT to not only demonstrate, but, to some degree, to also characterise non-calcified and calcified plaques in the coronary arteries on the basis of plaque CT attenuation. Early results from four-slice scanners demonstrated sensitivities of 72-98% and specificities of 71-98%, albeit only with the exclusion of smaller vessels (2 mm) and unevaluable segments (up to 32%). The most common reasons for vessel exclusion were motion artifacts and heavy coronary calcification; the partial-volume effect exaggerates calcification and obscures the underlying vessel lumen.\textsuperscript{1,2}

The MSCT in four- to eight-slice scanners still does not allow the input of the cardiac CT in normal work flow. It is almost impossible for patients with manifest heart disease to comply with the breath-hold time of about 40 seconds, required to cover the entire heart volume, approximately 12 cm with the four-slice MSC. Stents or severely calcified arteries constitute a diagnostic dilemma, mainly because of partial volume artifacts as a consequence of insufficient longitudinal resolution. Similarly, advanced 3D postprocessing techniques are omitted.

In 2002, the introduction of 16-slice MSCT, with faster gantry rotation speed and 16 detector rows, improved the feasibility, image quality and clinical accuracy; consequently, cardiac CT has become an important tool in cardiologic clinical practice.

Sixteen-row detector CT systems contain adaptive-array detectors, while the Somatom Sensation 16 scanner (Siemens, Forchheim, Germany) uses 24 detector rows. The 16 central rows define 0.75-mm collimated section widths at the isocenter, while the four outer rows on both sides define 1.5-mm collimated section widths. The total coverage in the longitudinal direction is 24 mm. The Toshiba Aquilion scanner (Toshiba, Tokyo, Japan) can provide 16 sections with a collimated section width of either 0.5, 1.0 or 2.0 mm, with a total coverage of 32 mm. The GE Lightspeed 16 scanner (GE Medical Systems, Milwaukee, USA) uses 16 sections with either 0.625- or 1.25-mm collimated section width; total coverage in the longitudinal direction is 20 mm.

Sixteen-row detector CT scanners increase the temporal resolution: a slightly increased gantry rotation speed of 0.42 seconds, with a conventional half-scan (180\textdegree) reconstruction, provides a temporal resolution of 210 msec. In addition, the combination of reconstruction algorithms and adaptive multicyclic parameter settings theoretically allows better temporal resolution at optimal heart rates.

The 16-slice MSCT scanners, thanks to submillimetre collimation, represent a break-through in true isotropic resolution for routine clinical applications.

Thanks to these characteristic techniques, the 16-slice MSCT considerably increased the feasibility, greatly reducing the apnoea time to 20-25 s while maintaining a high spatial resolution. The reduced time for scansion and coverage of about 20 cm also allows the assessment of bypass grafts in a single breath.

The use of the 16-slice MSCT with an adaptive array allows spatial resolutions of up to 0.4 mm, suitable for the evaluation of the segments of the most distal ends of the coronary arteries and for obtaining isotropic voxels for the entire volume of the scan. Good image quality, associated with post-processing with true isotropic voxels, considerably increases the accuracy in the detection and quantification of coronary artery stenosis, in particular in terms of sensitivity and negative predictive values.\textsuperscript{3}

One of the most important applications of Cardiac MSCT is the detection of coronary artery stenosis in patients with known or suggested coronary artery disease and in whom the presence of stenosis can safely be ruled out. This has a clinical impact on
the management of patients who are symptomatic but have a low pre-test likelihood of significant CAD.4

General limitations of MSCT for coronary artery imaging include the fact that not all patients can currently be investigated because of a high heart rate and insufficient breath-hold.

Sinus rhythm is a pre-requisite, and heart rates above 60-70 bpm are prone to create artifacts. Residual cardiac motion artifacts are a major cause of image degradation; the right coronary artery appears particularly vulnerable because of its extensive motion radius and short motion-free period.

Using the MSCT 16-slice technology, 65 beats per minute was defined as the upper heart rate threshold enabling to achieve a motion-free image quality.5

It is therefore mandatory to use blocking agents to maintain heart rates at a level below this threshold during image acquisition.

The arrival of clinical 64-row detector systems in 2004 brought further improvements in anatomic and physiologic cardiac imaging.

An approach adopted by Siemens (Somatom Definition, Siemens, Forchheim, Germany) in 2006 uses two x-ray tubes mounted on the gantry at 90° angles (2 x 32 x 0.6 mm collimation); therefore, only a quarter turn of the gantry is required to collect the 180° of attenuation data. Double source CT improved the temporal resolution, making the system less susceptible to variations in heart rate.

The GE Healthcare (VCT 64) and Toshiba (Aquilion 64) focused their system development on spatial resolution, developing the first detector scintillation material with a fast decay time; the latter company offers the thinnest detectors at 0.5 mm.

The simultaneous acquisition of 64 parallel cross sections enables the imaging of the entire coronary artery tree in a single breath-hold, and gantry rotation times of 0.33-0.40 s result in a heart rate-independent temporal resolution of 0.185-0.2 s.

The 64-slice MSCT scanner generation provides an in-plane resolution of 0.4 mm and a slice thickness of 0.6 mm, improving spatial resolution in a large craniocaudal field of view and allowing isotropic voxel dimensions, improving post-processing image quality.

At the same time, iterative reconstruction has been developed to overcome the shortcomings of filtered backprojection by forward reconstruction models and a more precise integration of scanner geometry and the underlying physics (system optics). Advantages of iterative reconstruction, compared with filtered backprojection, include higher spatial resolution and lower image noise.

The 64-slice MSCT is able to perform cardiac CT in retrospective and prospective mode.

The combined use of MCTC 64 with the retrospective ECG-gated helical scanning technique allows high-speed acquisition of motion-free volume data for the entire heart, with submillimetre spatial resolution during a single breath-hold to enable the selection of the reconstruction window throughout the cardiac phase. To reduce the effective dose, ECG-controlled tube current modulation maximizes the tube current for the limited cardiac phase (mid-diastole) and radically reduces the current for other phases that are unnecessary for image reconstruction.

In the prospective ECG-gated axial scan, called "step-and-shoot scan", the x-ray beam is turned on at predetermined cardiac phases to acquire sufficient scan data to reconstruct images during the minimal acquisition window. The use of a "padding technique" permits extra tube on time before and after the minimal acquisition window to acquire image data during additional cardiac phases and can compensate for heart rate variations during the coronary CT scan.

Compared with the retrospective ECG-gated helical scan, the step-and-shoot axial scanning technique reduces radiation exposure by limiting the number of phases for...
acquisition and by increasing the pitch to approximately 1. It also reduces helical-related blurring in the coronary vessels, particularly with coronary calcification or stents, and can improve image quality. The generation of 64-slice MDCT scanners permits robust, fast and reliable contrast-enhanced imaging of coronary arteries and coronary plaque.

The literature shows excellent diagnostic accuracy, with a sensitivity of 84-94%, in the detection of significant stenosis, also in smaller coronary artery segments and side branches. A high negative predictive value of 95-97% suggests that the use of 64-slice MSCT can reliably rule out significant CAD.\(^6\)

Furthermore, the ability to detect and characterise the extent, distribution and morphology of coronary atherosclerotic plaque may be useful for improving short-and long-term cardiovascular risk stratification.\(^7\)

In patients with a history of revascularisation, few data are available regarding the ability of 64-slice MSCT to assess stent patency or in-stent restenosis and the patency of the post-anastomotic segment in case of bypass grafts.\(^8,9\)

Because of their greater craniocaudal coverage per rotation, which allows shorter breath-holds of less than 12 seconds and, consequently, smaller contrast injection volumes, fewer artifacts related to patient breath-hold compliance occur with the 64-slice MSCT, resulting in lower heart rate variability. Slab artifacts attributed to high heart rates, heart rate variability and to the presence of irregular or ectopic heart beats are drastically reduced.

The fast volume coverage of the 64-slice MDCT, as well as the improved coronary evaluation feasibility, enable combined imaging of the coronary tree, ascending aorta and pulmonary arteries to assess the presence of pulmonary embolism, thoracic aortic dissection and CAD within a single CT examination. This way, CT has become an essential step in the thoracic pain and emergency department workflow.\(^10\)

\section*{256- and 320-detector raw scanners}

Manufacturers are continuously improving physical parameters and addressing limitations of current scanner technologies.

Gantry rotation time is a crucial factor influencing temporal resolution, which is half the gantry rotation time. To acquire motion-free coronary artery images or to ‘freeze the heart movement’, CT scanners should provide superb temporal resolution. With the available modern CT scanners, the fastest gantry rotation time is up to 270 ms, which results in a temporal resolution of 135 ms.

The x-ray tube technology also advanced, and x-ray tubes of the state of the art CT scanners provide a peak power of 100-120 kW: with a dual source system, these values double. Increasing the power of x-ray tubes may seem like increasing the radiation dose that the patient will receive. However, with faster gantry rotation and table speed, the exposure time will decrease significantly with high power levels. High x-ray power allows the use of strong prefiltration, which will remove low-energy photons that contribute to the dose and increase noise from the spectrum. In addition to high tube power values, recent developments in tube technology allow users to select voltages as low as 70 kV, an important factor in reducing patient dose with acquisition of the best possible signal-to-noise-ratio.

Great improvements in cardiac CT performance are also a result of technological advances in terms of increasing the detector size in the z-direction, thereby expanding the volume coverage per gantry rotation. Scanners with large detectors and 160-mm coverage are available these days, capable of imaging the entire heart in a single
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beat without moving the patient; one example is the Toshiba Aquillion One (Toshiba Medical Systems Corp., Tokyo, Japan), with 320 × 0.5 mm collimation at a rotation of 0.28 s, and the GE Revolution (GE Healthcare, WI, USA), with 256 × 0.625 mm collimation at 0.28 s of rotation. The Philips Brilliance iCT 256-slice scanner (Philips Medical System; Netherlands) has 128 detector rows and two focal spot positions. In this system, the number of slices will be doubled (256 slices); however, longitudinal or z-axis coverage of this scanner is 80 mm (128 × 0.625 mm) per gantry rotation.

The impact of the new-generation 256-320 row scanners is significant. There are several advantages of the great coverage. First, and most important, is the elimination of stair-step artifacts; great coverage significantly reduces post-processing and image interpretation times since less phases are required to render the study diagnostic. Second, the radiation dose is reduced compared to low-pitch helical scans. High spatial resolution, up to 0.23 mm, allows an accurate visualisation of the coronary tree and the small distal coronary arteries, and CT scanners can obtain an isotropic voxel size as low as 0.35 mm.13 Superb temporal resolution, achievable with modern CT scanners, allows motion-free coronary artery images or to ‘freeze’ the heart movement.

Modern scanners have a powerful diagnostic ability in coronary stenosis evaluation, and the severity, location and anatomy of stenoses can precisely be assessed. Furthermore, in clinical practice, 256- and 320-slice scanners improve the diagnostic performance in patients with high heart rates and heart rate variability, reducing beam hardening artifacts resulting from calcified plaques and motion artifacts.11, 12 The combined use of high spatial resolution, the latest generation of iterative reconstruction, fast gantry rotation time and an intracycle motion correction algorithm to improve temporal resolution also allows excellent image quality and diagnostic accuracy in patients with a heart rate of up to 100 beats per minute and chronic atrial fibrillation during scanning.13

In the routine clinical workflow, freezing the heart could be challenging in patients with very high and irregular heart rates. Therefore, besides the few options available to eliminate the motion problem, the use of HR-controlling drugs, including beta-blockers and ivabradine, before scanning is still recommended. High-coverage MSCT is useful to assess the patency of CABG cases with high diagnostic accuracy and low doses. This superior diagnostic accuracy may be due to fewer motion artifacts and to improved quality images of distal anastomosis and post-anastomotic vessels. Furthermore, previous studies show good accuracy in stent restenosis; high spatial and temporal resolutions reduce motion, beam hardening caused by metallic stents and partial volume from highly attenuated stent struts. Despite great technological evolution, intra-stent stenosis is still influenced by stent length, diameter, thickness and stent design.14

Simultaneous examination of the coronary arteries and other main thoracic vasculature, including the aorta and the pulmonary vasculature, provides adequate image quality for identifying the most critical causes of acute chest pain. The triple rule-out scan can, besides coronary artery disease, aortic dissection and pulmonary embolism, also detect other causes of chest pain, such as pneumonia and pneumothorax infection. In the 64-slice era, the triple rule-out protocol is characterised by a spiral gating scan in a single breath-hold, with high contrast volume and dose.15 The modern 256-320 scanner axial gating protocols, because of the high coverage and high temporal resolution, increase feasibility and accuracy, similar to the use of dedicated CTA, and require less contrast agents; as new dose-saving techniques, they further enable reductions in the effective radiation dose.16 Technological advances in cardiac CT scanners enabled the combination of morphological and functional imaging with a single imaging modality. With this new clinical application, it is possible to obtain images of myocardial perfusion and to determine myocardial ischemia, allowing to distinguish between healthy and damaged heart muscle tissue. With the 256- to 320-slice scanners,
multiple volume acquisitions can be acquired with low dose exposure, and the entire left ventricle myocardium can be covered in a single gantry rotation. The temporal resolution reduces motion artifacts due to high rates of post-adenosine and allows the right timing to image the transit of contrast material from the coronary artery to the myocardium.\textsuperscript{17}

\textbf{Double source}

In 2005, the introduction of Dual-Source (DSCT) scanners has marked the evolution of the MSCT technology. These Somatom Definition scanners (Siemens Healthineers, Forchheim, Germany) are equipped with two different systems of X-ray source-detectors, mounted in the gantry at about 90°. The first system has a coverage of 50 cm, while the second group allows a coverage of 26 cm. Each array consists of 40 detectors with an actual thickness of 0.6 mm and 32 power plants with four rows at each end, with an actual thickness of 1.2 mm. Using FFS (Flying Focal Spot), for each rotation, two overlapping sets of 32 layers are covered, used to reconstruct 64 layers with an overlap of 0.3 mm.

In a typical single-source CT scanner, the length of time required to perform a scan is limited by is the so-called ‘gantry rotation time’, which is the amount of time it physically takes to rotate the fan-shaped X-ray source and detector 180° through the field of view, gathering the necessary images to reconstruct a slice or an array of slices. By using the second-source X-ray tube and detector array, the time taken is halved to 165 ms while maintaining equivalent spatial resolution.

Feasibility studies have confirmed the technical capacity of DSCT to provide diagnostic image quality of coronary arteries in patients with high heart rates. Without heart rate control during scanning, DSCT technology reaches a sensitivity of 96.4\% and a specificity of 97.5\% for the detection of significant coronary stenoses. These results are comparable to those previously reported with conventional 64-slice CT; however, betablocker administration for strict heart rate control was needed to compensate for motion artifacts.\textsuperscript{18, 19}

Another significant innovation is the Dual-Energy technique. Providing two tubes at different Kv values, it is possible to obtain a simultaneous acquisition scan at a different voltage. The dual energy-mode, with software application for decomposition and tissue analysis, can distinguish iodine contrast medium from a bone, two materials that have a similar density on a CT standard. It is also possible to remove the bony structures or calcified plaques from the image so that only opaque vessels are visible by means of contrast; alternatively, in other circumstances, iodine can be subtracted from a precise image, thus creating virtual images without resorting to other scans before the injection of contrast medium.

A further development of the technology by Somaton Definition Flash (Siemens Healthineers, Forchheim, Germany) has led to the increase of double source speed detector tube systems to 0.28 s and increased the coverage of the second group up to 128 x 2-slice.

Thanks to its high scan speed, a heart could be scanned in only 0.22 s, which means that at low heart rates, a CT scan could be carried out in a single heartbeat, with a spatial resolution of up to 0.33 mm. This improved temporal resolution, with the use of dual-source CT high coverage (2 x 128 x 0.6-mm collimation; 280-ms gantry rotation), reduces coronary motion artifacts and makes the image quality of coronary CT not only less dependent on the heart rate, but also less dependent on the phase of the cardiac cycle during which the image is acquired.
In clinical practice, electrocardiography-gated cardiac CT remains the gold standard for the exclusion of anomalous coronary arteries and has an extremely high sensitivity and a high negative predictive value for the exclusion of significant coronary artery stenosis, similar to the single-source 64-slice CT scanners. Thanks to the reduced influence of the heart beat in retrospective-gated mode, doses can be reduced by limiting peak milliampere values to a single phase of the cardiac cycle. In axial prospective-gated CT, sequential mode scanning can be used (with or without “padding” plateaus) to mitigate the potential effects of arrhythmias.

With the use of the dual-source CT scanner and prospective ECG-gated high-pitch helical scan mode with a pitch as high as 3.4, single-cycle scanning time is 250-290 ms. Scan time is approximately 1 s to image the entire chest or 270 ms to image the heart; cardiac motion is essentially frozen. The use of this scan protocol is associated with high diagnostic accuracy for assessing coronary artery stenosis at a radiation dose of 1.7 mSv.20

The improved temporal resolution has led most institutions to discontinue the practice of beta-adrenergic blocker administration to control the heart rate. However, a strict indication stable sinus rhythm, with a heart rate of less than or equal to 65 beats per minute, is required to reduce motion artifacts. Pharmacological treatment for a low and regular frequency is still recommended, depending on the use of dose-saving scanning techniques.

Thanks to the second-generation double-source technical development and to new dedicated software, CT scanners are able to not only provide anatomical information about the coronary tree, but also to perform myocardial perfusion evaluation at the same time. With this new clinical application, CT scanners can be used to obtain images of myocardial perfusion and to determine myocardial ischemia, allowing to distinguish between healthy and damaged heart muscle tissue.

Perfusion techniques are used to image the transit of contrast material from the coronary arteries to the myocardium after adenosine administration. The use of adenosine during stress myocardial perfusion tests induces an increase of the heart rate of 10-25 beats above the heart rate at rest. Double-source technical skills are able to reduce cardiac motion artifacts and to perform scans during the early portion of first-pass circulation in the right timing in static CT perfusion or to provide several datasets over a period of time in dynamic CT perfusion.

The combination of anatomic and functional information improved the accuracy of coronary artery evaluation and stratified the prognostic risks, which is likely to provide a reliable basis for further assessment of the clinical situation and prognosis to select the best treatment.21-23 The third-generation dual-source CT system (Somatom Force; Siemens Healthineers, Forchheim, Germany) has led to significant improvements in detector width, gantry rotation time and pitch settings, which should improve both image quality and radiation dose reduction. The third-generation dual-source scanner provides a rotation time of 0.25 s and improves the temporal resolution to 66 ms, with increased z axis coverage per second (2 x 192 x 06-mm collimation).

These new technical features made the scans heart-beat independent, and feasibility and accuracy in coronary stenosis detection have reached almost 100%, even for other body districts (pre-TAVI evaluation and triple rule-out in acute thoracic pain evaluation), also without sinus rhythm, such as in atrial fibrillation.

The introduction of technical advances, such as enhanced tube power with automatic voltage selection, increased number of in-plane detector channels, a fully-integrated circuit detector system for noise reduction and new iterative reconstruction algorithms (advanced models), representing significant improvements in image quality, has led to an increased accuracy in stenosis detection in obese patients and also provides further improvements regarding in-stent lumen assessment, particularly when of significant (>50%) extent.24
Third-generation double-source scan timing also provides the advantage of reducing contrast volume and dose, and thanks to high spatial and temporal resolution and large volume coverage, static and perfusion CT have found entry into clinical routine.

**Temporal resolution**

Temporal resolution can be defined as the time needed by an imaging method to acquire every single frame of a dynamic process. This concept is important for cardiac CT, in which the object, a beating heart, is to image over an order of milliseconds into multiple frames. The best image quality can be achieved at minimum coronary artery motion, which usually occurs during the mid-end diastolic phase or during the end systolic phase, which is of a shorter duration than the diastolic phase at low heart rates.

In case of high heart rates, the diastole shortens relative to the systole, and diastasis shortens dramatically. Because images reconstruction requires only a tube rotation of 180°, the gantry rotation time decrees the time needed to acquire 180° of raw data projections. The approximate temporal resolution of the reconstructed images is thus dependent on the rotation time employed. The so-called “native” temporal resolution of a CT is given by the minimum gantry rotation time divided by 2 (i.e., a gantry rotation time of 500 milliseconds (ms) = native temporal resolution of 250 ms). For this reason, the minimum available gantry rotation time must be used to compensate for cardiac motion in cardiac CT. As an example, a CT scanner with a temporal resolution of 250 ms can acquire a single image over 250 ms of the cardiac cycle, resulting in a total of four images during a single R-R interval, assuming a heart rate of 60 beats per minute. Thus, extremely high temporal resolution is targeted by new CT scanners to achieve the best image quality, even in patients with high rates. The cardiac rest period, defined as "the time with a coronary artery displacement of <1 mm", has a mean duration of 120 ms (range 66-333 ms). Up to date, the best current temporal resolutions of single-source CT (135-140 ms) and dual-source CT (83 ms) are still distant from the temporal resolution of coronary angiography (1-10 ms) or magnetic resonance (20-50 ms). High temporal resolution in cardiac CT can be achieved by various means such as a faster gantry rotation time, multi-cycle reconstructions and the use of two X-ray tubes. Last-generation CT scanners have an improved gantry rotation time (about 135 ms, as listed above), combined with an improved z-axis coverage of up to 16 cm (in comparison with the 4-cm coverage of the 64-slice CT). Otherwise, the faster the gantry rotation, the higher the G forces caused by the increase in centrifugal force. Thus, substantial improvements in gantry rotation times are currently unlikely. In this regard, it must be mentioned that in case of a fast gantry rotation, the table cannot move as quickly due to gaps in the data acquisition. For this reason, high temporal resolution in CT requires low pitch values, with a consequent increase in radiation dose. In case of high heart rates, the shortening of the R-R interval leads to a reduction of the time needed for data acquisition from the entire cardiac cycle. Thus, a higher pitch value can be used, resulting in a lower dose. However, generally, single-tube CT scanners have no temporal resolution in the partial scan mode and the capability of image acquisition at high heart rates and therefore need multi-segment reconstruction techniques to improve temporal resolution (which do not allow the use of high pitch values). The use of multi-cycle reconstructions combines data from multiple contiguous heart beats to complete the half-scan of views (Figure 1.1). The most uncertain issue regarding this technique is that it is heart-rate dependent: it should only be used at specific heart rates to be effective because the cardiac cycle duration and the gantry rotation time must be asynchronous. Moreover, other disadvantages of this technique must be considered. To create images from data acquired from different cardiac cycles, detectors must be
able to cover the same position during different consecutive R-R intervals. Thus, the pitch should be lowered, increasing the radiation dose. Irregular heart rates would lead to different phases of the cardiac cycle to be sampled, resulting in misalignment artifacts of the images to be reconstructed and leading to blurred final images. Dual-source CT technology allows an increased temporal resolution because of the use of two tube/detector sets, arranged at 90-degree angles to each other. Thus, because of this gantry geometry, only a quarter gantry rotation is needed when partial scan reconstruction is used, with a reduction of the temporal resolution of up to about 83 ms (in comparison with mean values of 135-140 ms of single-tube CT), allowing coronary artery imaging in patients with high heart rate not responsive to β-blockers.

Besides dual-source CT, other recent advancements in technology have allowed the release of CT scanners with an increased number of detectors (256- and 320-slice) and with a z-axis coverage of up to 16 cm, which allows the entire heart scan in one heartbeat with only one gantry rotation. Applications and implications of these new CT scanners will be discussed later.

**FIGURE 1.1** Improved spatial resolution without impairment of image quality: the shown phantom study compares line-pair views of a standard sampling rate (A) with an increased sampling rate (B) with improved spatial resolution. Note the improvement in edge details, in particular for small line pairs (black arrows). In clinical routine, this improvement means an advantage in the detection of small coronary lesions or in stent patency assessment.