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REVIEW ARTICLE

Selecting a CT scanner for cardiac imaging: the heart of the matter

[1]MARIA A LEWIS, MSc, [2,3]ANA PASCOAL, PhD, MIPEM, [1,2,4]STEPHEN F KEEVIL, PhD, FIPEM and [2,3]CORNELIUS A LEWIS, PhD, FIPEM

[1]Department of Medical Physics, Guy's and St Thomas' NHS Foundation Trust, London, UK
[2]King's Technology Evaluation Centre (KiTEC), King's College London, London, UK
[3]Department of Medical Engineering and Physics, King's College Hospital NHS Foundation Trust, London, UK
[4]Division of Imaging Sciences & Biomedical Engineering, King's College London, London, UK

Address correspondence to: Mrs Maria Anna Lewis
E-mail: *maria_anna_lewis@yahoo.co.uk*

ABSTRACT

Coronary angiography to assess the presence and degree of arterial stenosis is an examination now routinely performed on CT scanners. Although developments in CT technology over recent years have made great strides in improving the diagnostic accuracy of this technique, patients with certain characteristics can still be "difficult to image". The various groups will benefit from different technological enhancements depending on the type of challenge they present. Good temporal and spatial resolution, wide longitudinal (*z*-axis) detector coverage and high X-ray output are the key requirements of a successful CT coronary angiography (CTCA) scan. The requirement for optimal patient dose is a given. The different scanner models recommended for CTCA all excel in different aspects. The specification data presented here for these scanners and the explanation of the impact of the different features should help in making a more informed decision when selecting a scanner for CTCA.

INTRODUCTION

Clinical interest in the application of CT for the imaging of coronary vessels dates back to 1998 with the introduction of "four-slice" CT scanners. These early multislice models posed limitations to performing coronary angiography; therefore, their use in cardiac applications was confined to coronary calcium scoring, a technique established on electron beam CT scanners and which has less demanding image quality requirements.

Following the introduction of "16-slice" scanners, CT coronary angiography (CTCA) became clinically feasible and improved results were achieved as scanner technology progressed through to "64-slice" systems and beyond. Currently, most CT manufacturers offer scanners capable of acquiring more than 64 slices simultaneously with features that facilitate high-quality cardiac imaging. Despite this, obtaining a successful CTCA scan can still be challenging in some patients.

Selecting a CT scanner is a demanding process, and particularly if the scanner is to be used for cardiac applications. In the UK, it is relatively uncommon to purchase a dedicated cardiac scanner; but, a large percentage of scanners will be used for cardiac applications, and because this is usually the most demanding application, it will often define the scanner specification requirements.

Many factors need to be considered in the selection exercise, including the cost, existing CT equipment, power and space requirements, usability (including ergonomics) and post-processing software. Ideally, procurement teams should include radiologists, radiographers, medical physicists and facility managers. The aim of this article was to discuss only the fundamental technical requirements of a cardiac CT scanner with CTCA in mind and how comparisons should be made in order to make a fair evaluation of the systems.

CT SCANNERS FOR CORONARY ARTERY IMAGING: THE CHALLENGES

Owing to the rapid motion of the heart, and the small structures to be imaged, CTCA is one of the most challenging clinical applications of CT. Recent CT scanner developments have focused on overcoming these challenges, particularly with respect to gantry rotation speeds and *z*-axis coverage, such that the majority of patients requiring a CTCA scan can now be imaged successfully. However, patients with certain characteristics still present difficulties. Recent guidance published by the National

Institute for Health and Care Excellence (NICE)[1] identified these patient groups and recommended that they should be imaged using particular CT scanner models. Four scanners were identified in the guidance, which at the time represented the highest specification model from each of the four major CT manufacturers, and these were termed "new-generation cardiac CT scanners". Since the publication of the NICE guidance, technology has continued to evolve and there are now additional scanner models that can be considered to meet the brief.

The patient groups identified in the NICE report, in which imaging was assumed to be difficult on previous generations of CT scanners, are those with one or more of the following characteristics:

- calcium score >400 AU
- coronary artery stents
- coronary artery bypass grafts
- heart rate >65 bpm
- arrhythmia (heart rate variation not specified)
- obesity—body mass index $>30\,\mathrm{kg\,m^{-2}}$.

The above patient characteristics pose specific imaging challenges. For example, to successfully scan a patient with a fast heart rate places a different demand on the technology to that of a patient with coronary artery stents. Although each of the "new-generation CT scanner" models offer particular technological advantages, currently no single scanner model has the optimal specifications to best overcome all of the challenges posed by the above patient groups.

IMAGING REQUIREMENTS IN CORONARY CT ANGIOGRAPHY: BEATING THE CHALLENGES

The technical CT scanner specification parameters that are considered key to successful CTCA imaging, and how each one of these might provide advantages in specific clinical challenges, are shown in Figure 1 and discussed further below. More detail on how each of these parameters can be enhanced is provided in the technical specifications section.

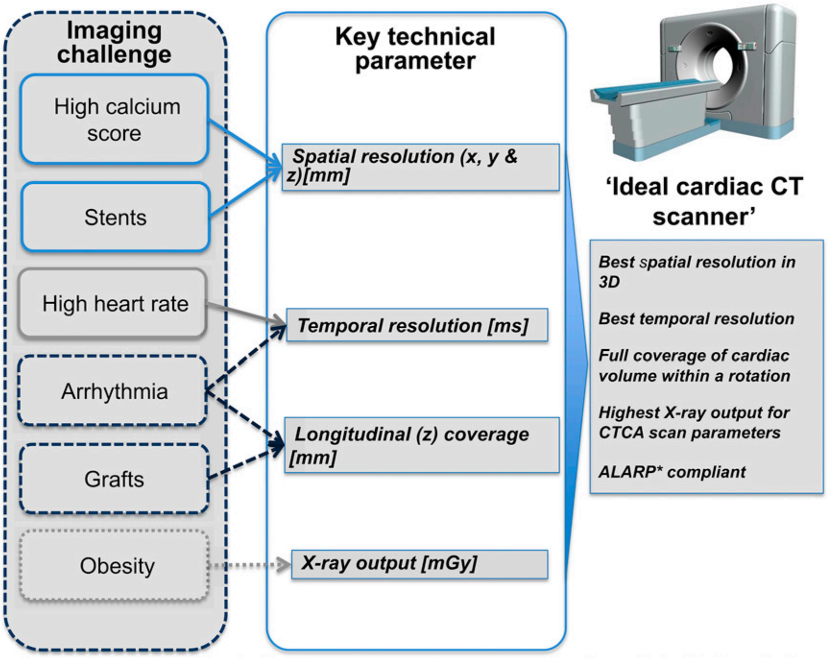
Spatial resolution: the devil is in the detail

The evaluation of coronary artery stenosis requires the accurate depiction of small structures and so, a high spatial resolution in three dimensions (Figure 2) is a key requirement.

The diameter of the coronary vessels tapers from 5 mm in the left coronary artery to 1-mm luminal diameter in the distal left anterior descending artery.[3] Adequate visualization of the coronary arteries requires submillimetre, isotropic spatial resolution. To differentiate a 10–20% coronary stenosis, an isotropic resolution of at least 0.3 mm must be achievable.[4]

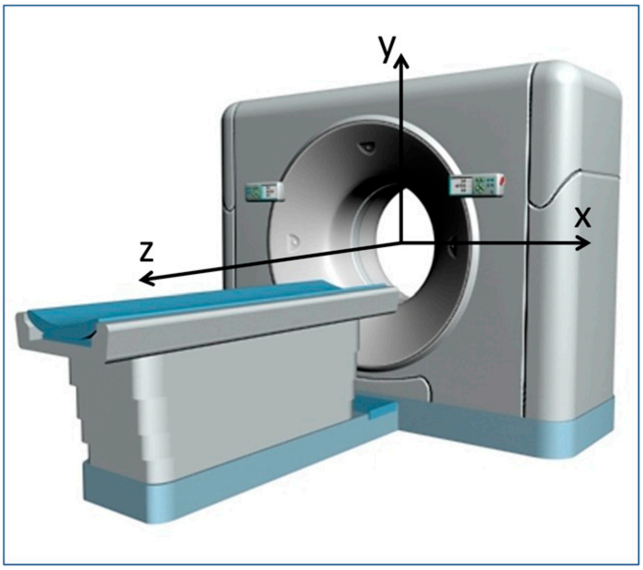
CT scanners have been capable of a scan (*x*–*y*) plane spatial resolution of <0.3 mm even prior to the multislice era. However, resolution along the *z*-axis was limited by the requirement for early scanners to acquire wider slices so that the scan could be completed within a breath-hold. The advantage of current CT systems, capable of imaging 64 slices or more, is their potential to scan routinely with submillimetre slices, thereby matching the *z*-axis spatial resolution to that in the *x*–*y* plane to achieve an

Figure 1. Diagram showing the relationship between the imaging challenge of different patient groups and the technical specification parameter that may help to meet that challenge (adapted from KiTEC report[2] with permission from KiTEC). 3D, three dimensional; CTCA, CT coronary angiography; mGy, milligray; mm, millimetre; ms, millisecond.



* All medical equipment using ionising radiation must be purchased and operated with the radiation protection principle 'as low as reasonably practicable' (ALARP) in mind

Figure 2. The co-ordinate system used in CT scanning.



isotropic spatial resolution. A uniform image quality in all planes results in improved multiplanar and three-dimensional (3D) imaging. Moreover, images in the axial (x–y) plane have reduced partial volume effect and thereby improved contrast resolution.

The detector z-axis dimension is a major determinant of the z-axis resolution, but sampling frequency, interpolation algorithm and detector design also play a part. An adequate spatial resolution is of particular significance in patients with coronary artery stents and/or a high calcium burden. Accurate estimation of the degree of artery stenosis in these patients can be hindered by "blooming artefacts" resulting mainly from heterogeneous attenuation coefficients within the voxels (partial volume effect) and leading to an artificial increase in the size of high-density structures. The artefact can be reduced with a high spatial resolution, leading to potential improvement in diagnostic accuracy.

Temporal resolution: in the blink of an eye

The coronary arteries move rapidly in a complex manner throughout the cardiac cycle. To avoid significant image blur, a CT scanner with not only a good spatial resolution, but also a good temporal resolution (TR) (analogous to a fast shutter speed on a photographic camera) is required.

Husmann et al[5] performed a detailed analysis of the motion of each of the main coronary arteries throughout the cardiac cycle and how it varied with patient heart rate. At a heart rate of 60 bpm, the velocity of the right coronary artery varied from 10 mm per second to 65 mm per second over the cardiac cycle.

The intrinsic TR of a CT scanner can be defined as the time interval over which data to reconstruct a CTCA image are acquired, and the primary requirement for a good intrinsic TR is a scanner with a fast gantry rotation speed. To improve TR, specialized cardiac reconstruction algorithms utilizing only 180° of data for image reconstruction can be employed. On a CT scanner with a single X-ray source, this enables an intrinsic TR of approximately half the gantry rotation time. On dual-source CT scanners, with the two sources positioned at approximately 90° to each other, sufficient data can be acquired in approximately one-fourth of a complete gantry rotation.

In the majority of the current, top-end, single-source cardiac CT scanners, the intrinsic TR is around 125–175 ms. This is generally adequate for patients with stable heart rates of 65 bpm and below. Beta-blocking agents can be used to reduce patient heart rates but, where these are not effective or are contraindicated, a better TR is required. Dual-source CT scanner models have intrinsic TR values of around 65–75 ms. Even on scanners with the best TR, to adequately "freeze" cardiac motion, electrocardiogram (ECG)-gating techniques are employed to enable selection of data for image reconstruction from the most stationary phase of the cardiac cycle.

The TR of CT scanners can be enhanced by various methods discussed later. However, a good intrinsic TR, together with selection of the optimal cardiac phase, is currently regarded as the most robust method for eliminating coronary artery motion artefacts.

Longitudinal (z-axis) coverage: the long and the short of it

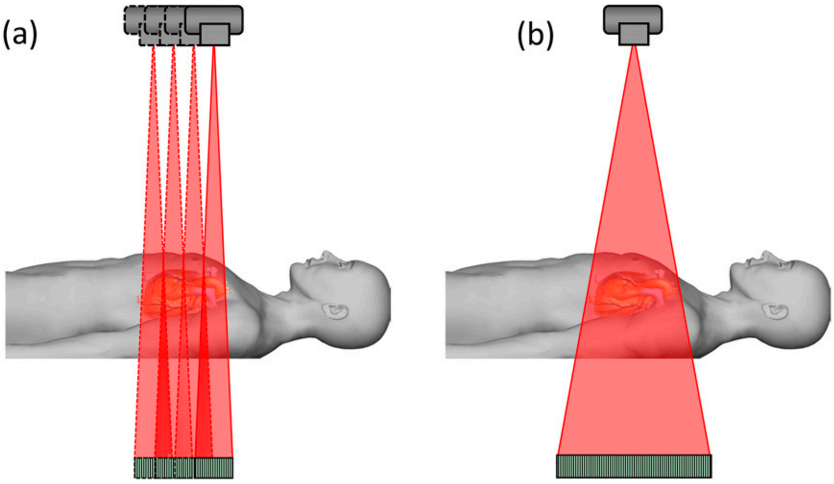
The length of the cardiac anatomy that has to be covered in a CTCA scan is typically around 120–140 mm. As the majority of high-end CT scanners have a z-axis detector length shorter than this, they generally cannot image the whole cardiac volume within a single gantry rotation. Coverage of the full anatomy is commonly acquired as a series of slabs over several heartbeats (Figure 3). The minimum requirement is that the overall scan time does not exceed a comfortable patient breath-hold so that respiratory motion artefacts are avoided. In addition, acquiring the scan in fewer heartbeats reduces the likelihood of misregistration between successively acquired slabs, a particular issue in patients with arrhythmia. Scanners with a detector array dimension of around 160 mm in the longitudinal (z-axis) direction will allow coverage of the whole cardiac volume within a single heartbeat.

Another approach to achieving whole volume coverage within a single heartbeat, available on dual-source scanners, is to perform a helical scan at a very high pitch (>3). The fast table speed allows the whole cardiac volume to be covered in around 250 ms.[6]

X-ray output: a little less noise please

The high TR requirements of CTCA scans require short gantry rotation times. This necessitates powerful X-ray generators capable of delivering high tube currents (mA) (600–1000 mA) to provide a sufficient number of photons for adequate image quality. The recently developed iterative reconstruction (IR) algorithms in CT have somewhat reduced this requirement owing to their noise-reducing characteristics. Despite this, high mA may still be advantageous, particularly in patients with obesity and because of the current trend towards employing low X-ray tube potential (kV) settings to reduce patient dose.

Figure 3. The number of gantry rotations required to cover the cardiac volume is dependent on *z*-axis detector array dimensions. (a) On the majority of scanners, several gantry rotations are required to cover the whole cardiac anatomy; (b) scanners with a 160-mm detector array, or above, can acquire the full cardiac anatomy in a single axial rotation.



Patient dose: how low can you go?

The holy grail of imaging modalities utilizing ionizing radiation is a satisfactory image quality at a minimum radiation dose to the patient. As well as the image quality requirements for successful CTCA imaging, national and European legislation requires that radiation doses from medical examinations adhere to the as low as reasonably practicable principle and that the benefit of the examination outweighs the risk from it.[7]

In recent years, great progress has been made in reducing radiation dose from CT, and this is particularly true for CTCA.[8] However, signal-to-noise ratio (SNR) requirements ultimately define the lowest patient dose that can be achieved whilst still maintaining adequate image quality.

The stochastic radiation risk to a standard patient is quantified in terms of the estimated effective dose.[9] The dose from a CT scan is dependent to some extent on the scanner model, but modern scanners are equipped with many dose-saving features and, if utilized correctly, all are capable of achieving comparatively low radiation doses. Dose variations that exist, on patients with similar characteristics, are mainly due to the scan protocol used. These variations can be particularly high in CTCA where various scan modes, giving very different doses, can be employed. The optimal scan mode and scan parameters are dependent on patient characteristics such as heart rate, stability of heart rate and weight; so, to achieve dose optimization, they must be tailored to the individual patient.

TECHNICAL SPECIFICATIONS: UNDERSTANDING THE NUMBERS

Each CT scanner manufacturer has a portfolio of CT scanner models covering a range from basic to high specification. The high-end scanners generally have capabilities for more complex examinations including cardiac and perfusion scanning and specialized features such as dual-energy scanning.

The scanner models from each manufacturer that would generally be considered in the UK when purchasing a scanner for cardiac applications are listed in Table 1 together with some of the technical specifications regarded as being key to a successful CTCA scan.

The recommendations that exist for the performance requirements of a "cardiac" CT scanner are fairly non-specific. An expert consensus document from 2010 states that such a CT scanner must be capable of simultaneous acquisition of 64 slices and of covering the cardiac volume in a breath-hold time of <20 s.[10] A joint [American College of Radiology (ACR)/North American Society of Cardiovascular Imaging (NASCI)/Society of Pediatric Radiology (SPR)] practice parameter document on the performance and interpretation of cardiac CT[11] gives the following minimum specifications:

- spatial resolution $\leq 0.5 \times 0.5$ mm in x–y plane and ≤ 1 mm in z-axis
- TR ≤ 250 ms
- an "adequate" tube capacity
- minimum section thickness ≤ 1.5 mm.

Otero et al[12] compared the ideal technical requirements of a scanner for performing CTCA against the capabilities of multislice CT scanners as of 2010. Their adapted table is presented (Table 2) with the CT scanner capabilities updated, where relevant, to reflect scanner specifications in 2015.

CTCA scans on patients with the characteristics that place them in the "difficult to image" categories present greater demands for the technology. In the past decade, CT manufacturers have taken different approaches to enhance the performance of scanners, and many of the developments have been focused towards cardiac CT. Some have directed their efforts at improving TR, whereas others have made advances in volume coverage. This makes the process of scanner comparison and selection even more challenging, particularly as technical specifications are not always presented in a comparable format. This section attempts

Table 1. Key specifications of current CT scanners recommended by vendors for CT coronary angiography

Vendor	Scanner model	X-ray source — detector design	Number of detector rows	Detector element z-dimension (mm)	Total detector z-axis coverage (mm)	Minimum gantry rotation time (ms)	Intrinsic TR (ms)	X-ray generator power (kW)
GE Healthcare, Chalfont St Giles, UK	Optima 660	Single	64	0.625	40	350	175	72
	Revolution HD/GSI	Single	64	0.625	40	350	175	107
	Revolution CT	Single	256	0.625	160	280	140	103
Philips Healthcare, Guildford, UK	Ingenuity	Single	64	0.625	40	420	210	80
	iCT Elite	Single	128	0.625	80	270	135	120
	IQon Spectral CT	Single	64	0.625	40	270	135	120
Siemens Healthcare, Frimley, UK	Somatom Definition Edge Stellar	Single	64	0.6	38.4	280	142	100
	Somatom Definition Flash Stellar	Dual	64	0.6	38.4	280	75	2 × 100
	Somatom Force	Dual	96	0.6	57.6	250	66	2 × 120
Toshiba Medical Systems, Crawley, UK	Aquilion PRIME[a]	Single	80	0.5	40	350	175	72
	Aquilion ONE	Single	320	0.5	160	350	175	72
	Aquilion ONE Vision	Single	320	0.5	160	275	137	100

GSI, gemstone spectral imaging; HD, high definition; TR, temporal resolution.

[a] The Aquilion PRIME is available in PRIME 80 and PRIME 160 versions. Both models have the same number of detector rows, but with a maximum of 80 and 160 reconstructed slices per rotation, respectively, in axial scan mode. On the PRIME 160, the two overlapping slices per detector row are achieved with ConeXact software for improved z-axis sampling.

Table 2. Comparison of technical requirement and current capabilities of CT scanners in CT coronary angiography[12]

Technical feature	Ideal requirement	Best currently available performance
Spatial resolution: *x*, *y*, *z* (mm^3)	$0.1 \times 0.1 \times 0.1$	$0.35 \times 0.35 \times 0.35^a$
TR (intrinsic): time to acquire 180° of data (ms)	30	66
z-axis detector coverage: Total *z*-axis detector dimension (mm)	Whole cardiac volume coverage	160
Radiation dose	Minimum to answer specific clinical question	Sub-mSv in an ideal patient but varies according to patient characteristics

mSv, millisievert; TR, temporal resolution.

[a] No systematic comparison data are available, but values of this order are reported.

to clarify some of the confounding areas to enable a more informed and equitable comparison of scanner models.

z-axis volume coverage and number of slices

The cardiac volume needs to be covered in as few heartbeats as possible, ideally within a single heartbeat; so, the length of the detector array in the *z*-axis is a key specification. CT scanners are often classified in terms of "number of slices", such that a "64-slice scanner" is regarded as superior to a "32-slice scanner". However, it is important to understand the distinction between "number of slices" and "number of detector rows". It is primarily the number of detector rows together with the *z*-dimension of each detector row that determines the total *z*-axis coverage per gantry rotation. Some scanners can provide two overlapping sets of data per detector row, thereby doubling the number of slices relative to the number of detector rows. So, for example, a 32-row detector scanner may have the capability of producing 64 reconstructed slices per gantry rotation.

Increasing the number of slices over the number of detector rows can be achieved through either hardware or software methods. The hardware approach utilizes the so-called "*z*-flying (dynamic) focal spot" to acquire the two sets of data,[13] whereas the software approach makes uses of 3D reconstruction algorithms to create overlapping slices.[14] Both these methods can enhance the *z*-axis spatial resolution, but neither help in reducing the overall scan time. Therefore, a 32-row detector, 64-slice scanner will take longer to cover the cardiac volume than a 64-row detector, 64-slice scanner. Patient breath-hold time will increase, with the possibility of an increase in heart rate and/or of ectopic beats, resulting in a greater likelihood of motion and misregistration artefacts.

Figure 4. *z*-axis detector array configurations of modern high-end CT scanners (adapted from KiTEC report[2] with permission from KiTEC). GSI, gemstone spectral imaging; HD, high definition.

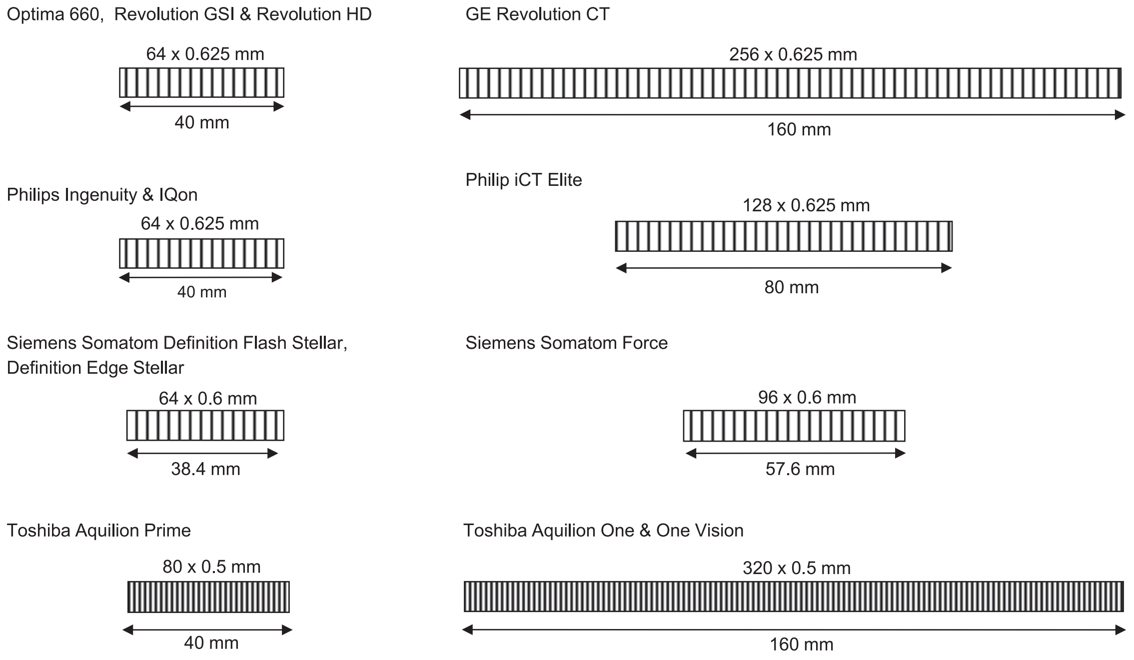


Figure 4 shows a schematic representation of the *z*-axis detector configurations of current high-end multislice CT scanners that range in *z*-axis coverage from just under 40 mm to 160 mm. The three Siemens Somatom Definition models all utilize *z*-dynamic focal spot technology and are generally referred to as 128-slice scanners. For the same reason, the Philips iCT Elite is termed a 256-slice scanner, and the Siemens Somatom Force a 192-slice scanner. The GE Revolution CT and the Toshiba scanners all have the capability of reconstructing two slices per detector row using 3D reconstruction algorithms. The Siemens scanners can further increase the number of reconstructed slices per acquired slice with 3D reconstruction; so, for example, on the Definition Flash Stellar, 384 slices per rotation can be reconstructed. The Philips IQon is said to have the capability of four reconstructed slices per detector row, but so far the amount of technical information available on this scanner is limited.

The "160-mm scanners" can acquire the cardiac volume in a single heartbeat and this has a number of significant advantages in CTCA. Firstly, misregistration artefacts are completely avoided, a particular issue in patients with irregular heart rates. Secondly, the volume of the iodine-based contrast agent can be reduced and thirdly, the scanners are ideally suited to performing dynamic myocardial perfusion studies[15]. In addition, if a better TR is required, the use of multisegment reconstruction is likely to be more robust.

Another factor that can affect the time in which the cardiac volume is acquired is the scan mode used. Scanners with a *z*-axis detector extent of 40 mm take around seven heartbeats in most scan modes. However, on the Siemens dual-source systems, a high-pitch, prospectively ECG-triggered helical mode is available. In this "Flash" mode, the cardiac volume can be acquired within a single heartbeat, although this mode is generally limited to patients with low heart rates, typically <65 bpm.

X-ray beam divergence is a particular consideration on scanners with wide volume coverage, as it can lead to "cone-beam" artefacts. Therefore, more sophisticated 3D reconstruction algorithms are required to mitigate these.[16]

Spatial resolution

In CT, the limiting spatial resolution is governed by focal spot size and detector element size in both the *x*–*y* plane and *z*-direction, but it is also influenced by a number of other factors, primarily the data sampling interval. In the *x*–*y* plane, it is also highly dependent on the type of reconstruction kernel (filter) applied and its cut-off frequency. The sharpest available kernels are often not utilized in CTCA, as they are associated with high levels of image noise, although on patients with stents and/or high calcium scores, sharper kernels are recommended in order to reduce blooming artefacts. Some GE scanners can operate in high-definition mode, in which the detectors are double-sampled in the *x*–*y* plane resulting in a higher scan plane spatial resolution.

It is important that the *z*-axis spatial resolution is matched to that in the *x*–*y* plane, in order to obtain equivalent image quality (*i.e.* isotropic resolution) in all planes. Manufacturers are currently quoting *z*-axis resolution values of <0.3 mm, achieved by *z*-oversampling as well as more advanced reconstruction algorithms and improved detector and data acquisition system characteristics. This is despite *z*-axis detector dimensions of 0.5–0.625 mm.

Table 2 gives the ideal spatial resolution of a CTCA scanner as 0.1 mm in all three axes for precise evaluation of coronary artery stenosis as compared with values of around 0.35 mm currently quoted, so there is still room for improvement in this area.

Comparable spatial resolution data between manufacturers, and even between different scanner models from the same manufacturer, are difficult to obtain, as there are no published standards for making this measurement and no comparative evaluations of technical CT scanner performance. Spatial resolution specifications in the *x*–*y* plane are commonly quoted in terms of the maximum number of line pairs per centimetre discernible or as the frequency at which the modulation transfer function (MTF) drops to a given percentage; *e.g.* 50, 10, 2 and 0%. In the *z*-direction, manufacturers may also provide data in terms MTF values, but often, slice or detector width is still used as a surrogate measure of *z*-axis spatial resolution.

The available spatial resolution data must be carefully scrutinized if values provided by manufacturers are to be compared. Note should be made of the following:

- reconstruction kernel; is the value quoted applicable to CTCA scans?
- % of MTF at which resolution is quoted; 50%, 10%...0%?
- Reconstruction field of view (spatial resolution can vary with this parameter)
- gantry rotation time; number of samples acquired may vary with time
- "high-resolution" modes, such as dynamic focal spot or attenuating "comb"; have they been used and are they available in CTCA?

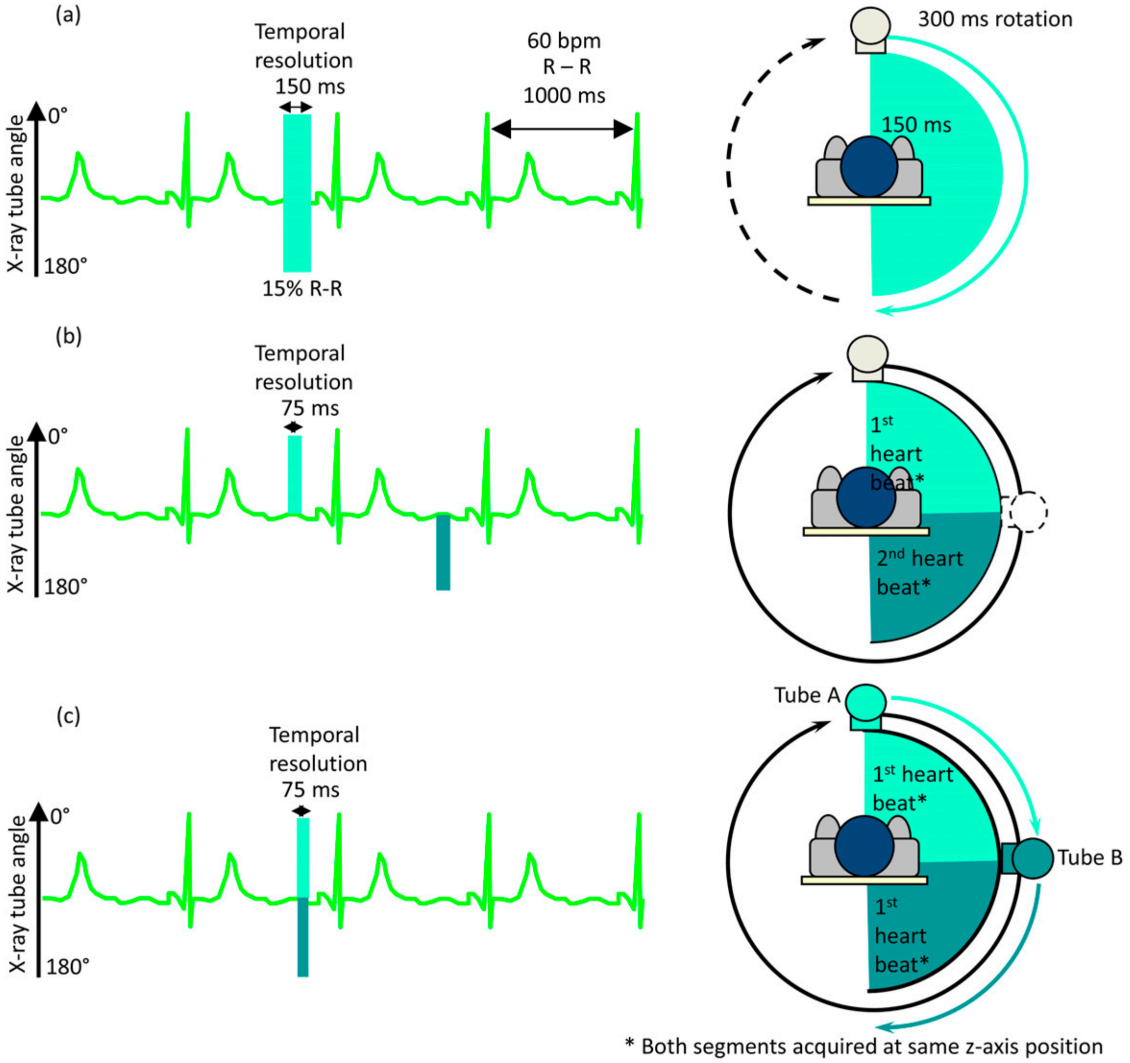
It is unlikely that all this information will be available, unless the manufacturers are specifically asked to provide it, and so visual assessment of images may be the only approach to comparing performance in this respect. Care should be taken to compare images from patients with similar characteristics and scanned at optimal settings on each scanner.

Temporal resolution and gantry rotation time

As stated earlier, a good TR (short data acquisition window) is a fundamental requirement of a scanner for CTCA, and the intrinsic TR can be defined as half or one-fourth of the gantry rotation time on single-source and dual-source systems, respectively. Comparison of intrinsic TR specifications should therefore be relatively straightforward.

A good intrinsic TR is the most robust method of achieving motion-free images and enabling scanning of patients with high heart rates without the necessity for beta blockers. It also allows a higher heart rate cut-off for scanning in lower dose modes, such as prospectively ECG-triggered axial scan mode. Dual-

Figure 5. Temporal resolution in cardiac CT scanning: (a) with a "half-scan" reconstruction algorithm and (b) with a "multisegment" reconstruction algorithm (two-segment reconstruction); (c) with dual-source CT scanner, the two 90° segments of data are acquired simultaneously (adapted from CEP Market review,[17] authors attempted to contact the original rights holder for permission but were unsuccessful). bpm, beats per minute; ms, millisecond.



source scanners have a good intrinsic TR, as they acquire the required data for image reconstruction in one-fourth of a rotation time (Figure 5c). Patients with mild arrhythmia should also benefit from good TR, as this allows more flexibility in the cardiac phase used for image reconstruction. Where the intrinsic TR is insufficient, other approaches can be used to achieve an improved effective TR.

One such approach, available on all scanners, is multisegment reconstruction, where data are taken from successive heartbeats to reconstruct images at a particular anatomical location. For example, in two-segment reconstruction, the 180° of data required is taken from two consecutive heartbeats instead of from a single heartbeat (Figure 5a,b). The optimal effective TR is achieved if 90° of data is taken from each of the two beats and in this case, it will be equal to half the scanner's intrinsic TR. Data from three successive heartbeats can achieve an optimal TR of one-third of the intrinsic TR. Manufacturers may quote TR values as low as one-tenth of the gantry rotation time, which would be the optimal value achieved for a five-segment reconstruction. However, use of the multisegment approach requires a very steady heart rate if motion and misregistration artefacts are to be avoided. Multisegment reconstruction also generally leads to a higher radiation dose because use of a lower pitch may be required.

A further drawback of using multiple segments is that the optimal TR can also only be achieved at specific heart rates, where the scanner rotation frequency and the heart rate are in asynchrony. A final shortcoming is that on the majority of scanners, it is only available when scanning in retrospectively gated helical scan mode. The exceptions to this are CT scanners with full cardiac volume coverage. On these scanners, multisegment reconstruction can also be performed in the lower dose prospectively ECG-triggered axial mode, sometimes referred to as prospectively ECG-triggered volume mode. However, it should be noted that the radiation dose in this mode increases in proportion to the number of segments acquired.

Another approach to improving the intrinsic TR is the use of software motion correction algorithms to correct for cardiac motion. GE has such an algorithm available on its scanners and claims an effective TR as low as 24 ms.[18] Early studies using this approach show promising results,[19] but the results of a prospective, international trial [validation of an intracycle CT motion correction algorithm for diagnostic accuracy (ViCTORY)] are still awaited.[20]

X-ray output and generator power

Powerful generators are required to provide the high X-ray tube current (mA) needed with the short image acquisition times used in CTCA. However, generator power alone cannot be taken as an indicator of good performance in this respect. Other specifications that need to be considered alongside generator power are the scanner geometry X-ray tube filtration and gantry rotation time. Scanners with a shorter geometry (focus-to-detector distance) will require a lower generator power to achieve the same photon flux at the detectors, all other things being equal. Also, scanners with slower rotation times will obviously achieve the same tube current—time product (mAs) at a lower mA; so, a lower generator power may be adequate, but at the expense of a reduced TR.

A measure of a high photon output that takes into account all the above considerations is radiation dose. Data on dose-related quantities are provided in specification documents as the CT dose index (CTDI), the absorbed dose (milligray) in standard dosimetry phantoms. Comparing CTDI values will provide a measure of the X-ray output achieved on different scanner models. This should be performed for the minimum rotation time available and maximum mA at the tube kilovoltage setting of interest. A scanner with a high CTDI value should perform well in terms of SNR. The caveat to making comparisons in this way is that it assumes that all scanners have the same dose efficiency. If scanners vary significantly in terms of dose efficiency, or in the level of noise reduction achieved with IR, then comparisons of this type will not be valid. However, they will still be more meaningful than considering generator power alone.

Effective dose and CT dose index

CT scanner technical specifications usually include data on the radiation dose in terms of the CTDI.[21] This is one of the few performance specifications that can be directly compared because standards exist for the measurement of this quantity. However, in the form that it is specified, the normalized CTDI (milligray per mAs), it provides no information on patient dose. A high, normalized CTDI value does not represent a high-dose scanner. For radiation risk comparisons, the CTDI value for the scan parameters employed clinically must be known, as well as the length of the volume scanned, to calculate the dose–length product (milligray centimetre).

Information on scan parameters used for CTCA scans is difficult to obtain because of the various scan modes that can be implemented, the choice of which is highly dependent on patient characteristics and user preference. Description of the CTCA scan modes available is well covered elsewhere[22] and is beyond the scope of this article. Generally, prospectively ECG-triggered scan modes result in a lower radiation dose than retrospectively ECG-gated modes and so the former are the choices of preference where appropriate. Use of these lower dose modes has had a significant impact on the reduction in doses from CTCA scans. However, they are often limited to patients with low and stable heart rates. On some scanners, for example those with a high TR, the cut-off heart rate for low-dose modes is higher and so they can be used even on some challenging patients, where heart rate cannot be reduced with the use of beta-blocking agents. This is something that should be considered in scanner selection.

Noise reduction software, particularly the recent introduction of IR methods in CT, will achieve a given SNR at a lower radiation dose. All manufacturers now have iterative algorithms available; however, some methods are more refined, leading to greater noise reduction. Further considerations are the time penalty that may be involved with iterative algorithms and also whether the particular iterative approach is available for cardiac applications. The availability of other dose reduction features such as automatic mA and kV selection and dynamic collimators to reduce the dose in helical scanning should be ascertained. A low X-ray kV is another dose reduction strategy, as it improves the contrast-to-noise ratio in CTCA scans, particularly in patients who are small. The minimum kV available is generally 80 kV, although some Siemens scanners models also have a 70-kV setting.

Estimates of effective dose (millisievert) in CT are commonly made by applying conversion factors to the dose–length product data obtained from the scanner.[23] Various tables of such conversion factors exist in the literature based on average values for different ranges of CT scanner models, different International Commission of Radiological Protection organ sensitivity values and different anatomical scan ranges. The factor commonly used by manufacturers when quoting effective doses for cardiac CT is $0.014\,\mathrm{mSv\,mGy^{-1}\,cm^{-1}}$. However, this factor is now technically obsolete and a more appropriate factor is regarded as being in the order of $0.03\,\mathrm{mSv\,mGy^{-1}\,cm^{-1}}$, resulting in an approximate doubling of the effective dose.[24] Therefore, when making radiation risk comparisons, attention should be paid to the conversion factor that has been used. Patient size also needs to be considered, as these calculations are only applicable to patients who are standard sized (approximately 70-kg weight).

DISCUSSION AND SUMMARY

Based on CT scanner technology currently available, the ideal CT scanner for CTCA examinations would be a dual-source scanner with 160-mm detector dimension in the *z*-axis and the highest spatial resolution in all planes, whilst achieving satisfactory images at the lowest radiation dose. This is a simplistic approach, as many other scanner features need to be considered. However, the purpose here has been to demonstrate that the main imaging requirements in CTCA, namely TR, spatial resolution, volume coverage and X-ray output, are important considerations when purchasing a CT scanner and that no single existing scanner model has the highest specification for each of these parameters.

There is plentiful evidence showing the advantages of the high intrinsic TR achieved on dual-source systems in the various "difficult to image" patient groups, and the benefits of this are indisputable for patients with high heart rates.[25–27] Where this is not available, the TR can be improved using multisegment reconstruction and this is most effectively implemented on scanners where the detector banks extend over the whole cardiac volume. An alternative approach, implemented by GE, is the use of motion correction software to correct for cardiac motion.

Similarly, publications exist showing the advantages of scanners with *z*-axis detector array dimensions covering the full cardiac anatomy and thereby avoiding misregistration artefacts that can occur when acquiring the cardiac volume over several heartbeats.[28,29]

Comparisons of spatial resolution specifications are difficult, as quoted data are not easily comparable. GE has a "high-definition" mode available for an improved *x*–*y* plane spatial resolution. However, it is important to ascertain whether equivalent resolution can be achieved in the *z*-direction and all manufacturers provide methods of oversampling in the *z*-axis to try to meet this aim.

To achieve an adequate SNR with the fast rotations needed in CTCA requires high tube current (mA) and so scanners now have more powerful generators. This allows use of low tube kilovoltage settings, which can enable dose reduction through improved contrast-to-noise ratios. Powerful generators also enable improved image quality on patients with obesity. A fairer comparison than the high generator power is the CTDI value obtained with appropriate scan parameters, as the latter primarily determines the achievable SNR. The level of noise reduction achievable with various iterative algorithms should also be ascertained.

Comparison of patient radiation dose on different CT scanner models is arguably the most challenging issue, as this is highly dependent on the scan mode used and the numerous scan parameters selected. In turn, these will be dependent on the patient characteristics. Manufacturers are often reluctant to quote typical doses even when the patient characteristics are specified. However, it is important to ascertain which dose reduction features are available on each scanner model and whether they can be utilized in cardiac mode.

Although coronary angiography is currently the most common cardiac examination performed on CT scanners, further applications are being explored. Functional imaging, to assess the haemodynamic status of the myocardium and complement the anatomical assessment of coronary stenoses, is a developing application.[30] Another emerging area is the application of dual-energy CT in cardiac investigations.[31] In these areas, manufacturers have again used different approaches to achieve the same aim, and different aspects of scanner technology need to be considered if the efficacy of these applications is to be compared.

Although the selection of the "ideal" scanner for CTCA is challenging, systematic comparison of specification data and a clear understanding of the implications of each technical parameter on scanner performance will lead to a more informed choice of the CT scanner model.

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