SELECTING A CT SCANNER FOR CARDIAC IMAGING

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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.

Keywords— **CT scanner, Coronary angiography, Selection of Imaging equipment, BJR.**

I. INTRODUCTION

Clinical interest in the application of computed tomography for the imaging of coronary vessels dates back to 1998 with the introduction of '4-slice' CT scanners. These early multislice models posed limitations for performing coronary angiography, therefore their use in cardiac applications was confined to coronary calcium scoring, a technique established on electron beam CT (EBCT) 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's specification requirements.

Many factors need to be considered in the selection exercise, including 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 facilities managers. The aim of this paper is 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.

II. CT SCANNERS FOR CORONARY ARTERY IMAGING: THE CHALLENGES

Due to the rapid motion of the heart, and the small structures to be imaged, CTCA is one of the most challenging clinical applications of computed tomography. 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 greater than 400 Agatston units;
- Coronary artery stents;
- Coronary artery bypass grafts;
- Heart rate greater than 65 bpm;
- Arrhythmia (heart rate variation not specified); and
- Obesity - BMI greater than 30 kg/m2.

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 offers 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.

III. IMAGING REQUIREMENTS IN CORONARY CT ANGIOGRAPHY (CTCA): 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.

•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 not only requires a CT scanner with a good spatial resolution, but also one with a good temporal resolution (analogous to a fast shutter speed on a photographic camera).

•Longitudinal (Z-axis) coverage: The long and the short of it

The length of cardiac anatomy that has to be covered in a CTCA scan is typically around 120 mm to 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).

•X-ray output: A little less noise please

The high temporal resolution requirements of CTCA scans require short gantry rotation times. This necessitates powerful x-ray generators capable of delivering high tube currents [600 – 1000 mA] to provide a sufficient number of photons for adequate image quality.

•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 ALARP (as low as reasonably practicable) principle and that the benefit of the

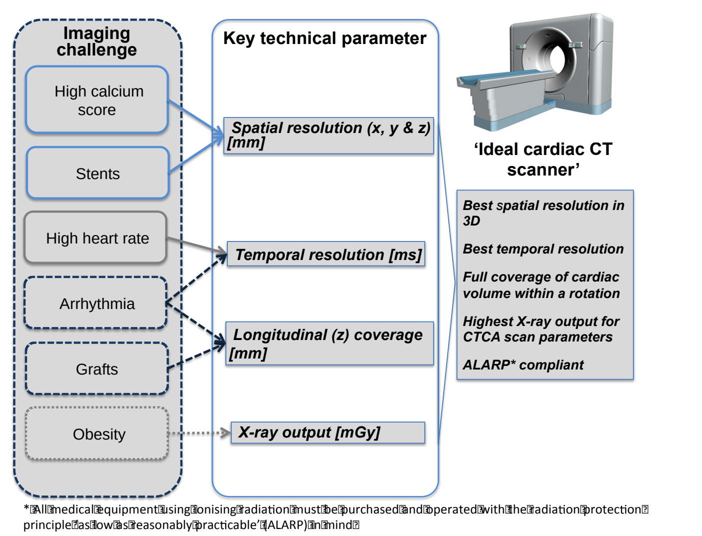

Figure 1. Diagram showing the relationship between the imaging challenge of different patient groups and the technical specification parameter that may help to meet that challenge (adapted from [2])

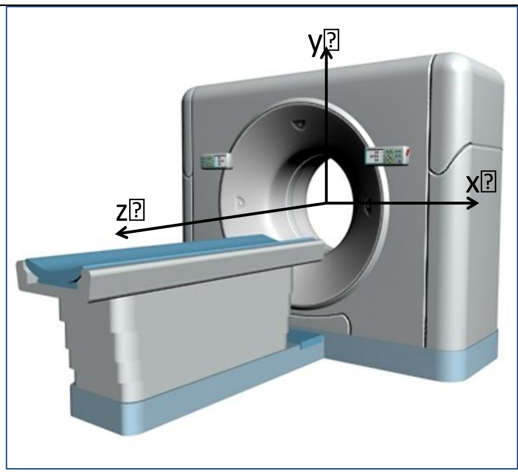

Figure 2. Co-ordinate system used in CT scanning

examination outweighs the risk from it [3].

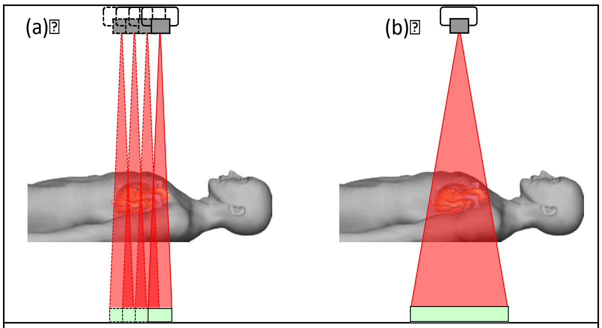

Figure 3. Number of gantry rotations required to cover the cardiac volume is dependent on z-axis detector array dimensions.
(a) on the majority of scanners several gantry rotations are required to cover the whole cardiac anatomy
(b) scanners with an 160 mm detector array, or above, can acquire the full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

IV. 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 specialised 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 less than 20 seconds [4]. A joint (ACR/NAsSCI/SPR) practice parameter document on performance and interpretation of cardiac CT [5] gives the following minimum specifications:

• spatial resolution ≤ 0.5 x 0.5 mm in x-y plane and ≤ 1 mm in z-axis;
• temporal resolution ≤ 250 ms;
• an 'adequate' tube capacity;
• minimum section thickness ≤ 1.5 mm.

Otero et al compared the ideal technical requirements of a scanner for performing CTCA against the capabilities of multislice CT scanners as of 2010 [6] 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 last decade CT manufacturers have taken different approaches to enhance the performance of scanners, and many of the developments has been focused towards cardiac CT. Some have directed their efforts at improving temporal resolution, 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 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-detector row 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 either through hardware or software methods. The hardware approach utilises the so-called 'z-flying (dynamic) focal spot' to acquire two sets of data [7] whereas the software approach makes uses of three dimensional (3-D) reconstruction algorithms to create overlapping slices [8]. Increasing the number of slices over the number of detector rows can be achieved either through hardware or software methods. Both these methods can enhance the z-axis spatial resolution through z-over-sampling, but do not to reduce the overall scan time.

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 '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 iodine-based contrast agent can be reduced, and thirdly the scanners are ideally suited to performing dynamic myocardial perfusion studies [9]. In addition, if a better temporal resolution is required the use of multisegment reconstruction is likely to be more robust.

Another approach to achieving single heartbeat cardiac coverage is with dual x-ray tube systems available from Siemens. A high pitch, prospectively ECG-triggered helical mode ('Flash' mode) is employed, but this is generally limited to patients with low heart rates, typically less than 65 bpm.

X-ray beam divergence is a particular consideration on scanners with wide volume coverage as it can lead to 'cone beam' artifacts. Therefore, more sophisticated 3-D reconstruction algorithms are required to mitigate these [10].

•*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 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. Some GE scanners can employ a HD (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. Despite z-axis detector dimensions of 0.5 – 0.625 mm, manufacturers are currently quoting z-axis resolution values of less than 0.3 mm, achieved by z-over-sampling (described in the previous section) as well as more advance reconstruction algorithms and improved detector and data acquisition system characteristics.

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 to values of around 0.35 mm currently quoted, so there is still room for improvement in this area.

Vendor	Scanner model	x-ray source – detector design	No. of detector rows	Detector element z-dimension (mm)	Total detector z-axis coverage (mm)	Min. gantry rotation time (ms)	Intrinsic temporal resolution (ms)	x-ray generator power (kW)
GE Healthcare(1)	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(2)	Ingenuity	Single	64	0.625	40	420	210	80
	iCT Elite	Single	128	0.625	80	270	135	120
	IQon Spectral CT (5)	Single	64	0.625	40	270	135	120
Siemens Healthcare(3)	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 x 100
	Somatom Force	Dual	96	0.6	57.6	250	66	2 x 120
Toshiba Medical Systems(4)	Aquilion PRIME	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

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

(1) Chalfont St. Giles, UK
(2) Guildford, Surrey, UK.
(3) Frimley, Surrey, UK.
(4) Crawley, West Sussex, UK.
(5) As of April 2016 Philips IQon spectral CT is not yet CE marked

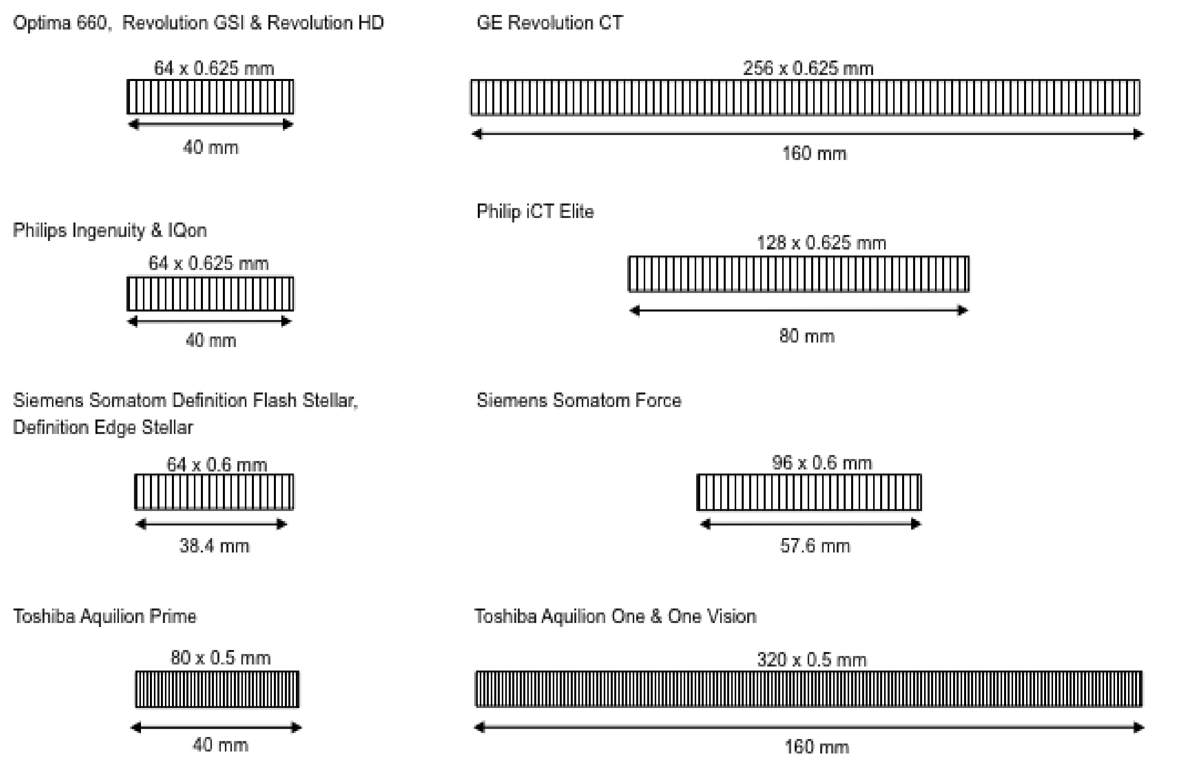

Figure 4 z-axis detector array configurations of modern high-end CT scanners (adapted from [2])

•*Temporal resolution (TR) and gantry rotation time*

As stated earlier, good temporal resolution (short data acquisition window) is a fundamental requirement of a scanner for CTCA, and the intrinsic TR can be defined as half or a quarter 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 to stabilize the hear rate. It also allows a higher heart rate cut-off for scanning in lower dose modes, such as prospectively ECG-triggered axial (PTA) scan mode. Dual source scanners have a good intrinsic TR as they acquire the required data for image reconstruction in one quarter of a rotation time (Figure 5c). Patients with mild arrhythmia should also benefit from good temporal resolution as this allows more flexibility in the cardiac phase used for image reconstruction. Without a sufficient intrinsic TR, other approaches can be used to improve the effective temporal resolution where required.

One such approach, available on all scanners, is multi-segment 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 five segment reconstruction. However, there are a number of drawbacks associated with the use of multisegment reconstruction, including higher radiation doses.

Another approach to improving the intrinsic TR is the use of software motion correction algorithms to correct for cardiac motion. General Electric (GE) has such an algorithm available on its scanners and claims an effective TR as low as 24 ms [12]. Early studies using this approach show promising results [13], but the results of a prospective, international trial (VICTORY) are still awaited [14].

Technical feature	Ideal requirement	Best currently available performance
Spatial resolution: x, y, z (mm^3)	0.1 x 0.1 x 0.1	0.35 x 0.35 x0.35 (1)
Temporal resolution (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 ideal patient but varies according to patient characteristics

Table 2. Comparison of technical requirement and current capabilities of CT scanners in CTCA (adapted from Otero et al [6])
(1) No systematic comparison data available, but values of this order are reported

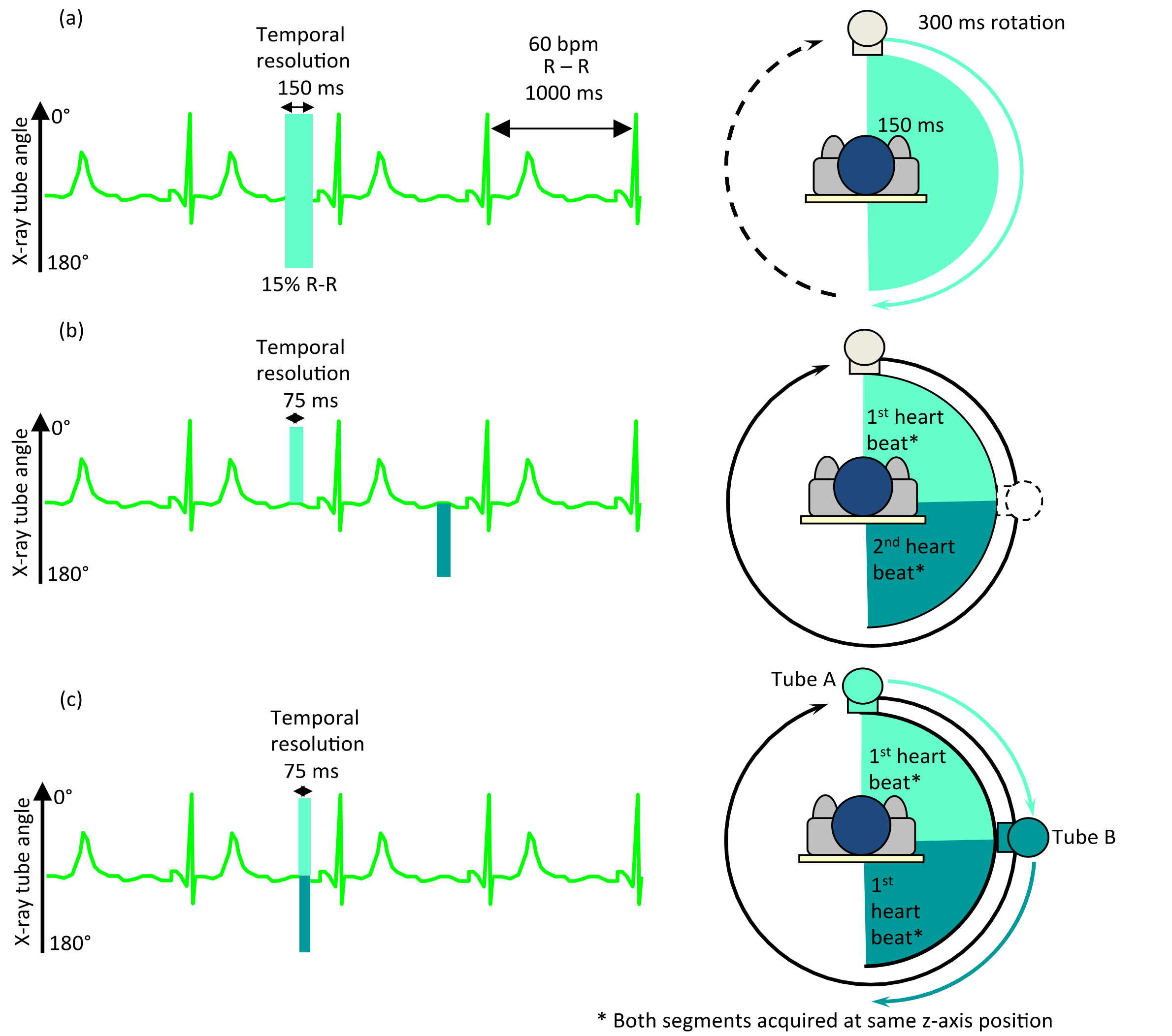

Figure 5. Temporal resolution in cardiac CT scanning: (a) with 'half-scan' reconstruction algorithm; (b) with 'multi-segment' reconstruction algorithm (2 segment); (c) with dual source CT scanner the two 90° segments of data are acquired simultaneously (adapted from [11])

•*X-ray output and generator power*

Powerful generators are required to provide the high x-ray tube currents 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 and the 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 tube current (mA) so a lower generator power may be adequate but at the expense of a reduced temporal resolution.

•*Effective dose and CTDI*

CT scanner technical specifications usually include data on the radiation dose in terms of the CTDI. This is one of the few performance specifications that can be directly compared because standards exist for the measurement of this quantity [15]. However, in the form that it is specified, the normalised CTDI (mGy.mAs-1), provides no information on patient dose. A high, normalised 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 (mGy.cm).

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.

Noise reduction software, particularly the recent introduction of iterative reconstruction (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. The availability of other dose reduction features such as automatic tube current and tube potential selection and dynamic collimators to reduce the dose in helical scanning should be ascertained.

V. 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 temporal and 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 temporal resolution 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 [16,17,18]. Where this is not available the TR can be improved using multi-segment reconstruction and this is most effectively implemented on scanners where the detector banks extend over the whole cardiac volume. An alternative approach, implemented by, one manufacturer, 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 [19,20].

Spatial resolution specifications quoted by manufacturers are not easily comparable. Fpr example, one manufacturer has a ‘high definition’ (HD) mode available for 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 over-sampling in the z-axis to try to meet this aim.

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

Comparison of patient radiation dose on different CT scanners 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 [21]. Another emerging area is the application of dual energy CT in cardiac investigations [22]. 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 proper understanding of their implications will allow fairer comparison and lead to a more informed choice of CT scanner model.

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