I.1

A Practical Approach to MDCT

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Introduction

Over the past 8 years, computed tomography (CT) technology has developed tremendously with the introduction of multidetector-row CT (MDCT) scanners to the clinical radiology practice [1]. Use of CT scanning has increased immensely over the last decade with introduction of newer applications. Demand for better technology continues to propel vendors to develop further innovations in very short time periods. As a result, it has become difficult for many radiologists, physicists, and technologists to keep up with the pace of development. This chapter outlines growth patterns in MDCT application and use and the history of CT technology and describes the fundamentals of MDCT technology.

MDCT: Explosive Growth Patterns

It is estimated that there are more than 25,000 CT scanners in the world, and since 1998, worldwide CT sales have doubled. In 2002, the CT market was reported to be worth in excess of US$2.6 billion [1]. A recent survey indicates that every year, about 90 million CT examinations are performed globally, which corresponds to a frequency of 16 CT examinations per 1,000 inhabitants [1, 2]. According to the 2000–2001 Nationwide Evaluation of X-ray Trends (NEXT) – a survey of patient radiation exposure from CT, performed under the auspices of the United States Food and Drug Administration – approximately 58 million (± 9 million) CT studies are performed annually in 7,800 CT facilities in the United States [1]. As regards CT applications, during 1991–2002, vascular and cardiac applications of CT showed highest growth rates (over 140%), followed by much smaller increments in abdominal, pelvic, thoracic, and head and neck applications (7–27%).

MDCT: Chronology of Technological Advances

- **1971**: The Nobel laureate Sir Godfrey Neobold Hounsfield at the Electrical and Musical Industries, London, a British electronics and music company, developed the first conventional CT scanner. It took 15 h to scan the first patient using this CT instrument and 5 min to acquire each image.

- **1971–1976**: During this period, four generations of conventional CT scanners were developed, and the scan time for each image dropped manifolds to 1–2 s. These conventional scanners revolved a single X-ray tube and detector array on a gantry assembly around the patient. Following each revolution, the X-ray tube and/or detector array returned to their initial position to “unwind” their attached wires and prepare for the next revolution after table movement.

- **Early 1990s**: Just as magnetic resonance imaging (MRI) threatened to make in-roads into several “CT applications,” introduction of slip-ring or spiral or helical CT technology marked the beginning of a resurgence of CT scanning in clinical practice. Helical scanning obviated the need for wires and hence the “unwinding” time by using innovative slip-rings on the gantry assembly. An increase in temporal resolution (decrease in scan time) to subsecond durations and acquisition of contiguous volumetric scan data with helical CT scanners improved dynamic contrast-enhanced studies and three-dimensional (3-D) rendering of axial source data.

- **Late 1990s to 2005**: During this period, different vendors offered MDCT scanners with several different slice options from 2, 4, 6, 8, 10, 16, 32, 40, and 64 slices per revolution. The addition of multiple detector rows to the detector array of helical

CT scanners in the scanning direction or Z-axis allowed acquisition of more than one image per revolution of X-ray tube and detector array around the patient and led to development of multidetector or multisection, multichannel, multislice, or multidetector-row helical CT scanners. MDCT scanners offer several advantages over the prior helical and nonhelical CT scanners. In addition, there are several differences in the hardware and software components of single-slice helical CT and MDCT scanners. Depending on the detector configuration, MDCT scanners have multiple detector rows in the scanning direction or Z-axis. The number of detector rows in MDCT scanners can be less than the number of slices reconstructed per rotation (Siemens Sensation 64 with double Z-sampling), equal to the number of slices per rotation (LightSpeed VCT, General Electric Healthcare Technologies), or more than the number of reconstructed slices (LightSpeed QXi, General Electric Healthcare Technologies). For most MDCT scanners, the smallest reconstructed slice thickness is equal to the thickness of an individual detector row. For example, with 64*0.625 detector configuration (LightSpeed VCT), minimum slice thickness is 0.625 although it is possible to generate images with 1.25-, 2.5-, 3.75-, 5-, and 10-mm slice thickness also. However, one vendor (Siemens Medical Solutions) provides scanners that can acquire 0.4-mm slices with 0.6-mm detector width, due to double Z-sampling that occurs due to dynamic, online motion of the focal spot (Z-flying focal spot) and X-ray beam projections over adjoining detector rows.

Compared with single-slice CT, MDCT permits image reconstruction at various slice thicknesses different from the one chosen prior to the scan. Also, MDCT scanners allow faster scan times (330–350 milliseconds), wider scan coverage, and thinner section thickness. Higher temporal resolution helps in vascular and cardiac scanning, better utilization of contrast medium injection bolus, as well as scanning of uncooperative, breathless, or pediatric patients (less need for sedation or shorter duration of sedation). Wider scan coverage with MDCT scanners helps in vascular studies over longer regions, such as chest, abdomen, pelvis for aortic aneurysms or dissection workup, and peripheral CT angiography from origins of renal arteries to feet. Along with wider coverage, MDCT can also acquire "isotropic" scan data, which helps create exquisite 3-D or orthogonal multiplanar images. In addition, due to the wider detector configuration and use of cone-shaped X-ray, more complex cone-beam reconstruction techniques are used for MDCT compared with single-slice CT scanners. These cone-beam reconstruction techniques help reduce streak artifacts, particularly at the site of inhomogeneous objects in the scanning direction, such as ribs.

- **2005**: At 330–350 ms gantry revolution time, MDCT scanners are approaching the engineering limits of the gantry to withstand the mechanical forces from gantry components, so further improvements in scan time appear challenging. For cardiac or coronary CT angiography studies, however, a higher temporal resolution may imply better quality examinations in patients with higher or irregular heart rates. In this respect, dual-source MDCT scanners (Siemens Medical Solutions), with two X-ray tubes (both 80 kW) and two detector arrays (both with 64-slice acquisition per rotation with double Z-axis sampling), may prove beneficial by decreasing single-segment reconstruction scan time to 83 ms [3, 4]. However, patient studies are needed to validate the findings of initial phantom studies. Another recent innovation in MDCT technology is introduction of "sandwich" detector array (Philips Medical Systems), which can enable acquisition of images with characteristics of dual-energy spectra. The dual-source MDCT can also acquire dual kilovoltage (kVp) or energy image data when different kVp are selected for the two sources. However, rigorous studies will be required to assess the clinical potential of dual-energy CT scanning.

MDCT: Practical Approach to Building Scan Protocols

Several important considerations apply when building an "optimum" scanning protocol (Table 1). An "optimum" scanning protocol may be defined as one that provides adequate diagnostic information with an appropriate amount of contrast media and as low as reasonably achievable radiation dose (Table 2). Important aspects of a diagnostic CT study that must be considered while making a protocol are summarised in Figure 1 and include [5]:

- **Diagnostic indication**: Will help determine the number of phases (one or more, arterial, venous, delayed), scan area of interest, need for contrast (oral and/or rectal and/or intravenous), contrast administration protocol, scanning parameters, and appropriate radiation dose required to generate images to answer the diagnostic query. Development of specific scanning protocols for different clinical indications can help in optimizing workflow and managing radiation dose [6, 7].

- **Scan area of interest and scan direction**: It is important to predetermine the appropriate region of interest based on clinical indication [6, 8], for example, scanning of regions such as abdomen only, abdomen-pelvis, or chest-abdomen-pelvis. Concerns have been raised about "overextending" the scan area of interest, as faster MDCT scanners require very little extra time to cover extended scan

Table 1. Important scanning parameters and contrast considerations that must be addressed during development of scanning protocols for a given diagnostic indication

CT scanning parameters	Contrast consideration
Scan area of interest	Contrast versus noncontrast
Scan direction	Route
Localizer radiograph	Concentration
Scan duration	Volume
Gantry revolution time	Rate of injection
Table speed, beam pitch, beam collimation	Trigger-fixed, automatic tracking, or test bolus
Reconstructed section thickness	
Extent of overlap	
Reconstruction algorithms	
Tube potential	
Tube current and automatic exposure control	
Radiation dose	

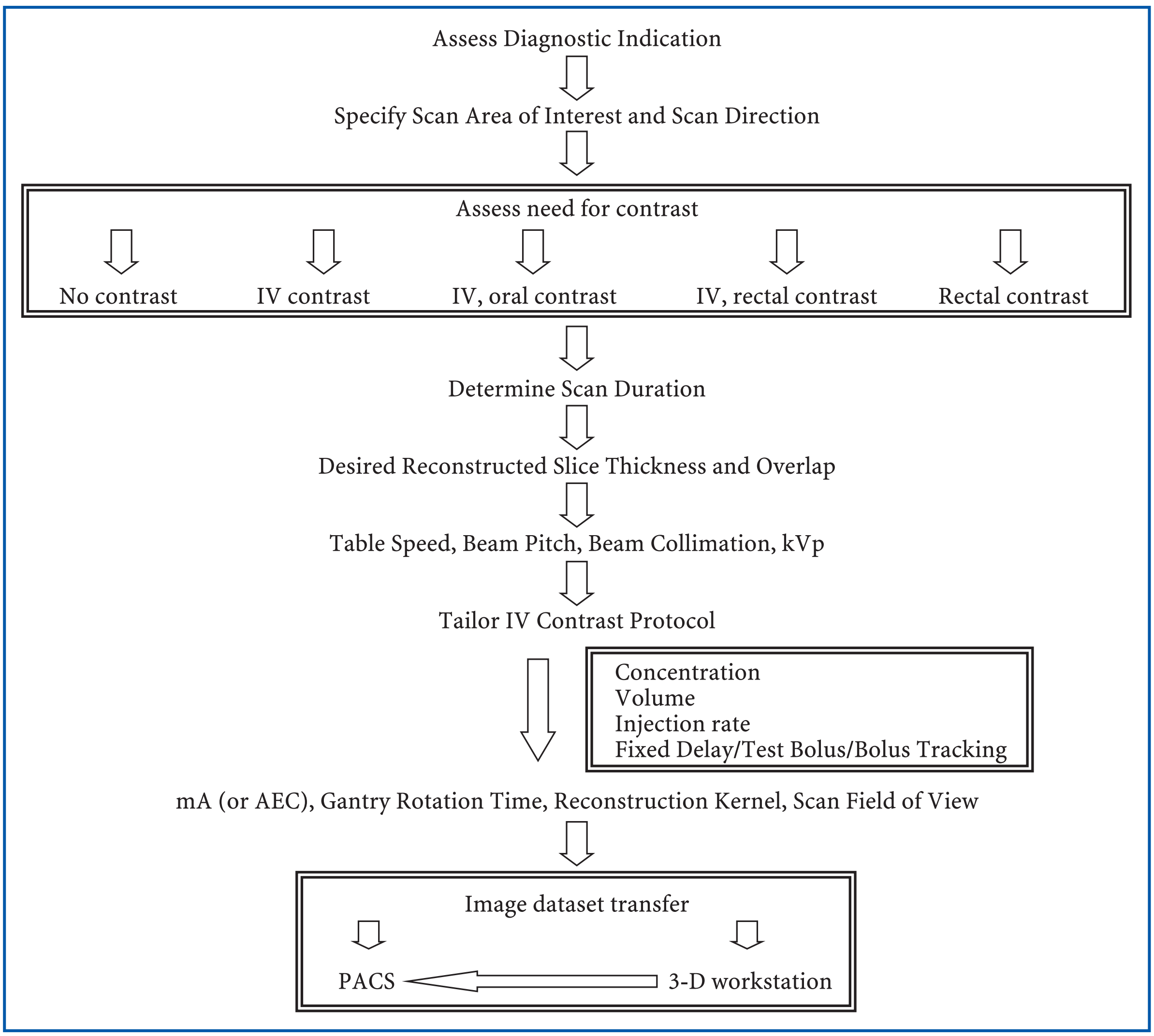

Fig. 1. Building blocks for scanning protocols

Table 2. Salient features of multidetector-row computed tomography (MDCT) scanners

Features	Details
X-ray tube	80–100 kW Higher tube current output (up to 800 mA) Less issues with tube cooling Z-flying focal spot (double Z-sampling)[a]
X-ray filters	Prepatient beam filters – to improve dose efficiency Bowtie filters – to reduce dose (especially cardiac applications)
Detector array:	> one detector row in scanning direction (Z-axis) Effective detector widths: may be constant or variable Effective detector row width (64-MDCT): 0.5, 0.6, or 0.625 mm Most scanners: effective detector width = section width Double Z-sampling: effective detector width ⩾ section width[a]
DAS:	Represents data acquisition system or data channels Determines slice profiles (number of slices per rotation) Example: 4 data channels: 16 detector rows for 4-slice MDCT 64 data channels: 64 detector rows for 64-slice MDCT
Detector configuration	Describes number of data channels and effective detector row width Example: 16×1.25 mm = 16 data channels; 1.25-mm row width
Beam collimation	Refers to X-ray beam width Cone-shaped beam leads to “overbeaming” (penumbra effect) = number of data channels × effective detector row width Example: 16-slice MDCT a. 16 data channels × 1.25-mm row width = 20 mm b. 16 data channels × 0.625-mm row width = 10 mm Radiation dose: b > a
Beam pitch	Table speed in mm per gantry revolution/beam collimation in mm Smaller effect on image quality for MDCT than for SSCT > 1: nonoverlapping, interspersed acquisition = 1: nonoverlapping, contiguous acquisition < 1: overlapping acquisition Low-contrast lesions (liver): prefer beam pitch <1 High contrast lesions (CT colography): prefer beam pitch >1
Table speed	Closely related to beam pitch and beam collimation Usually described as table travel in mm per gantry revolution For mm/second: multiply with number of revolutions per second Compared with SSCT, MDCT provides higher table speed, allows faster scanning for thinner sections with dose savings

[a] Siemens 64-slice MDCT
MDCT multidetector-row computed tomography
SSCT single-slice CT

length. Determination of scan area of interest or scan length (which also depends upon patient length or height) can help to determine scanning parameters, scan duration, and contrast administration protocol. Scan direction is an important determinant of vascular contrast enhancement. In general, direction of scanning is similar to the direction of blood flow in the area of interest in order to follow the contrast flow column (for example, peripheral MDCT angiography – craniocaudal) with few exceptions (for example, MDCT angiography of pulmonary embolism to avoid streaks from contrast in systemic veins – caudocranial).

• **Localizer radiograph**: With availability of automatic exposure control techniques and bow-tie filters (a hardware component of the scanner), it is important to emphasize to technologists that patients must be centered appropriately in the scanner. Acquisition of localizer radiograph with miscentering of patient in the gantry isocenter can lead to erroneous calculation of tube current with use of automatic exposure control technique, and this can affect resulting image quality [9, 10]. Likewise, localizer radiograph length must also include the entire scan area of interest, as some automatic exposure control techniques (Z-axis and XYZ-axis modulation) require these radiographs to estimate tube current [9].

• **Contrast consideration**: This aspect of scanning protocol is discussed elsewhere in the textbook.

• **Scan duration**: State-of-the-art MDCT scanners cover most routine CT studies of chest, abdomen and/or pelvis in a single breath hold, fast acquisition (less than 15 s). Further reduction in scan duration with MDCT will also be helpful to avoid or reduce need for sedation in uncooperative patients or children. Estimation of scan duration with MDCT scanning is most critical for catching the peak contrast enhancement over the scan length. Thus, estimation of scan duration can help optimize contrast media injection duration. Scan duration depends on several factors, such as gantry revolution time, table speed, and pitch, as well as scan area(s) of interest.

• **Gantry revolution time**: In general, the shortest gantry revolution time (such as 0.4–0.5 s) must be used for most CT studies. An exception to this rule is CT evaluation of a large patient, where use of longer gantry rotation time helps increase total tube current – time product [milliampere second (mAs)].

• **Table speed, beam pitch, and beam collimation**: For MDCT scanners, change in these parameters affects scan duration and radiation dose more than image quality. However, there are some exceptions to this rule. In the liver, use of higher pitch (>1:1 beam pitch) and faster table speed has been shown to be inferior to lower pitch and slower table speed for detection of small metastatic lesions [11]. Conversely, in high-contrast situations, such as CT colography and CT angiography, use of higher pitch (>1:1 beam pitch) and faster table speed does not affect image quality [2].

From scan length and scan duration, table speed can be estimated. For example, a 350-mm scan length for abdomen-pelvis in 10 s can be covered with a table speed of 35 mm/s or 17.5 mm per gantry revolution (at 0.5-s gantry revolution time). For a given MDCT scanner, desired table speed can then be achieved by selecting beam pitch, number of data channels, effective detector-row width, and gantry revolution speed. Thus, for an 8-slice MDCT scanner, a table speed of 35 mm/s can be achieved with 0.875:1 beam pitch, 8 data channels with 2.5-mm effective detector-row width (detector configuration of 8*2.5 mm = 20 mm beam collimation), and 0.5-s gantry revolution time. When selecting the detector configuration and beam pitch – most notably, the effective detector-row width – one must take into account the required reconstructed section thickness. For example, if 1.25-mm section thickness is required for an 8-slice MDCT scanner, one must select 8*1.25-mm detector configuration (effective detector-row width = 1.25 mm) and not 8*2.5-mm detector configuration (effective detector-row width = 2.5mm). This becomes redundant for MDCT scanners with matrix array detector configuration, such as 64*0.625 mm (LightSpeed VCT) since users select the same detector configuration (64* 0.625 mm) to obtain any section thickness (0.625, 1.25, 2.5, 3.75, or 5 mm).

• **Reconstructed section thickness**: Compared with single detector-row CT scanners, MDCT (⩾4-slice scanners) allows acquisition of thinner section thickness in shorter duration and with less radiation exposure. However, an increase in indications for thinner sections with MDCT scanners can lead to overall increase in radiation dose contributions from these scanners. In such circumstances, radiation dose can be reduced by acquiring thicker sections and reconstructing thinner images from the volumetric raw data. Thinner sections have more noise content but higher spatial resolution and less partial volume averaging so that greater noise can be tolerated. Whereas thinner sections can now be acquired in a short duration, this also poses interpretation and archiving challenges to radiologists and their departments. Therefore, scanning protocols must define use of thinner sections- for interpretation or three-dimensional postprocessing on PACS or dedicated, stand-alone, image postprocessing workstations.

In general, for most routine abdominal CT studies, a section thickness of 2.5–5 mm is preferred for diagnostic interpretation. For these studies, multiplanar reconstructions can be performed at the scanner console from thinner reconstructions or directly from the volumetric raw data. Thinner sections are generally acquired for imaging of other regions of the body, including CT angiography studies of the abdomen.

• **Extent of overlap**: With isotropic scan data from most modern MDCT scanners, need for overlapping intersection distance is limited and can be avoided.

• **Reconstruction algorithms**: Reconstruction algorithms are an important component of scanning protocols. Selection of higher spatial resolution kernels (or sharper kernels) is necessary for viewing bones and lungs but can lead to unacceptably noisy images for soft tissues. Therefore, appropriate algorithms must be selected for specific regions of interest. A softer kernel (or a kernel with lower spatial resolution) provides smoother images and can help in decreasing noise content for low-contrast lesions, lower-dose studies, obese patients, or thinner sections.

- **Tube potential**: Most CT studies in adults are performed at 120 kVp. Tube potential (kVp) has a complex relationship with image noise, CT attenuation values (contrast), and radiation dose. A decrease in kVp increases noise and decreases radiation dose if other parameters are held constant but leads to higher attenuation values (except for water) and image contrast irrespective of other scanning parameters. The latter can help reduce the volume of intravenous contrast media administered for CT scanning. Low kVp CT can help in dose and contrast media volume reduction. Low kVp CT studies are especially well suited for high-contrast regions of interests, such as chest CT and CT angiography. To avoid inadvertently high image noise with low kVp CT studies, tube current may be raised. Several pediatric CT examinations can also be performed at lower kVp in order to reduce associated dose. However, kVp reduction in obese or large patients must be avoided to ensure adequate signal-to-noise ratio for acceptable diagnostic interpretation.

- **Tube current**: Unlike kVp, a change in tube current [milliampere (mA)] does not affect image contrast or CT attenuation values. However, reduction in mA is the most common method of reducing radiation dose. Either fixed tube current or automatic exposure control techniques can be used for maintaining adequate image quality and for managing radiation dose associated with MDCT [9, 12]. These techniques have been discussed in details in the chapter on radiation dose. Automatic exposure control techniques can help optimize tube current and dose irrespective of other scanning parameters. As automatic exposure control techniques allow dose optimization during each gantry revolution (XY-axes) and from one to the next gantry revolution (Z-axis), it may be more dose-efficient to use automatic exposure control over fixed tube current protocols [10, 13].

- **Radiation-dose consideration**: This aspect of scanning protocols is described comprehensively elsewhere in this textbook.

MDCT: Are there Disadvantages to the Technology?

Used appropriately, most state-of-the-art MDCT scanners can help reduce overall radiation dose compared with the prior single-slice or conventional CT scanners. Although each technological breakthrough in MDCT has contributed to improved resolution and coverage with expansion of its clinical applications, recent trends in radiation dose contribution from MDCT scanners are alarming. CT scanning contributes the most radiation dose among all medical radiation-based imaging procedures. Several experts have raised concerns over potential overuse and inappropriate use of MDCT scanners. Several vendors have introduced sophisticated techniques, such as automatic exposure control, detectors with better dose efficiency, improved reconstruction kernels, and noise-reduction filters, but much remains to be accomplished for optimization of radiation dose. Most importantly, the definition of "optimum image quality at lowest possible dose" for different-sized patients in different body regions for different clinical indications remains elusive. In the absence of these guidelines, users must employ strategies for dose reduction, when indicated.

Summary

In summary, understanding the fundamentals of MDCT helps adequate planning of scanning protocols.

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