Methods and Strategies for Radiation Dose Optimization – and Reduction – in MDCT with Special Focus on the Image Quality

6

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CONTENTS

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6.1 Introduction: Should We Optimize/Minimize the Patient's Radiation Exposure?

The danger of ionizing radiation is related to the potential long-term risk of carcinogenesis. In Chapters. 1 and 2 of this book, Chadwick and Cohen have detailed how this risk is evaluated and considered in the field of low-level radiation in which diagnostic imaging (including CT) in comprised. The linear no threshold (LNT) theory of carcinogenesis is based on the risk of hereditary mutations deriving from cellular effects in germ cells. This theory considers that the cancer risk is linearly proportional to the dose at high doses as well as at low doses, from zero dose up. On the other hand, failure of the LNT theory is based on series of investigations showing that there is substantial evidence that low-level radiation does not have any carcinogenic effect and may even be protective against cancer, a view known as "hormesis".

Important here is the fact that the Recommendations of the International Commission on Radiological Protection (ICRP), outlined in its Publication 60 (ICRP 1991), implicitly have adopted the LNT concept, because of the precautionary principle. ICRP considers that the risks estimated using the LNT concept are probably conservative. The concept has formed the basis for the development of a radiological protection philosophy including the ALARA (as low as readily achievable) principle. In 1991, the ICRP quantified the radiation risk by adopting a value of 5% for the nominal lifetime excess absolute risk per Sievert (Sv) for fatal cancer for a general population exposed to low-level radiations.

The radiation dose received by patients undergoing diagnostic radiological examinations by CT are generally in the order of 1–24 mSv per examination for adults (UNSCEAR 2000) and 2–6.5 mSv for children (Shrimpton et al. 2003). These effective doses can be classified as low even though they are invariably larger than those from conventional diagnostic radiography. Typically, a chest radiographic examination (including two views) delivers between 0.08 and 0.30 mSv whereas a standard dose multidetector-row CT (MDCT) represents a 100 times higher risk, delivering 8 mSv. One fatal cancer should be expected for every 250,000 chest X-rays whereas this risk is 1/2,500 for a chest MDCT scan. More than one-half of the collective dose delivered for diagnostic imaging procedures is due to CT (Golding and Shrimpton 2002). Thus, particular attention has to be paid to dose optimization and reduction while using CT.

In this chapter, we will review the many faces of limiting the radiation dose from CT and in particular from MDCT. We will comment on the alternatives to using CT, on the CT parameters managed by the radiology team that have an impact on the radiation dose, and on how to minimize this dose per acquisition, per examination, and per patient. Finally, we will propose dose values suitable for an optimized use of MDCT.

6.2 Guidelines for Appropriate Use of Imaging

CT and in particular MDCT is a fabulous technique with regard to its liability, rapidity, and availability. The spatial resolution provided by MDCT with isotropic voxels makes radiologists and physicians highly confident in the diagnosis yielded by these examinations. As a practical result, the radiologists, the clinicians, and even the patients probably prefer dealing with CT than with other imaging methods or medical tests that could be more difficult to interpret. In addition, new indications of CT have been validated (i.e., ureteric stone disease, virtual colonoscopy, CT angiography including the coronary arteries, etc.). As modern MDCT scanners can now process 60–70 patients a day, as compared to 30–40 patients in the 1990s, the increase in the number of procedures can easily be overcome by modern radiology departments. Most importantly, image-based media now have a central role in our modern societies. CT scans, by showing directly “what is happening inside the patient”, seem easy to read and are thus more attractive than conventional radiography, which often suggests the diagnosis through indirect signs. This evolution has already resulted in a huge increase in CT examinations and subsequently in collective dose.

To overcome some abuse in the use of CT, it should be kept in mind that alternative imaging techniques such as ultrasonography (US) and magnetic resonance imaging (MRI) are also widely available. Substitution of CT with US and MRI is an important factor in collective radiation dose reduction. As an example, a CT scan of the central nervous system (brain and spine) can be replaced by MRI in almost all patients except those with acute trauma. However, this would need a number of MR units approximately as high as that of CT units. There are equal numbers of MR and CT units in some countries, such as Japan, but in others the number of MR units is still three times lower than that of CT. This relative shortfall of MR compared to CT equipment contributes to the excess collective dose.

In order to define diagnostic strategies for clinicians in their consideration of patient radiation protection, guidelines for the prescription of imaging tests have been proposed by the Royal College of Radiology (Royal College of Radiologists 2006). Ideally, such guidelines should be evidence based.

As an example of an evidence-based study, diagnostic strategies including MDCT angiography of pulmonary arteries (CTPA) have been investigated by the group in Geneva (Perrier et al. 2004). These authors have documented the clinical potential of a diagnostic strategy for ruling out pulmonary embolism (PE) based on D-dimer dosage combined with lower-limb US before performing CT pulmonary angiography (CTPA) in outpatients. Such an approach led to a recurrence rate of PE of only 1% (95% confidence interval: 0.5%–2.1%), and CTPA was performed in only 593 out of 965 outpatients (61%). Perrier et al. (2004) concluded thus that a noninvasive diagnostic strategy combining clinical assessment, D-dimer dosage, lower-limb US, and helical CT scanning – necessary in approximately two-thirds of patients only – yields an accurate diagnosis in 99% of outpatients suspected of having PE.

Nowadays, it appears in clinical practice that CTPA is ordered for almost all patients suspected of having a PE. Indeed, in emergency departments of almost all community hospitals, MDCT has now become as available as D-dimer dosage. In addition, the results of CTPA are more rapidly obtained than those of D-dimer dosage and MDCT can deliver very important information on possible alternative diagnoses. As a consequence, it has been recently reported that not more than 10% of CTPA ordered to rule out PE were actually positive for PE (Schaefer-Prokop and Prokop 2005) whereas this percentage ranged from 20% to 40% 10 years ago.

Other evidence-based studies have been conducted on patients presenting with acute abdominal pain. In such circumstance, the high diagnostic performance of CT for the diagnosis of various acute abdominal diseases – including trauma, small bowel obstruction, acute appendicitis, acute colon diverticulitis, pelvic inflammatory disease, and pyelonephritis – has been reported. This is extensively discussed in Chapter 10 by Keyzer et al. The success of CT in diagnosing acute abdominal disorders has resulted in the wide use of this technique with a subsequent decrease – from 40% to 20% – of the proportion of positive results (Chen et al. 1999). In other words, the collective radiation dose has been doubled for diagnosing a constant number of acute abdominal diseases. The risk versus benefit ratio of CT has thus been reduced. In addition, promising results collected in studies dealing with acute abdominal pain have been extended to subacute abdominal pain without any robust evidence. One possible reason for this extension is the ability of CT to demonstrate unsuspected diseases, as illustrated in Figure 6.1. However, the risk versus benefit ratio of CT in subacute abdominal pain remains unknown.

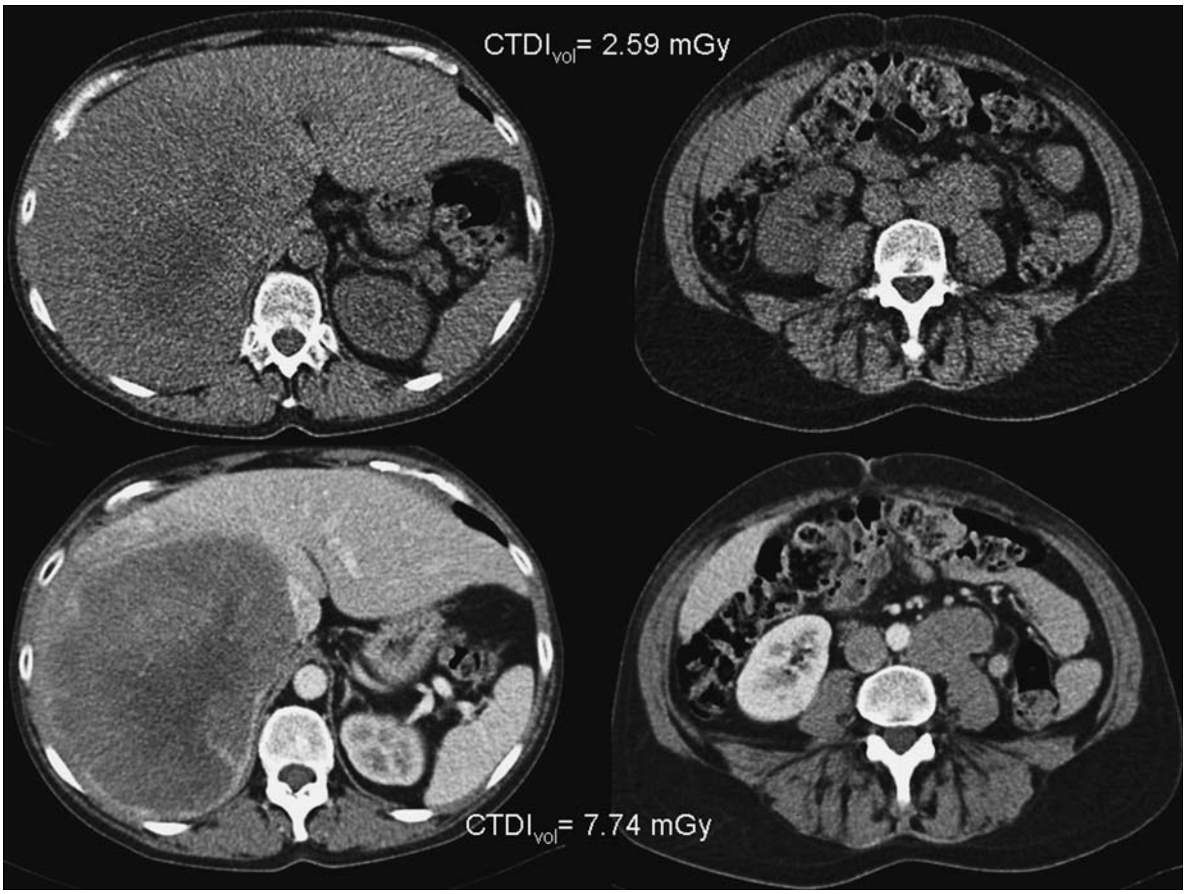


Fig. 6.1a–d. A 42-year-old woman 1.62 m tall and weighing 67 kg referred for an abdomino-pelvic CT complaining of chronic abdominal pain for 4 months. Unenhanced low-dose CT of the abdomen (**a**, **c**) and pelvis is obtained with a dose–length product (*DLP*) of 115 mGy·cm, equivalent to one-quarter of the mean value from the UK 2003 survey (NRPB 2005). This acquisition shows a focal hepatic mass (**a**) and retroperitoneal lymphadenopathies (**c**). Enhanced standard-dose CT confirms liver metastases and lymphadenopathies (**b**, **d**). Biopsy of the cervix confirmed adenocarcinoma. Enhanced CT delivered 300 mGy·cm, corresponding to less than one-half of the mean values from the NRPB 2003 survey study. The CT scanner was a Siemens Emotion 16® with 16×0.6 mm collimation, 130 kVp, an image quality index of 130 mAs (effective) and used an AEC device

In summary, it is of utmost important to remember that the most efficient way to limit a patient's radiation dose is to avoid imaging by CT, and whenever possible to substitute CT with MRI and/or US. If still needed, CT technique optimization is mandatory.

6.3 Optimization of the MDCT Technique

Once the clinical indication of CT is well established, the appropriate CT technique is then required in order to optimize the image quality with the lowest possible radiation dose. The influences of the numerous CT components and/or parameters on radiation dose are detailed in the present edition by Nagel (Chap. 4). We will therefore restrict our discussion to those that can be easily modified and adapted by the operator performing the examination. As a general rule, it should be noted that the use of standardized and fixed acquisition parameters leads to unnecessary overexposure of patients.

6.3.1 CT Parameters

6.3.1.1 Tube Potential (*U*)

The relationship between the dose and the tube potential (*U*) is not a straight and linear one, but rather exponential and varying according to the specific circumstances. The intensity of the radiation beam at the detector array, for example, varies with *U* to the power of 3.5. If the tube potential is increased, e.g., from 120 kVp to 140 kVp, the intensity of the electrical signal obtained from the detectors changes by a factor of 1.7.

Tube potential *U* is usually modified only through the kilovoltage (kVp) settings, which are restricted to a small number of possible levels. These kVp values differ from one manufacturer to another, as well as from one CT scanner to another, and vary from 80 kV to 140 kV. As the effect of increasing *U* has a huge influence on radiation dose, a general rule for selecting kVp could be the following:

- To avoid 140 kVp except for CT of the chest, the abdomen, and the pelvis in extremely obese patients [i.e., with a body mass index (BMI) greater than 35 kg/m^2], and for CT of the lumbar spine in obese patients (i.e., with BMI > 30 kg/m^2).
- To prefer 100–110 kVp for CT of the chest, the abdomen, and the pelvis in thin patients (i.e., with a BMI < 22 kg/m^2), and in 10- to 15-year-old children.
- To prefer 80–90 kVp for CT angiography and in children younger than 10 years old.
- In all other circumstances, to select 120–130 kVp.

6.3.1.2 Tube Current–Time Product (*Q*) and Adaptation to Patient's Size

As in conventional radiography, a straight linear relationship exists between the tube current–time product (*Q*) and the dose; i.e., all dose quantities will change by the same amount as the mAs setting applied. The settings for *Q* should be adapted to the characteristics of the scanner unit, the patient's size (see Chap. 4), and the dose requirements for each type of examination.

Examinations with high intrinsic contrasts (as of the chest and the skeleton), which are displayed with wide window width, can most often be carried out with strongly reduced mAs settings and no impairment of image quality.

Appropriate use of *Q* also depends on the patient's size, which is an important parameter to consider in dose optimization. Considerable reductions in *Q* are appropriate for slim patients, and particularly for children. In order to avoid unnecessary overexposure, *Q* should be intentionally adapted by the operator unless automatic exposure control (AEC) devices, or similar, are available. A detailed description of how AEC devices work and what they bring in terms of dose optimization is given in Chap. 7.

As a general rule, one should remember that the *Q* setting may be halved when the patient's trunk diameter – typically 30 cm – decreases by 4 cm without loss of image quality. For a CT scan of the adult trunk, if the CT unit is not equipped with an AEC device, the following settings may be proposed (with the effective mAs being defined as *Q* divided by the pitch factor):

- 1.0 mAs/kg (effective) for chest CT scan
- 1.5 mAs/kg (effective) for abdominal and pelvic CT scans.

In a patient weighting 70 kg and 1.70 m tall (i.e., representative of the typical Monte Carlo Model and

Rando Anthropomorphic Phantom used for effective dose calculations by ICRP), the dose–length product (DLP) delivered for a chest CT scan at 120 kVp and 70 mAs (effective) would be approximately 180 mGy·cm. Using 1.5 mAs/kg (effective), an abdomino-pelvic CT scan would deliver approximately 320 mGy·cm. These two DLP values correspond to approximately one-half of the reference values (i.e., the 75th percentile in survey studies) used in the European Union in 1999 (EUR 1999).

If the CT unit is equipped with an AEC device, the reference image quality has to be defined, according to the scanned body region, and/or the clinical indication. Recommendations for the appropriate value of *Q* in brain and neck CT studies as well as in CT examination of sinonasal cavities are discussed by Mulkens et al. in Chapter 8 of the present edition. Recommendations for appropriate use of *Q* in CT studies of the trunk are discussed below.

6.3.1.3 Slice Collimation

Detailed descriptions of the influence of slice collimation, slice thickness, overbeaming, and overranging on the radiation dose are given in Chapter 4. As modern MDCT scanners can provide isotropic voxel resolution, thin-slice collimations are now widely used. Radiologists have to keep in mind that the image noise represented by the graininess or mottle aspect of the images not only depends on the radiation dose but also on the algorithm used for reconstruction and on slice thickness. In order to reduce the image noise due to thin collimation, it is not appropriate to increase the dose (mainly by increasing *Q*). Indeed, adapted reconstruction algorithms generating little noise, slightly thickened sections, and multiplanar reformations (MPR) designed to erase most image noise from native images may be valuable alternatives. An example is given in Figure 6.2.

6.3.1.4 Pitch Factor

With single detector row CT (SDCT) scanners, increased pitch serves primarily to decrease the duration of the acquisition, but it also decreases the radiation dose proportionally. However, as a side-effect, the slice profile width, i.e., *z*-resolution, is impaired.

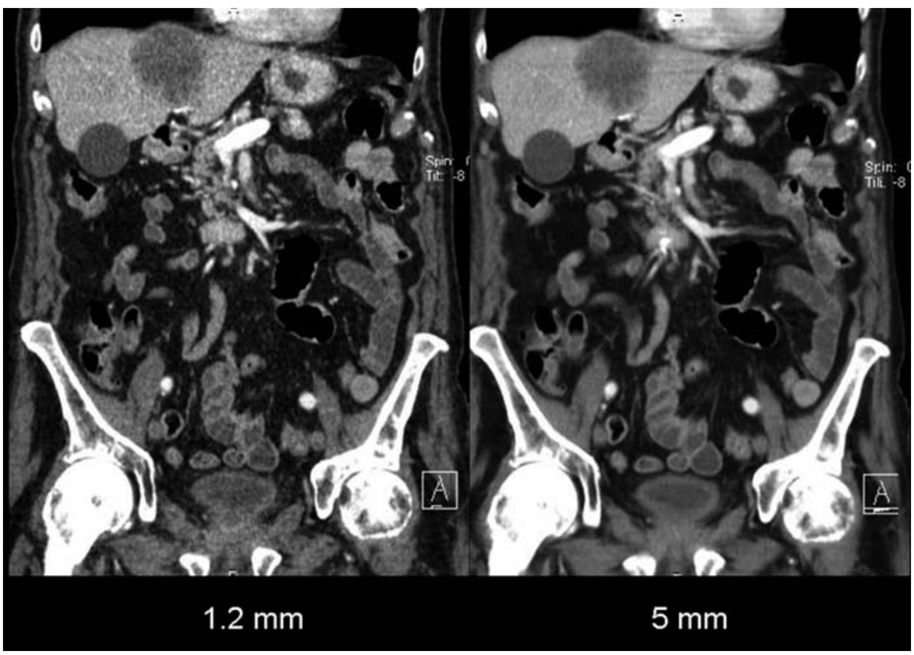


Fig. 6.2. Enhanced standard-dose MDCT of the abdomen showing a liver metastasis in a man with prostate carcinoma. Left CT image is reconstructed in the coronal orientation with a thickness of 1.2 mm and shows quite an important mottle aspect of the abdominal structures. Right CT images is reconstructed in an identical orientation but with a thickness of 5 mm. The mottle aspect seen in the thin-section coronal CT slice is no longer visible. The effect of image smoothing by thickening the CT slice is seen when the noise is due to low-dose scanning and when the noise is related to high-frequency reconstruction algorithms

With MDCT scanners, the spiral interpolation scheme is different than that on SDCT scanners. With MDCT, the slice profile width is unaffected by the pitch but the image noise is influenced by it (see Fig. 4.34a) unless the tube current is adapted accordingly. This adaptive process is named the "effective mAs" concept.

Scanners based on the effective mAs concept not only keep slice profile width constant, but also the image noise when the pitch is modified. In order to keep the slice profile width and image noise independent of pitch, the electrical mAs product supplied to the X-ray tube is automatically adapted through a straight linear relationship with pitch. As a consequence, the patient's dose – expressed as $CTDI_{vol}$ – and the slice profile are no longer modified with the pitch. On the other hand, MDCT scanners that are not based on the effective mAs concept still limit dose by increasing the pitch with, as a consequence, impaired image quality (i.e., increased noise) if mAs settings are not adapted manually by the operator.

With MDCT scanners, the pitch should be selected exclusively with respect to the scan speed, spiral artifacts, and tube power. Radiation dose considerations no longer play a role if MDCT scanners are based on the effective mAs concept or if the mAs setting can be adapted to pitch in order to achieve a constant image noise. Nevertheless, this simple rule has limitations with scanners that have more than 32 detector rows, because they have a large beam width such that the overranging effect generates an additional exposure that depends on the pitch. With such scanners, high pitch values can amount to 30% of the dose as compared to low pitch values (i.e., pitch of 1.75 with a 64-row MDCT scanner for an acquisition on the upper abdomen).

6.3.1.5
CT Dose Index and Dose–Length Product

Definitions of the CT dose index (CTDI) and DLP – the two most commonly used dose descriptors – are in Chapter 4. Newer scanners must be equipped with a dose display; at present, only display of the volume computed tomography dose index ($CTDI_{vol}$) is mandatory (IEC 2001). However, many scanners also show DLP, either just per scan series, or both per scan series and per exam. Such a dose display enables comparison with recommended values. In addition, changes in scan parameter settings and their effect on patient exposure are visible on the CT screen. Thus, these displays are appropriate for dose optimization. Finally, $CTDI_{vol}$ can also be used as a fair estimate of the dose delivered to the organs located within the scan range. The interpretation of dose values displayed on the scanner's console needs special attention in the following situations:

- Many dose recommendations are expressed in weighted CTDI ($CTDI_w$), in order to allow comparisons; therefore, the pitch correction involved in $CTDI_{vol}$ should be reverted by multiplying $CTDI_{vol}$ by the pitch factor.
- Until now, dose values used for body scanning have been based on body-CTDI, regardless of the patient's size. In pediatric examinations, the figures displayed should be multiplied by a factor of 2 for children and of 3 for infants in order to give a realistic estimate of the patient's dose.

6.3.1.6
Number of Acquisitions per Examination

The radiation dose depends linearly on the number of CT acquisitions performed. As an example of optimizing this parameter, one has to define the following:

- The need for unenhanced acquisition prior to enhanced acquisition (in many instances, unenhanced CT prior to enhanced CT is not mandatory).
- The number of acquisitions in dynamic CT scanning:
  - for the assessment of a pulmonary nodule, determining the enhancement patterns of a pulmonary nodule may require up to four acquisitions (Swensen et al. 2000);
  - for the detection of hepatocarcinoma, a multiphasic examination may include four acquisitions (Lim et al. 2002).

6.3.1.7
Z-coverage

Z-coverage is defined as the length of the acquisition and is expressed in centimeters. The radiation dose is grossly proportional to *Z*. The *Z*-coverage is included in DLP. In the daily practice, it is important to limit *Z*-coverage to what is strictly necessary. The risk of limiting *Z*-coverage is misdiagnosis.

An example of optimization of *Z*-coverage in abdominal CT performed to rule out acute appendicitis is given in Chapter 11. It has been proposed to limit *Z*-coverage to a height of 12 cm. However, the proportion of alternative diagnoses that could be missed in the upper abdomen has not yet been quantified.

For the diagnosis of acute pulmonary embolism, SSCT proved to have a 98% negative predictive value (Tillie-Leblond et al. 2002). This technique included *Z*-coverage of approximately 15 cm, from the aortic arch to the diaphragm. Using MDCT, one has the possibility of extending *Z*-coverage to the whole chest by using a thinner collimation but with reduced duration of acquisition. With this MDCT technique, *Z*-coverage has been grossly doubled but the negative predictive value has not been modified (98.5% vs. 98.0%). Regarding alternative diagnosis, SSCT with 15 cm *Z*-coverage showed an alternative diagnosis in up to 40% of patients whereas MDCT is now reported to show an alternative diagnosis in 28% of patients (Weiss et al. 2006).

6.3.1.8
Patient Centering

CT users should be aware of the potential overexposure due to inadequate patient centering in the *Y*-axis, due to bow tie filters. A detailed description of this effect can be found in Chap. 8.

6.3.1.9
Automatic Exposure Control (AEC)

As explained in Section 6.3.1.2, dose requirements are strongly dependent on the patient's size, weight or diameter, and absorption. Chapter 4 shows how dose requirements can be expressed by Brook's formula. This formula has been studied on phantoms by Boone et al. (2003) and by Siegel et al. (2004). A reduction of 12 cm (i.e., from 32 to 20 cm) of the phantom diameter can be associated with a 71% reduction in mAs without any decrease in image quality. Newer CT scanners are equipped with AEC that can automatically adapt the mAs settings to the patient's size and shape. AEC are described and discussed in detail in Chapter. 7. Using an AEC device, the role of CT users is to define the expected image quality – and the subsequent radiation dose – suitable for the acquisition.

6.3.1.10
Intravenous Injection of Iodine Contrast Material

Compared to unenhanced CT, enhanced CT with intravenous iodine contrast injection does not require a higher tube current–time product. This can be easily demonstrated by comparing the DLP delivered by a CT scanner equipped with an AEC device between two consecutive acquisitions, one without and one with iodine injection. In such circumstances, the DLP delivered automatically – with unchanged CT parameters – varies by less than 1%.

6.3.2
Determination of a Standard of Reference for Image Quality

6.3.2.1
Definition and Methodology

Image noise, an important determinant of image quality, is inversely proportional to the X-ray beam energy. Although a decrease in tube current or in tube voltage results in a dose reduction, such a decrease is associated with an increase in image noise, which may compromise the image quality to a variable extent. Thus, while dose reduction is crucial because of the possible risks of radiation exposure, it is equally essential to realize the benefit of a "quality CT examination" that adequately addresses pertinent clinical issues affecting patient care (Rehani et al. 2000). Therefore, radiation dose reduction, although prudent when appropriate (i.e., in pediatric CT), must not compromise the diagnostic outcome of clinically relevant examinations. It is worthwhile remembering that, in most circumstances, strategies should be directed toward radiation dose optimization rather than dose reduction per se, so that the image quality maintains a diagnostic standard. For instance, a high radiation dose may not necessarily provide substantially improved image quality and increased lesion conspicuity in comparison with standard or even low-dose scanning.

As explained above, one of the most difficult parameters to account for in dose optimization is the patient's mass, weight, or BMI. If an AEC device is not available on the CT scanner used, one has to adapt the mAs setting for each patient. We suggest using 1.0 and 1.5 mAs (effective) per kg of weight, respectively for the chest and the abdomen.

As modern scanners are now equipped with AEC devices, they are thus able to deliver a homogeneous image quality throughout the acquisition regardless of the patient's diameter, weight, absorption, and shape. The parameters of such acquisitions are to be set by the users and are thus not dependent on the patient's weight, rather only on the desired level of image quality. However, it remains extremely difficult to define the required image quality, as what is acceptable to one radiologist may be unacceptable to another, even with uncompromised diagnostic performance.

In order to optimize the dose by determining a "reasonable" image noise or a "reasonable" image quality, robust references could be considered as a starting point. Survey studies conducted through the US and EU may serve as such starting points. The reference levels elicited by theses surveys correspond to the 75% percentile of the delivered dose in participating CT departments. As these levels reflect very heterogeneous scanning methods and CT equipment, they are quite high. As a balance between diagnostic performance, diagnostic confidence, and radiation dose has not yet been critically defined, it is mandatory to proceed step by step in order to optimize the dose.

The aim of the following paragraphs is thus to comment on and illustrate a possible approach to achieving appropriate image quality and radiation dose using modern scanners equipped with AEC devices. This can be applied to adults only. Pediatric CT scanning is discussed by in Chapter 15.

6.3.2.2
Optimization of Standard-Dose MDCT Acquisitions

In our approach to dose optimization, we considered the results of clinical research conducted by our group on low-dose CT (Tack et al. 2003a–c; Keyzer et al. 2004; Tack et al. 2005a, b), and the mean or median dose values (instead of reference dose values) from survey studies (Brix et al. 2003; NRPB 2005) recently conducted in Germany and UK. Survey studies reflect the dose delivered in hospitals using a wide range of CT scanners, including SDCT, MDCT with two, four, and eight detector rows. In general, the CT dose tends to decrease with a constant image quality when using newer generations of MDCT scanners. In addition, as the survey studies cover a large variety of CT scanners, it should be noted that dose optimization with MDCT should aim to reach approximately the 25% percentile of dose as reported in the surveys. This is detailed in Chapter 5.

6.3.2.2.1
Brain CT Examination

Based on their personal experience and on published data, Mulkens et al. (Chap. 9) recommend the use of a $CTDI_w$ of 30 mGy (equivalent to $CTDI_{vol}$ if the pitch factor is set at 1), a 50% reduction as compared to reference values obtained from a 1999 survey (EUR 1999). A comparison of two CT acquisitions of the brain obtained with $CTDI_{vol}$ values of 40 mGy, and 31 mGy is shown in Figure 6.3. No clinically relevant loss of image quality is detectable at 31 mGy as compared to 40 mGy. It should be noted that there is no need to apply AEC when scanning the brain, as the differences in attenuation between orientations and/or between slices are minimal. Therefore, modern scanners equipped with AEC devices do not apply them when in head mode.

6.3.2.2.2
Chest CT Examination

Unhenhanced CT of the Lung Parenchyma and Mediastinum

Naturally high contrasts between thoracic structures, particularly in the lung parenchyma where air is abundant, reduce the need for high doses to produce excellent image quality. Using MDCT equipped with an AEC device, the user has to set the required image quality. This image quality is expressed by indexes varying from manufacturer to manufacturer. Siemens expresses this quality by a "reference mAs value". Figure 6.4 shows images acquired on such an MDCT scanner at 120 kVp, with 32×0.6 mm beam collimation, and 90 mAs (effective) as reference quality mAs. The AEC device automatically reduced the tube current–time product to 61 mAs, as the patient was thin (BMI = 21 kg/m^2).

$CTDI_{vol}$ and DLP were, respectively, 4.67 mGy and 176 mGy·cm, corresponding to 50% of the reference dose (P75) reported in the German survey (Brix et al. 2003), and to less than 50% of the mean dose value reported in the UK survey (NRPB 2005).

How AEC devices react to obese patients is illustrated in Figure 6.5. The image quality of Figure 6.5a was set to the same reference quality mAs as in Figure 6.4 [90 mAs (effective)]. As this woman was obese (BMI = 35 kg/m^2), the automatically adjusted $CTDI_{vol}$ was 10.5 mGy, a value corresponding to the mean dose reported in the UK survey (NRPB 2003) and to 80% of that reported in the German survey

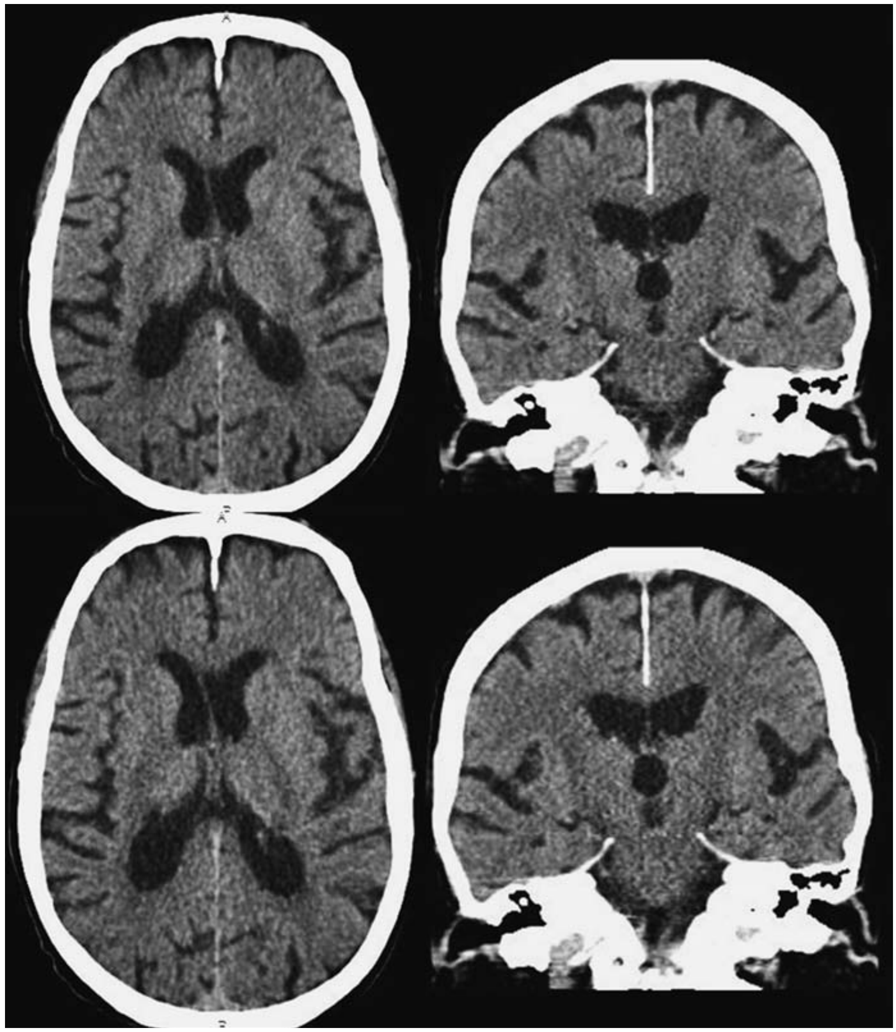


Fig. 6.3a–d. CT of the brain obtained with two acquisitions at a $CTDI_{vol}$ of 40 mGy (**a** in axial orientation and **b** in coronal orientation) and at a $CTDI_{vol}$ of 31 mGy (**c** in axial orientation and **d** in coronal orientation). Scans in **a** and **c**, and in **b** and **d** show comparable image quality

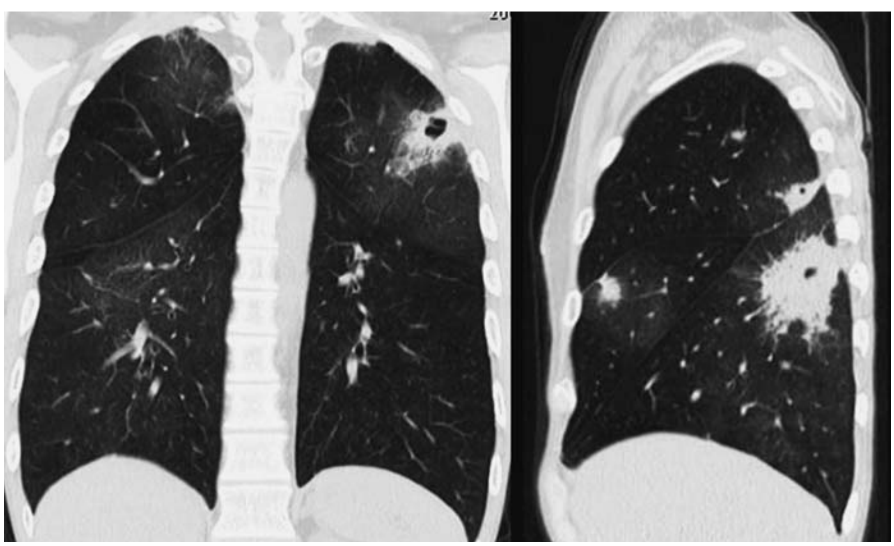


Fig. 6.4. A 38-year-old man 1.79 m tall and weighing 67 kg complains of mild fever and dyspnea. Multiple irregular excavated pulmonary nodular consolidations are demonstrated by MDCT and correspond to infections due to *Legionella*. MDCT parameters are displayed at the bottom of each coronal and sagittal reconstruction. In this thin patient, the AEC device reduced the mAs from 90 to 61 mAs

(Brix et al. 2003). On this particular woman, a second acquisition was obtained with 60 mAs (effective) as the reference quality mAs (Fig. 6.5b). This 33% dose reduction did not affect the image quality, as illustrated by comparing Figure 6.5a with Figure 6.5b, which appear very similar.

Another example comparing image quality index at 90 and at 60 mAs is shown in Figure 6.6 in a thin patient. In this example, the delivered dose resulted in $CTDI_{vol}$ values of respectively 4.4 and 2.9 mGy only. In this patient with a tumor infiltrating the carina, mediastinal images at 90 and 60 mAs (effective) as reference of image quality (Figs. 6.6a, b) illustrate similar and clinically acceptable image quality.

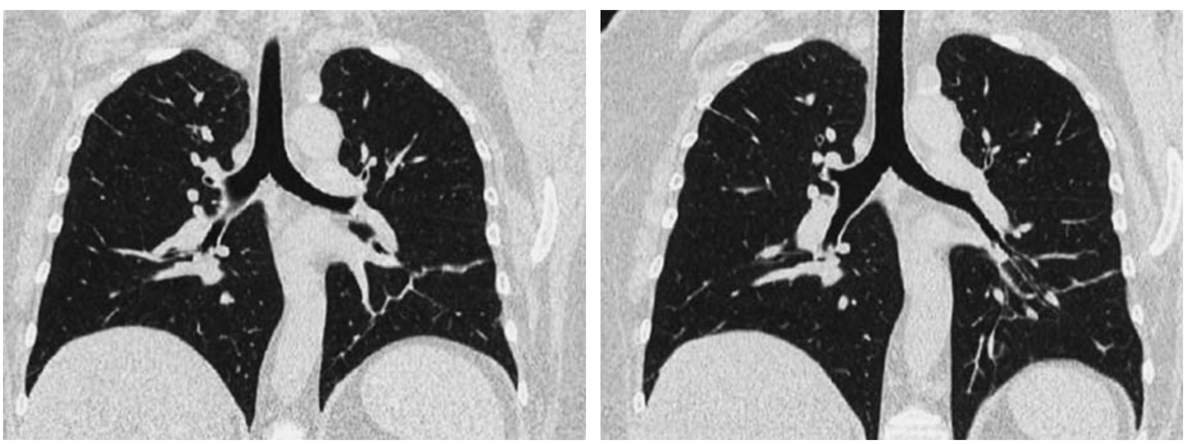
CT Angiography of Pulmonary Arteries

Dose optimization of CT angiography of pulmonary arteries (CTPA) relies more on reduction of *U* than on reduction of *Q*. As discussed in Chapter 10, the use of low, or very low mAs settings is associated with a huge amount of noise (Tack et al. 2005b). Even if pulmonary emboli are still visible in noisy images, the effect of noise on overall diagnosis of pulmonary embolism and alternative diagnoses remains unknown. A low tube potential setting has been validated in clinical practice (Sigal-Cinqualbre et al. 2004) at 80 kVp, at least in patients weighing less than 75 kg. This study was conducted with a CT scanner that was neither equipped with an AEC device nor able to scan at 100 kVp. As shown in Chapter 4, the signal of iodine at 80 kVp is much higher than that at the standard kVp setting (120 kVp). Newer scanners are now able to modulate the mAs setting at 100 kVp. Figures 6.7 and 6.8 show CTPA acquisitions at 110 kVp (16×0.6 mm beam collimation scanner) and 100 kVp (32×0.6 mm beam collimation scanner), respectively, in a thin and in an obese patient with acute and chronic pulmonary embolism.

The DLP values delivered by these CTPA acquisitions were respectively 99 and 163 mGy·cm, a very low dose as compared to the mean value from the UK (400 Gy·cm) and German (331 mGy·cm) surveys.

6.3.2.2.3 Abdominal CT

Standard dose abdominal MDCT scans require a higher dose than standard dose chest MDCT because the abdominal cavity contains solid organs that absorb much more the X-rays than the lungs. As explained above, if the MDCT scanner is not equipped with an AEC device, the operator should chose 120 kV and 1.5 mAs/kg weight. For patients of a normal weight, an abdomino-pelvic MDCT scan obtained with these parameters would deliver a DLP of 320 mGy·cm, corresponding to one-third of the



a b

Fig. 6.5a,b. A 45-year-old woman 1.68 m tall and weighing 95 kg (BMI = 35 kg/m^2) is referred for CT for follow-up of breast carcinoma and opacity in the left bases at chest radiography. Two CT acquisitions were performed, both using AEC. The first one (**a**) was obtained while the reference quality mAs was set at 90 mAs (effective). The second one (**b**) was obtained with a reference mAs reduced to 60 mAs (effective). Dose descriptors ($CTDI_{vol}$ and DLP) are displayed. Compared to Fig. 6.4 obtained from a thin patient, the dose for **a** obtained in this obese patient was doubled automatically by the AEC device in order to maintain the image quality constant

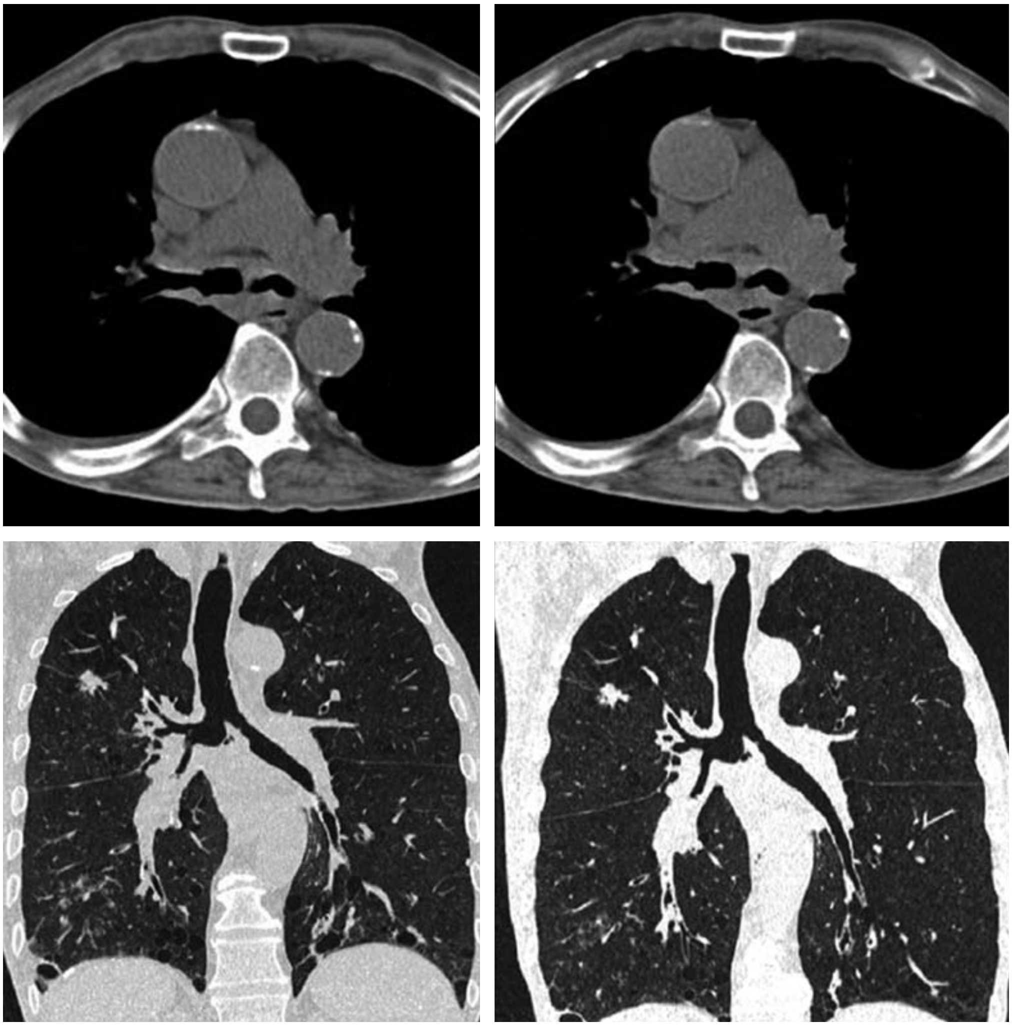


Fig. 6.6a–d. A 67-year-old man 1.83 m tall and weighing 69 kg (BMI = 20 kg/m^2) is referred for CT for cough and fever. MDCT chest acquisitions with parameters displayed at the bottom of the figure are obtained using an AEC device and a 32×0.6 mm beam collimation, at 120 kVp. A nodule is seen in the right upper lobe, centrilobular ill-defined nodules are seen in the right lower lobe and a tumor infiltrating the carina is seen in the mediastinal window. **a, c** Obtained with a reference quality mAs set at 90 mAs; **b, d** obtained with a reference quality mAs set at 60 mAs (effective). Delineation of mediastinal structures is not modified by the 33% dose reduction applied between **a** and **b**, and **c** and **d**

European reference value (EUR 1999), and to two-thirds of the mean dose reported by the UK survey (NRPB 2005). With modern scanners equipped with an AEC, the dose varies according to the patient's weight by a factor ranging from 2 to 5 as illustrated in Figures 6.9 and 6.10.

Compared to the doses reported by survey studies, these examples illustrate that one can select CT settings that enable one to perform standard acquisitions with a dose not higher than one-fifth to four-fifths of the European reference values (EUR 1999).

6.3.2.2.4 Spine

Cervical Spine

Optimizing the dose for CT of the cervical spine seems difficult to achieve as this segment of the spine is very close to the skull base and to the shoulders, two regions where dose requirements are high. As a consequence, only well-designed AEC devices are able to adapt the dose while maintaining the image quality constant.

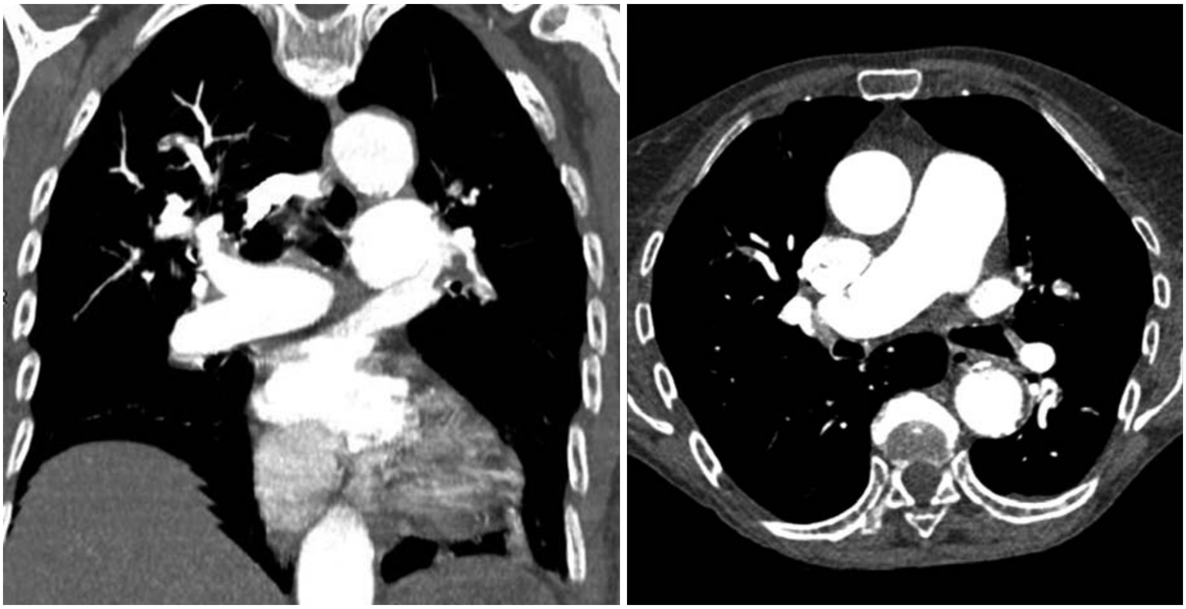


Fig. 6.7. An 84-year-old woman with dyspnea and a BMI of 21.6 kg/m^2, referred for CTPA. CTPA shows patterns of acute and chronic pulmonary embolism. Acquisition was obtained with a 16×0.6 mm beam collimation, 110 kVp and an AEC device. The reference effective mAs value reflecting the desired image quality is set at 100 mAs. The AEC device reduced this value to 44 mAs. The DLP for the entire acquisition was 99 mGy·cm, and the corresponding effective dose was 1.5 mSv, a dose no higher than that of a chest CT for screening for lung cancer

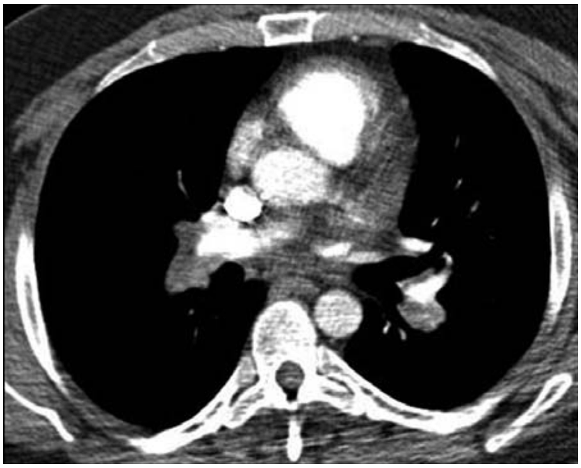


Fig. 6.8. A 58-year-old man with dyspnea and a BMI of 38.8 kg/m^2, referred for CTPA. CTPA shows patterns of acute and chronic pulmonary embolism. Acquisition was obtained with a 32×0.6 mm beam collimation, 100 kVp and an AEC device. The reference effective mAs value reflecting the desired image quality was set at 100 mAs. The AEC device has added 44 mAs to the 100 mAs, which was suggested in order to compensate for the noise generated by the patient's obesity. $CTDI_{vol}$ values were however only 6.6 mGy and a DLP of 163 mGy·cm

Lumbar Spine

As for the cervical spine, high image quality is required for distinguishing a herniated disk from nerve roots. Consequently, dose reduction obtained by decreasing the mAs setting is limited as it results in increased image noise. Similar finding have been shown for CT of the lumbar spine. As shown by Bohy et al. (2007), if the CT radiation dose is adapted to the patient's weight (i.e., using AEC), the potential to reduce the mAs setting was shown to be limited to a 35% reduction. Larger reductions in the mAs setting have a significant effect on image analysis. Thus, the most important determinants of limiting the radiation-related risks induced by scanning the lumbar spine are reducing the height of the scanned region and modulating both *U* and mAs settings according to the patient's weight, as illustrated in Figure 6.11.

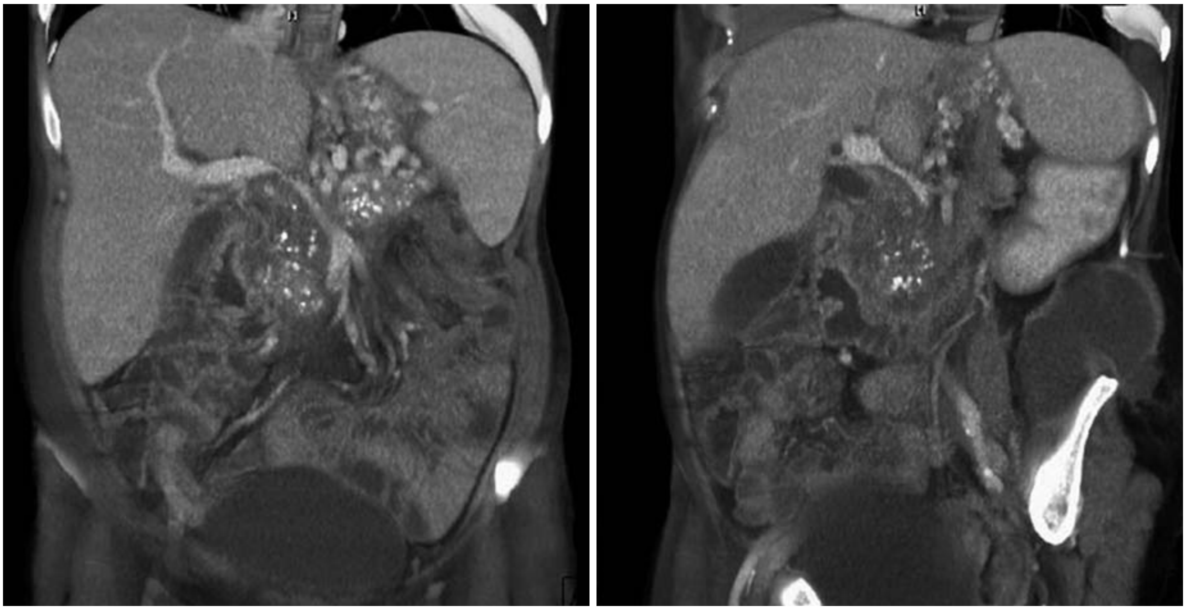


Fig. 6.9. A 44-year-old woman with known chronic pancreatitis due to alcohol abuse is referred to CT for pain and tender mass in the left flank. Her BMI is 23.6 kg/m^2. Enhanced MDCT of the abdomen with one phase was obtained during the portal vein phase. Pancreatic calcifications, portal vein stenosis, and gastric varicose are demonstrated on a coronal VRT reformation (*left image*) and an abscess is demonstrated in the left flank (*right image*). The acquisition was performed with 16×0.6 mm collimation, 110 kVp, and a reference effective mAs (representing the image quality index) of 90 mAs. This image quality index is 30% lower than that recommended by the vendor for standard MDCT. For this acquisition, AEC has automatically reduced the mean mAs setting to 53 mAs. The entire abdomen was scanned with a resulting DLP of 167 mGy·cm, which corresponds to one-seventh the reference dose for CT for EUR 1999, and less than one-half of the mean dose from the UK 2003 survey

The left image was obtained from an obese patient (BMI > 35 kg/m^2), and the right image was obtained from a patient of normal weight (BMI = 24 kg/m^2). The DLP delivered to the obese patient was three times higher than that to the patient of normal weight, but the image quality was higher in the right image than in the left.

In terms of optimizing CR dose parameters, the most significant factor is to avoid the use of a high tube potential, and 120 kVp should be sufficient in almost all patients unless they are obese.

6.3.2.3
Optimization of Low-Dose CT Scanning

The expression "low-dose CT" is not clearly defined. Reducing the dose recommended by the manufacturer could be considered as achieving a low dose, whatever the magnitude of reduction. In the literature, the concept of low dose is quite heterogeneously interpreted, and the same value can be considered as low by some authors and as standard by others. As a mater of fact, the so-called low-dose CT pro-

Fig. 6.10. A 64-year-old woman with left iliac fossa pain. This extremely obese patient has a BMI of 46.1 kg/m^2. Unenhanced MDCT was obtained using 130 kVp (the maximum possible for the MDCT), 16×0.6 mm collimation and a reference mAs (index of image quality) set at 110 mAs. The AEC device automatically elevated the mAs to 168 mAs. The resulting DLP for this unenhanced acquisition was 757 mGy·cm, which is nearly 5 times the dose delivered to the patient in Figure 6.8. The figure shows peritoneal fat infiltration around the descending colon in the left iliac fossa indicating acute diverticulitis

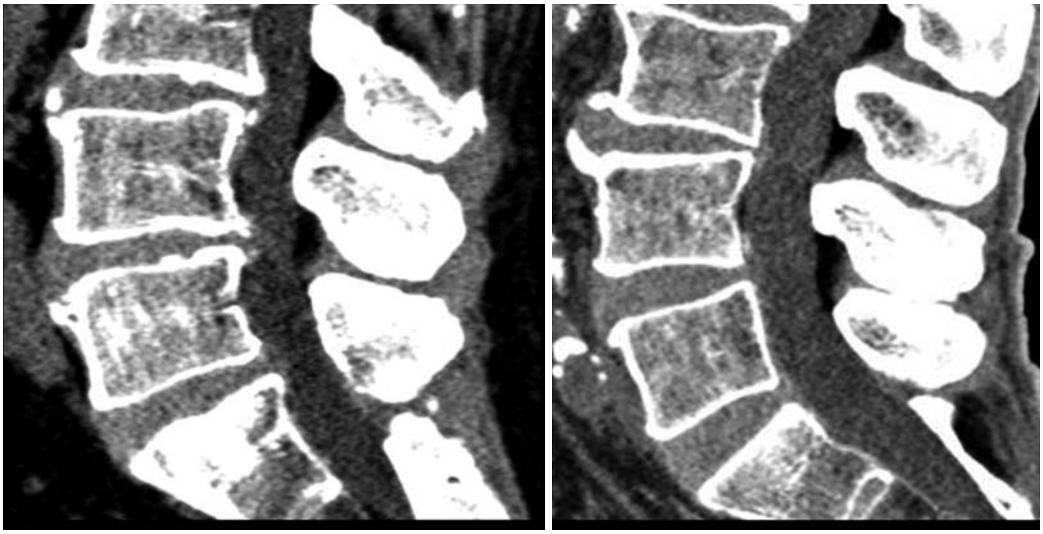


Fig. 6.11. Sagittal reconstructions in an obese patient (*right image*) with a BMI of 54.2 kg/m^2, and in a thin patient (*left image*) with a BMI of 21.5 kg/m^2 are shown. Automatic exposure-controlled acquisitions were obtained with tube voltage settings respectively of 140 and 120 kVp and with indexes of image quality expressed in effective mAs respectively of 350 and 280 mAs. The resultant $CTDI_{vol}$ values were 33.8 and 9.8 mGy. Despite a five times higher dose, the image noise seen in the obese patient's image on the *right* is greater than that obtained from the thin patient on the *left*. These dose levels are lower than the mean reference values from surveys of CT scans of the lumbar spine

tocols still deliver a high dose, since they use high kVp values.

A more appropriate use of the expression "low-dose CT" may be based on the fact that low-dose CT corresponds to a substantial dose reduction as compared to an optimized standard-dose CT, where optimized standard-dose CT corresponds to the lowest possible dose for an image quality ranging from good to excellent. Examples of optimized standard-dose CT scans are given in Figures 6.3–6.11.

With such definition, the radiation dose related to "low-dose CT" should be approximately at the level of radiographic examinations of identical body regions. As a general rule, low-dose CT should produce images of reduced photographic quality but with unchanged diagnostic quality. Low-dose CT scans have been used increasingly and were applied to early lung cancer screening programs (see Chap. 17.1), and the detection of colon polyps (see Chap. 17.2). Such low-dose CT protocols were also proposed in clinical practice for the diagnosis of chronic sinusitis (see Chap. 9), parenchymal lung diseases and CT pulmonary angiography (see Chap. 10), and most importantly for abdominal diseases as detailed in Chapter. 11.

6.3.2.3.1 The Sinonasal Cavities

As shown in Chapter 9, the radiation dose reached by low-dose MDCT is at the same level or even lower than that delivered by conventional radiographic examinations. Low-dose CT should thus be recommended in the clinical assessment of chronic sinusitis, with standard-dose CT, which delivers a dose approximately five times higher than that given by low-dose CT, only being recommended in cases of facial trauma.

6.3.2.3.2 The Thorax

As detailed in Chapter 10, low-dose CT of the lung parenchyma has been proposed since the early 1990s. However, low-dose CT is rarely applied in routine chest CT examination. The major reason for that is probably related to the low life expectancy of most patients referred for chest CT examinations, particularly in the case of thoracic or extrathoracic malignancies. Low-dose MDCT delivering less than 1 mSv per examination is thus almost always only used in screening of patients

Fig. 6.12. Curved coronal reconstruction delineating the left ureter and showing a left ureteral stone in the lower pelvis. Low-dose CT acquisition with an AEC device, 110 kVp, 16×0.6 mm collimation and an image quality reference index of 50 mAs (effective). As the patient has a normal BMI of 24.6 kg/m^2, the AEC has reduced the current–time product to 33 mAs (effective). DLP of the entire examination was of 112 mGy·cm. This dose represents 20%–25% of the mean reference values from recent CT surveys

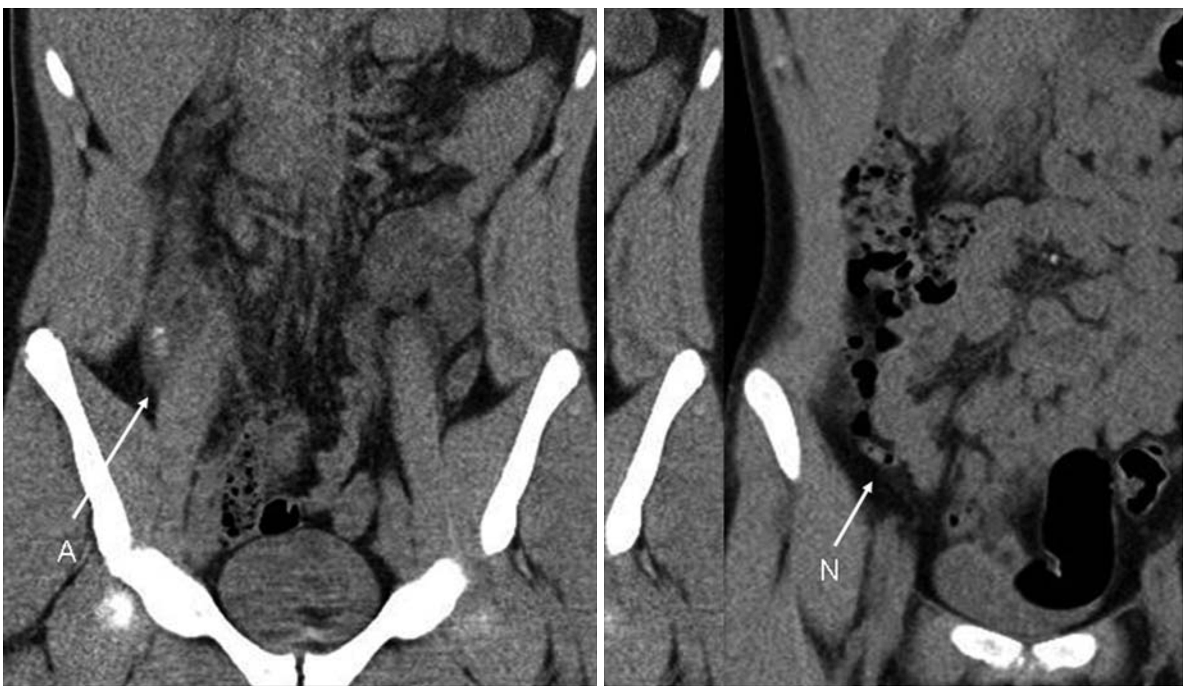


Fig. 6.13. Two patients with suspected appendicitis have undergone a low-dose MDCT of the abdomen and pelvis using an AEC device with the reference image quality effective mAs value set at 50 mAs. The patient on the *left* has a BMI of 24.4 kg/m^2, received a dose of 110 mGy·cm and has an acute appendicitis without abscess (*A* and *arrow*). The patient on the *right* has a BMI of 22.1 kg/m^2 and weighed 70 kg. He received a dose of 73 mGy·cm and had a normal appendix (*N* and *arrow*). The patient on the *left* has a BMI of 28 kg/m^2 , and weighed 85 kg. He had an acute appendicitis and received a radiation dose of 110 mGy·cm. As in Figure 6.12, the hereby delivered radiation dose represents 20%–25% of the mean reference values from recent CT surveys. This dose is equivalent to the dose of a radiographic examination of the abdomen including three views and is no higher than one-tenth of the reference values for abdomino-pelvic CT scanning

at risk of lung carcinoma, as detailed in Chapter 16.1.

6.3.2.3.3
The Abdomen

Low-dose CT has great potential in clinical investigations of the abdomen. As detailed in Chapter 11, low-dose abdominal CT should be used in young patients complaining of acute or subacute abdominal pain, with suspected benign diseases that may eventually recur, such as acute appendicitis, colon diverticulitis, renal colic, and Crohn's disease. An example of a low-dose CT protocol is shown in Figures 6.12 and 6.13 showing low-dose MDCT scans obtained while using an AEC device in patients suspected of having renal colic and acute appendicitis. This example illustrates the fact that low-dose MDCT of the abdomen can be achieved with a dose not higher than a radiographic examination of the abdomen with three views (1.9 and 1.2 mSv respectively). These doses are less than one-tenth of the references levels for abdomen-pelvis CT examinations, and one-quarter of the mean dose observed in the German survey study. For low-dose MDCT using an AEC device, the index of image quality expressed in effective mAs can be set at 50.

6.3.2.4
Optimized Radiation Doses for MDCT: In Summary

The most recent reference levels for MDCT of the chest and the abdomen are listed in Table 6.1. The optimized dose levels for imaging these two regions by low-dose MDCT as well as the corresponding validated dose levels are summarized in Table 6.2.

Table 6.1. Reference radiation doses for standard helical MDCT of the trunk (per scan series)

Body region	Dose reference	Survey 2003 Germany		Survey 2003 UK	
		CTDIvol (mGy)	DLP/series (mGy·cm)	CTDIvol (mGy)	DLP/series (mGy·cm)
Chest	Mean	13.2	398	12	400
	P75	14.7	442	14	580
Abdomen and pelvis	Mean	10	395	11	470
	P75	12.9	515	14	560

Table 6.2. Optimized radiation doses for helical MDCT of the trunk (per scan series)

Body region	Body weight	Standard-dose Multidetector CT (MDCT)		Low-dose Multidetector CT (MDCT)	
		CTDIvol (mGy)	DLP/series (mGy·cm)	CTDIvol (mGy)	DLP/series (mGy·cm)
Chest	Thin patient	4.5	135±20%	2	40–70
	Normal patient	7	210±20%	3	70–120
	Obese patient	11	330±20%	5	140–180
Abdomen and pelvis	Thin patient	4–6	150–270	3	80–120
	Normal patient	7–10	280–400	5	150–200
	Obese patient	11–15	450–600	7–10	350–400

Note: Acquisitions obtained using an automatic exposure control device

6.4 Comments

Images illustrating this chapter were selected from our daily practice because they are a reflection of optimized CT protocols based on data reported in peer-reviewed journals. The subsequent dose delivered is lower than mean or median doses reported in survey studies. The dose delivered by such acquisition protocols is indeed in the same range of magnitude as the 25th percentile reported in these survey studies. As the image quality obtained with such a reduced dose is still very high, further dose reduction should be investigated in terms of diagnostic accuracy.

Dose optimization has some limitations. The dose recommended by radiologists who can accept image noise in CT images may not be tolerated by others, despite the fact that several published reports have demonstrated that the diagnostic performance was not compromised by low-dose and even very low-dose MDCT.

Radiologists play a very important role in dose optimization. He or she indeed determines the number of acquisitions, *Z*-coverage, mAs and kVp settings, etc. As a matter of debate, should the CT protocol used in a radiology department have to satisfy radiologists and clinicians, as the use of CT cannot be restricted to one single person but has to be interpreted and managed by a multidisciplinary team? Thus, CT protocols should provide an image quality sufficient to address the patient's clinical issue through an accurate diagnosis obtained with an appropriate radiation dose.

6.5 In Summary

Reducing the collective as well as the individual radiation dose requires the following factors:

- Avoiding unnecessary examinations
- Substituting CT examinations with MRI or US examinations
- Using an optimized CT technique including
  - *Z*-coverage
  - An appropriate number of acquisitions
  - Appropriate CT settings adapted to the patient, and to the clinical context.

When scanning the chest, the abdomen or the sino-nasal cavities, once the image quality has been optimized for the standard settings and results in mean dose values no higher than one-quarter to one-half of the reference values, further dose reductions can be applied for really low-dose scanning, with radiation doses no higher than those of a plain film examination. These scanning conditions have been validated in numerous indications, i.e., for the acute abdomen, follow-up of chest diseases and chronic sinusitis.

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