Dose Optimization and Reduction in MDCT of the Abdomen

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11.1 Introduction

Computed tomography is nowadays widely used in abdominal imaging in various circumstances including acute abdominal pain. This use is explained by the fact that this technique is highly reproducible, very rapid, highly sensitive and specific, quite easy to perform, and it causes little discomfort to the patient. With multi-detector row CT (MDCT) scanners, rapid volume acquisition became possible and examination of the whole abdomen is more and more frequently performed as a screening test in patients suspected of abdominal disorder. Such examinations of the whole abdomen are justified by the ability to detect alternative and/or additional diagnoses. However, since the abdomen contains sensitive organs, the radiation dose delivered to patients becomes a particular concern, especially in young patients and in those with chronic diseases who undergo repeated CT studies. Strategies to reduce the radiation dose delivered by CT have been developed and clinical investigations have shown that in several abdominal disorders the diagnostic performance of CT is not decreased by dose reduction. Reducing the dose was first investigated in conditions characterized by intrinsic high contrast between structures, such as ureteral stones, and later on in conditions characterized by intrinsic low contrast between structures, such as acute appendicitis.

11.2 Usual Radiation Dose and Reference Levels

Ideally, the dose delivered to the patient should be at the level below which the image quality would be insufficient to yield an accurate diagnosis. Practically, the delivered dose should be adapted first to the patient's size and second to the clinical indication. As evidence-based recommendations do not exist, guidelines have been derived from survey studies reporting the large-scale distribution of the delivered dose. The arbitrary fixed recommended dose threshold corresponds to the third quartile of the distribution observed in these surveys (Shrimpton et al. 2005), doses higher than the upper third quartile being considered as of unacceptable practice

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(EUROPEAN COMMISSION 1999). Detailed results of these survey studies, conducted mainly in United Kingdom and in Germany, are reported and discussed in Chapter 5.

The guidelines established by the Commission of the European Union have proposed that reference levels for routine abdominal CT examination (from the top of the liver to the aortic bifurcation) should be, respectively for the weighted CT dose index (CTDIw) and dose–length product (DLP), 35 mGy and 780 mGy·cm. For CT examinations of the liver and the spleen, the corresponding values should be 35 mGy and 900 mGy·cm. For the pelvis, they should be 35 mGy and 570 mGy·cm (EUROPEAN COMMISSION 1999). More recently, the National Radiological Protection Board (NRPB) has reported a snapshot of doses delivered in United Kingdom in 2003 (Shrimpton et al. 2005). In this report, the third quartile value of dose distribution, expressed in DLP, was 559 mGy·cm for routine abdominal CT examination obtained with MDCT. The corresponding value for liver examination in patients with possible metastases was 472 mGy·cm. These doses are clearly lower than those proposed in 1999 by the Commission of the European Union. This lowering probably reflects the increasing concern in reducing the dose as observed recently as well as technological advances in CT technology (i.e. the introduction of solid-state detectors).

The indication of each examination is very important to consider in order to select the required image quality and subsequently the lowest acceptable radiation dose. As an example, the dose delivered when searching for metastases or for imaging trauma can be higher than that for imaging acute abdominal pain. Nevertheless, as the minimum radiation doses needed for accurate diagnosis are unknown in most abdominal disorders, many examinations are actually performed with unnecessarily elevated radiation doses.

Furthermore, with MDCT scanners, the ability to rapidly scan large volumes tempts the operator to increase this volume along the z-axis, and/or to use multiple-pass CT instead of single-pass CT. Therefore *z*-coverage should be adapted to the clinical indication and to the possible alternative diagnoses. Unjustified screening the entire abdomen because of a "you never know" policy should thus be banished. Such policy is unacceptable in young patients who are at a low risk of having an incidental associated disease. Similarly, repeated acquisitions should not be performed in circumstances where they do not specifically yield additional information.

Automatic exposure control (AEC) devices that are nowadays available in modern equipment modulate the tube current as a function of the table position along the z-axis and of the image quality requested by the radiologist. Such devices reduce the tube current in thin patients and increase it in obese and overweight patients, tending to maintain the image quality constant. Therefore, radiologists using these devices should think in terms of image quality and not of tube current. Mulkens et al. (2005) showed that systems based on both angular and z-axis modulation reduce the mean tube current by 20%–68% when applied to standard MDCT protocols at constant tube current. With such systems, these authors also showed a good correlation between the mean effective tube current and the patient's body mass index (BMI), with an adaptation in obese and overweight patients leading to the reference tube current level being exceeded. These devices, which are only a partial response to the issue of the radiation dose, are extensively described in Chapter 7.

11.3 Dose Reduction in Acute Abdominal Disorders

11.3.1 High Contrast Between Structures

Unenhanced CT has been validated for the diagnosis of ureteral stones and it has been shown to be superior to intravenous urography (IVU) (Smith et al. 1995; Katz et al. 2000; Liu et al. 2000; Hamm et al. 2001). It also has the advantage of avoiding intravenous administration of iodine contrast material and may provide the basis for suggesting or establishing alternative and/or additional diagnoses (Sourtzis et al. 1999). On the other hand, CT scanning exposes the patient to radiation doses higher than that delivered by IVU and patients with ureteral stone may be young, will have repeated control examinations, and are at risk of recurrence.

With single detector row CT (SDCT), dose reduction can be achieved by increasing the pitch and by increasing the X-ray beam width. Such modulation provides thick transverse sections that could theoretically predispose smaller stones to be missed. Nevertheless, it has been shown that the number of ureteral stones missed by using such sections is not substantially higher than that detected by IVU. On the other hand, ureteral stones smaller than 5 mm in diameter are detected at CT but not at IVU (Liu et al. 2000). Diel et al. (2000) showed that increasing the pitch up to 2.5 or 3.0 is an effective method of reducing the radiation dose even if the image quality decreases with a pitch of 3.0. With these methods of reducing the dose, these authors delivered an effective dose ranging from 2.8 to 5.7 mSv, which is higher than doses delivered by IVU (Tack et al. 2003). Using the SDCT scanner, Hamm et al. (2002) have both reduced the tube current and increased the pitch on SDCT, resulting in a lower radiation dose than IVU. These authors showed that, except in obese patients, unenhanced SDCT has a sensitivity and specificity of 96% and 97%, respectively, for the diagnosis of ureteral stone.

Dose reduction by increasing the pitch is possible on SDCT and MDCT scanners constructed by GE and Toshiba, but not on MDCT scanners by Philips and Siemens. These two manufacturers have introduced the concept of "effective mAs"; the scanner automatically increases the tube current proportionally with the table speed, i.e. the tube current is doubled if the table speed or the pitch doubles. With these scanners, the dose and the slice profile are thus independent from the pitch. However, on the newest MDCT scanners with 16 or more detector rows, increasing the pitch factor has a negative effect on the radiation dose, because of overranging. Overranging elongates the scan length and corresponds to the dose delivered by additional rotations at the beginning and the end of the helical scan that are required for data interpolation. The amount of additional dose due to overranging depends on the pitch and the beam width, and is higher on 64 MDCT scanners than on 16 MDCT scanners. This is extensively discussed in Chapter 4.

Since MDCT scanners have been equipped with solid-state detectors, it has become possible to reduce the tube current as compared to SDCT. Using an MDCT scanner and acquisitions performed with a beam collimation of 4×2.5 mm, 120 kVp, and 30 mAs eff., Tack et al. (2003) have reported accuracy higher than 93% and excellent intra- and interobserver agreements in the detection of ureteral stone. The higher agreement reported by Tack et al. as compared to SDCT could be explained by thinner collimation with higher *z*-resolution and by the use of cine-viewing, multiplanar, and curved reformations as illustrated in Figure 11.1. The mean effective dose delivered by these authors – 1.2 mSv in men, and 1.9 mSv in woman – was approximately the same as that delivered by a three-film IVU (approximately 1.5 mSv). However, in this study performed without an AEC device, additional images obtained at 60 mAs were required to complement those at 30 mAs. This requirement could be explained by

a b

Fig. 11.1. a Ureteral stone (*arrow*). A 3 mm curved MPR from a low-dose acquisition performed with MDCT (4×2.5 mm, 120 kVp) at 30 mAs eff., without automatic exposure control (*AEC*). **b** Ureteral stone (*arrow*). A 3 mm curved MPR from a low-dose acquisition performed with MDCT (4×2.5 mm, 120 kVp) at 30 mAs eff., without AEC

greater image noise in the pelvis than in the abdomen at the same tube current due to the pelvic bones. In such circumstances, the AEC technique, unlike the fixed tube current technique, offers the opportunity to select the desired image quality in order to automatically reduce or increase the tube current according to the patient's size ("light" versus "heavy" patients) and body attenuation (abdomen versus pelvis). Kalra et al. (2005) showed that AEC along the z-axis can be used in patients suspected of urinary stone with 43%–66% dose reduction without compromising stone detectability. A recent report mentioned that ultra-low-dose MDCT – 120 kVp, 6.9 mAs eff. – delivering an effective radiation dose equivalent to one conventional abdominal X-ray view (approximately 0.5 mSv) achieved a sensitivity and specificity of, respectively, 97% and 95% for this diagnosis (Kluner et al. 2006).

Most importantly, it has been extensively demonstrated that low-dose unenhanced CT can also provide alternative diagnoses (Diel et al. 2000; Liu et al. 2000; Tack et al. 2003; Keyzer et al. 2004; Kluner et al. 2006). This will be discussed in the following paragraphs.

11.3.2 Low Contrast Between Structures

Reduction in radiation dose was first investigated in diagnostic conditions characterized by high intrinsic contrast between structures, such as lung nodule screening (Rusinek et al. 1998), CT colonography (van Gelder et al. 2002), and ureteral stones (Diel et al. 2000; Liu et al. 2000; Hamm et al. 2002; Tack et al. 2003; Kalra et al. 2005). In these early studies, it was suggested that alternative diagnoses can be made despite the reduced dose. Indeed, periureteric and perinephric fat stranding is still visible at low-dose CT (Heneghan et al. 2003), suggesting that any intra-abdominal fat stranding, as in numerous acute abdominal conditions, could also be detectable. These low intrinsic contrast conditions – characterized by peritoneal and retroperitoneal fat stranding – are visible in acute colon diverticulitis and acute appendicitis.

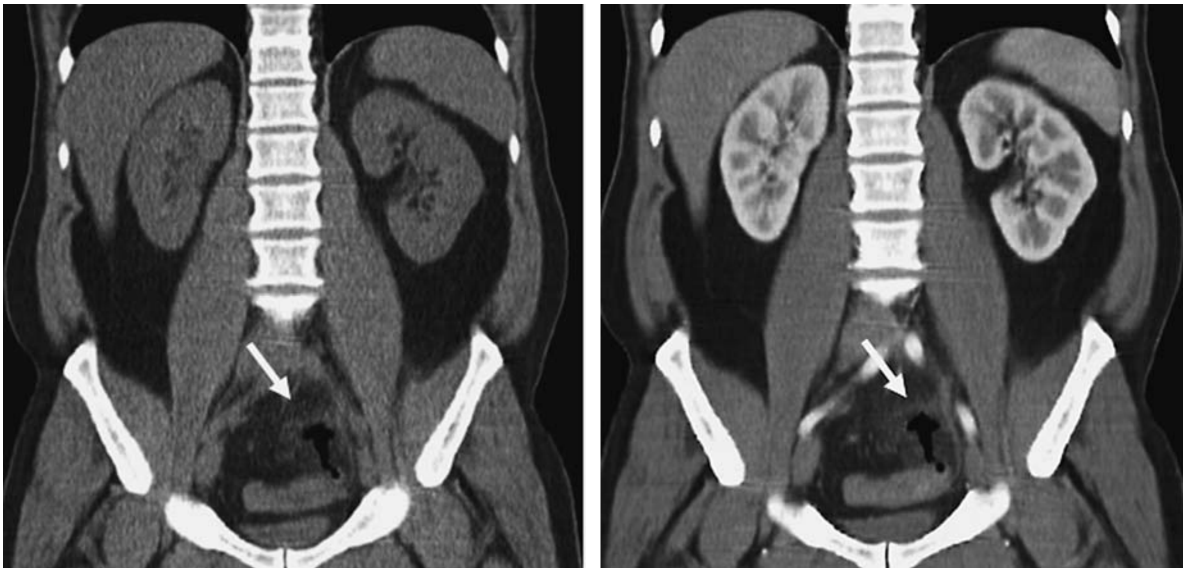
11.3.2.1 Acute Colon Diverticulitis

CT is known to be the optimal method for diagnosis and severity grading in patients suspected of having acute colon diverticulitis (Rao et al. 1998). In addition, CT is a fast technique and enables possible alternative and/or additional diagnoses (Birnbaum and Balthazar 1994). With the recently introduced MDCT technology, repeated acquisitions, extended z-axis coverage and thin collimations contribute to increase the radiation dose per examination as compared with that delivered with SDCT. This is especially of concern in patients with diverticulitis as they can be young and have a high risk of recurrence (Ferzoco et al. 1998).

Tack et al. (2005) compared unenhanced low-dose MDCT (30 mAs, 120 kVp) and enhanced standard-dose MDCT (120 mAs, 120 kVp) in patients suspected of acute diverticulitis. These authors showed that sensitivity and specificity are similar regardless of dose, and that CT has the potential to depict alternative disease. For the diagnosis of acute diverticulitis, the sensitivity and specificity of low-dose unenhanced MDCT range respectively from 85% to 100% and from 92% to 99%, depending on the reader, and are associated with good to excellent reader agreements. In this study, the final diagnosis was achieved without intravenous injection of iodinated contrast medium and with an effective radiation dose corresponding to that of a three-view conventional radiographic examination of the abdomen (Wall and Hart 1997). Indeed, the effective dose of low-dose CT scans obtained with the parameters used by Tack et al. was calculated at 1.6 mSv in women and 1.2 mSv in men. Fat stranding, known as an excellent sign of acute colon diverticulitis (Kircher et al. 2002), was demonstrated as the most predictive sign of this diagnosis regardless of the dose. In addition, this study revealed that low-dose MDCT enables the correct assessment of the presence of abscess and air collections distant to the colon (Fig. 11.2). Subsequently, dose reduction has no effect on the severity grading.

11.3.2.2 Acute Appendicitis

Because of its high sensitivity and specificity in the diagnosis of acute appendicitis – even without intravenous injection of iodinated contrast material (Lane et al. 1999; Ege et al. 2002) – CT has been used more and more frequently in the past decade in order to increase the accuracy of clinical diagnosis. CT, especially without any contrast material, is rapid and causes little discomfort to the patient. Nevertheless, as many individuals suspect-



a b

Fig. 11.2. a Acute sigmoid diverticulitis with a gaseous collection (*arrow*). Acquisition performed with MDCT (4×2.5 mm, 120 kVp) at 30 mAs eff., without AEC and without any contrast material. **b** Acute sigmoid diverticulitis with a gaseous collection (*arrow*). Acquisition performed with MDCT (4×2.5 mm, 120 kVp) at 120 mAs eff., without AEC, with intravenous iodine contrast material

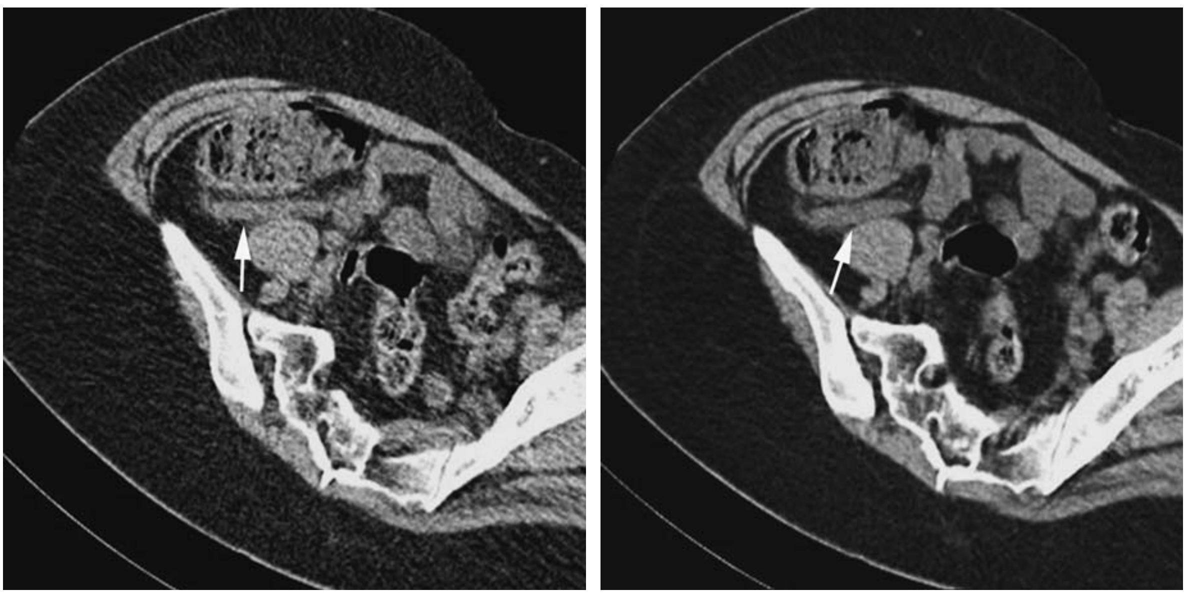


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Fig. 11.3. a Acute appendicitis (*arrow*). Enlarged appendix with periappendiceal fat stranding. A 3 mm oblique reformation. Acquisition performed with MDCT (4×2.5 mm, 120 kVp) at 30 mAs eff., without AEC and without any contrast material. **b** Acute appendicitis (*arrow*). Enlarged appendix with periappendiceal fat stranding. A 3 mm-oblique reformation. Acquisition performed with MDCT (4×2.5 mm, 120 kVp) at 100 mAs eff., without AEC and without any contrast material

ed of acute appendicitis are young – with a mean age of 30 years (Flum et al. 2001) – the radiation dose should be reduced. Keyzer et al. (2004) compared unenhanced low-dose (30 mAs, 120 kVp) and standard-dose (100 mAs, 120 kVp) MDCT in patients with suspected acute appendicitis. The frequency of visualization of the appendix and the diagnostic performance were similar regardless of the radiation dose (Fig. 11.3). Unenhanced MDCT achieves sensitivity and negative predictive values of 98% or even more. These two characteristics are the most important in patients suspected of acute appendicitis as this condition is potentially life-threatening and can be easily treated by a very efficient surgical procedure (Krieg et al. 1975). Specificity and positive predictive values are lower than sensitivity and negative predictive values but they are not different between doses. These values range respectively between 80%–94% and 69%–88%. As in acute colon diverticulitis, fat stranding – i.e. periappendiceal fat stranding – is the most predictive sign of acute appendicitis whatever the dose. Finally, the ability to propose a correct alternative diagnosis is not influenced by the dose (Fig. 11.4a, b). Another example of alternate diagnosis is illustrated in Figure 6.1 of Chapter 6 by D. Tack in the present edition.

These results could not be extended to children. Indeed, in a study performed with a phantom-based simulation technique, diagnostic performances of simulated low-dose CT (20 mAs) were reported as significantly lower than those of standard-dose CT (median, 126 mAs) (Fefferman et al. 2005). Sen-

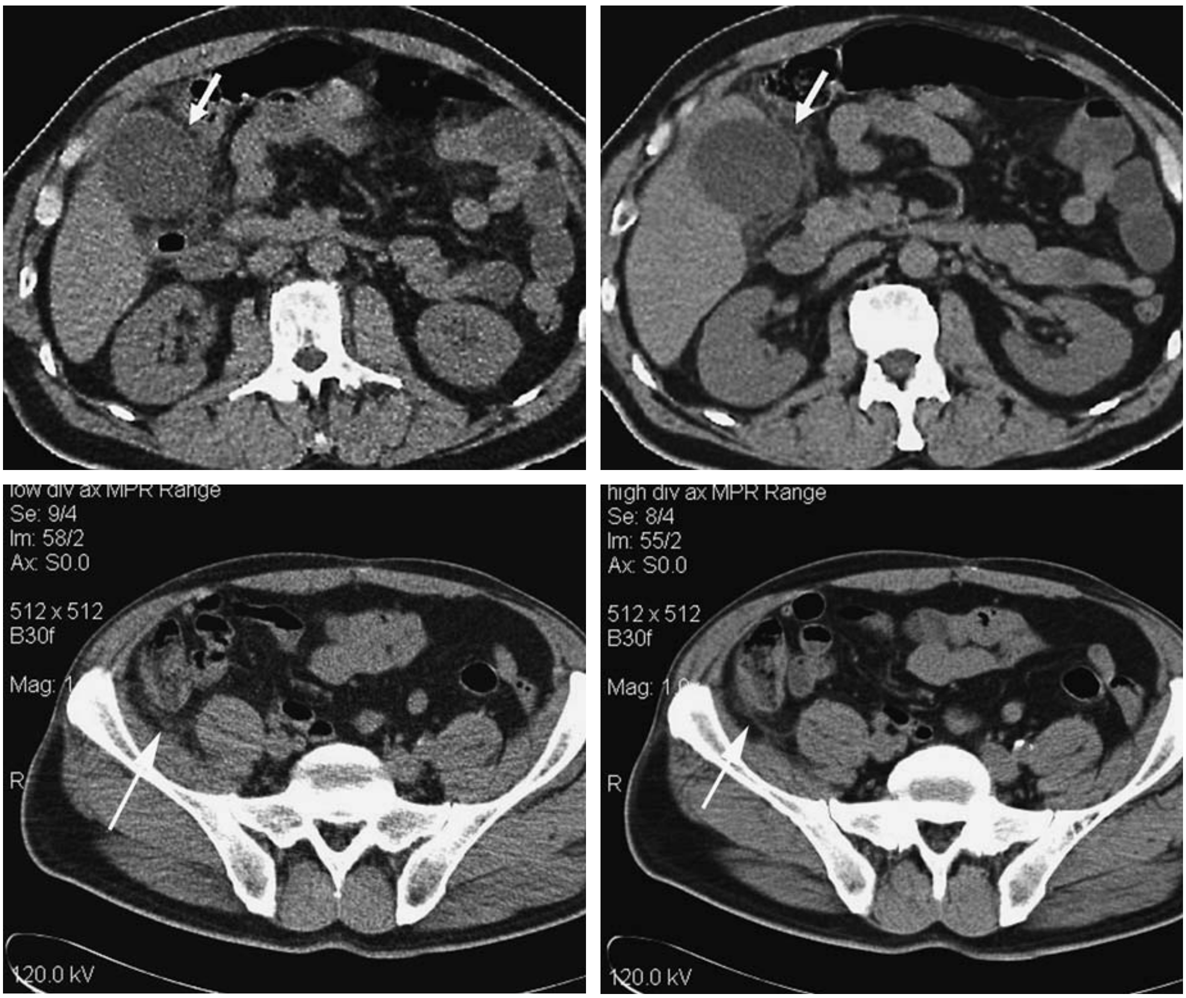

Fig. 11.4. **a** Patient with suspected acute appendicitis. Definite diagnosis of acute cholecystitis (*arrow*) that was visible at MDCT; 3 mm axial reconstructions. Acquisition performed with MDCT (4×2.5 mm, 120 kVp) at 30 mAs eff., without AEC and without any contrast material. **b** Patient with suspected acute appendicitis. Definite diagnosis of acute cholecystitis (*arrow*) that was visible at MDCT; 3 mm axial reconstructions. Acquisition performed at 100 mAs eff. (4×2.5 mm, 120 kVp), without AEC and without any contrast material. **c** Patient with suspected acute appendicitis. Definite diagnosis of acute caecal diverticulitis (*arrow*) that was visible at MDCT; 3 mm axial reconstructions. Acquisition performed at 30 mAs eff. (4×2.5 mm, 120 kVp), without AEC and without any contrast material. **d** Patient with suspected acute appendicitis. Definite diagnosis of acute caecal diverticulitis (*arrow*) that was visible at MDCT; 3 mm axial reconstructions. Acquisition performed at 100 mAs eff. (4×2.5 mm, 120 kVp), without AEC and without any contrast material

sitivity, specificity and accuracy are 77% versus 91%, 94% versus 93%, and 86% versus 92%, respectively, at low-dose and at standard-dose CT. It must be noted that this study was performed on SDCT and that these results have not been confirmed on MDCT.

11.4 Dose Reduction in Chronic Abdominal Disorders

In chronic disorders, repeated abdominal CT investigation are performed, even in young patients, in various conditions such as inflammatory bowel disease, pancreatitis and postoperative complications. Of course, in cases of cancer, dose reduction is of minor importance for the patient as he or she is at higher risk of dying of the existing cancer than of developing 20 years later another cancer induced by the radiation.

Most follow-up investigations need the use of intravenous contrast enhancement but no published study has evaluated the diagnostic performance of enhanced low-dose CT in chronic abdominal disorders. Studies have only compared image quality between CT at standard tube current and reduced tube current. Kalra et al. (2002) have addressed the possibility of reducing CT radiation dose in relatively thin patients (i.e. with small abdominal dimensions) with an acceptable image quality. This quality was achieved with a DLP of 550 mGy·cm (140 kVp, 120–150 mA). On the other hand, Nakayama et al. (2005) have proposed to reduce the tube voltage from 120 kVp to 90 kVp with a constant tube current of 300 mAs. These authors have shown that, despite increased noise and streak artefacts, the image quality is acceptable and that these artefacts rarely affect the diagnostic. Interestingly, with such reduction in tube voltage, the amount of contrast material can be reduced by at least 20% without degradation of image quality and organ enhancement, or sacrifice of low-contrast detectability (Funama et al. 2005). Such tube voltage reduction results in a dose reduction of 57% with CTDIw of 13.2 mGy and 5.7 mGy, at respectively 120 and 90 kVp (with a high tube current of 300 mAs). This is also of potential interest in CT angiography, which is discussed separately in Chapter 12.

11.5 Effect of Body Mass Index

Image noise increases with body size and the noise can be of huge importance in obese patients, particularly in the pelvis. Early studies were first performed on scanners that were not equipped with AEC. In these studies, mAs presets were maintained constant whatever the patient's size. With 30 mAs eff., Keyzer et al. (2004) showed that for the visualization of the appendix and the diagnosis of acute appendicitis, standard-dose and low-dose CT have equivalent diagnostic performance in patients with a BMI greater than 30 kg/m^2. This observation can be explained by the fact that the negative effect of an increase in BMI could be, at least in part, balanced by the accumulation of intra-abdominal fat around the appendix. On the other hand, for scanners not equipped with an AEC device, it has been proposed that in patients with a BMI greater than 30 kg/m^2 who are suspected of having ureteral stone or acute colon diverticulitis, the tube current should be increased up to 60 mAs eff., but maintained below the usual standard dose (Tack et al. 2003, 2005).

As detailed by H.D. Nagel in Chapter 4, the Brooks formula enables us to predict that mAs settings may be divided by a factor of 2 if the patient's diameter is reduced by 4 cm, with unchanged image quality. Thus, 60 mAs eff. in obese patients provides similar image quality to 30 mAs eff. in patients of normal mass. As the effective dose is higher in thin patients as compared to obese patients with constant CT parameters, the radiation risk for an obese patient scanned at 60 mAs eff. is similar to that of a normal-mass patient at 30 mAs eff. Using modern scanners equipped with AEC devices, the image quality and radiation risks are thus both kept constant regardless of the patient's size.

With modern scanners equipped with AEC devices, an image quality index corresponding to 50 mAs eff. is grossly equivalent to the previously investigated 30 mAs eff. (in normal-mass patients) and 60 mAs eff. (in obese patients) on 4-detector-row scanners with no AEC. Examples of optimized standard-dose and low-dose acquisitions acquired with AEC are shown in Figures 6.8–6.12 in Chapter 6 by D. Tack in the present edition.

If the dose reduction is achieved by decreasing the tube voltage from 120 to 90 kVp, the signal-to-noise ratio is decreased, implying that noise has a greater effect on images obtained at 90 kVp than on those at 120 kVp (Nakayama et al. 2005). Therefore, the use of the low-voltage technique could be restricted to normal and underweight patients or compensated by a higher tube current. Simultaneous reduction of tube voltage and tube current needs to be investigated.

11.6 Proposals of Presets and Doses

In this paragraph, doses appropriate for abdominal MDCT will be proposed. Such proposals are still a matter of debate. They are based on published references, if there are any; if there are none, we suggest reasonable doses as used in our clinical routine.

The presets, z-axis coverage and repeated exposure before and after intravenous administration of iodinated contrast material should always be adapted to the suspected diagnosis.

The standard presets recommended by the manufacturers with regard for the guidelines from the Commission of the EU and the NRPB should only be used in patients with suspected neoplasia and/or metastasis, old patients and those with severe trauma.

In suspected diagnoses such as ureteral stone, acute appendicitis and acute diverticulitis, reducing the dose is recommended by adapting the presets to the patient's size – i.e. patient's BMI – especially in those who are young and who could have repeated follow-up CT examinations. When one of these three diseases is clinically suspected, unenhanced low-dose MDCT is recommended as a first-line examination because it can confirm the clinical suspicion as well as demonstrate alternative diagnoses. If unenhanced low-dose examination is insufficient, one acquisition at standard dose after intravenous injection of iodinated contrast material can be focused on the abnormality detected at unenhanced CT. Suggestions of presets and the effective resulting dose are listed in Table 6.2 of Chapter 6 by D. Tack in the present edition. If the equipment includes an AEC device, the image quality can even be reduced in order to ensure an additional dose reduction.

For all other suspected diagnoses for which there are no published reports, we recommend the following general guidelines. First, a tube voltage of 120 kVp can be used in clinical routine and reduced to 100 kVp in thin or underweighted patients (without any subsequent decrease in image quality). Second, 140 kVp should not be used unless in extremely obese patients, as an increase from 120 to 140 kV will increase the radiation dose by 45% to 50%. Third, an AEC device should be used. Fourth, if the reconstructed images appear too noisy, multiplanar reformation with increased slice thickness can be used (Fig. 11.5).

Fig. 11.5. Ureteral stone (*arrow*) 5 mm coronal MPR from a low-dose acquisition performed with MDCT (4×2.5 mm, 120 kVp) at 30 mAs eff., without AEC, in an obese patient with a BMI of 39.7 kg/m^2

11.7 Perspectives

The "as low as reasonably achievable" principle asserts that the radiation dose should be kept to a minimum while giving an image of sufficient quality to make a correct diagnosis possible. This minimal dose should be evaluated for all specific clinical circumstances. In order to investigate the relationships between the radiation dose and the diagnostic performance without repeated acquisitions (with the subsequent increased dose delivered to the patients included in such clinical investigations), noise simulation techniques could be used. Such noise simulation techniques are obviously useful in clinical trials but also in day to day routine, as they can be used to determine the mAs settings needed to obtain the requested image quality. Such functionality is already available with some recent MDCT scanners.

In the near future, further studies are needed to investigate simultaneous tuning of tube current and tube voltage and should pay particular attention to anthropometric measurements in order to minimize the radiation dose without compromising diagnostic performance.

From a technological point of view, noise-reducing filters should be developed as a tool for imaging with very thin collimation. Indeed, thin sections are acquired with higher radiation dose than thick images, because of narrower beam collimation, slower table feed, lower scanner dose efficiency and higher tube current. Kalra et al. (2004) and Rizzo et al. (2005) have indeed demonstrated that such filters reduce the image noise quantitatively and visually, without affecting the attenuation values of both normal and abnormal tissues.

11.8 Conclusion

Survey studies have shown that collective doses have increased as MDCT has replaced SDCT. However, the radiation dose has been optimized over the last decade, mainly through AEC devices and reasonable use of tube current and tube voltage presets. This was achieved thanks to technological improvements and the willpower of several study groups to investigate the effect of dose reduction in terms of image quality and diagnostic performance. Nevertheless, as both the number of examinations and the number of clinical indications for CT increase, a major effort should be made in order to optimize the radiation dose. In addition, as survey studies have shown that great variations in doses among institutions remain, a supplementary effort should be made in order to recommend standardized acquisition protocols.

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