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MANAGING PATIENT DOSE IN COMPUTED TOMOGRAPHY

Task Group Members

Madan M. Rehani, TG Chairman, New Delhi, India

Professor Georg Bongartz, Basel, Switzerland

Professor Willi Kalender, Erlangen, Germany

Dr. Stephen J. Golding, Oxford, UK

Dr. Lena Gordon, Stockholm, Sweden

Professor Takamichi Murakami, Osaka, Japan

Dr. Paul Shrimpton, Didcot, UK

Corresponding Members

Dr. Roxie Albrecht, Albuquerque, NM, USA

Professor Keda Wei, Beijing, China

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1. *What is the motivation for this report?*

The motivation for this report are the relatively high radiation doses to the patient in CT examinations and the increasing frequency and variety of examinations. This report aims to provide radiologists and clinical staff with the means to successfully manage patient doses.

2. How high are the doses?

Absorbed dose in tissues from CT are among the highest observed from diagnostic radiology (i.e. 10-100 mGy). These doses can often approach or exceed levels known to increase the probability of cancer.

3. What practical actions can be used to manage patient dose ?

The referring physician should evaluate whether the result of examination will affect patient management. The radiologist should be assured that the procedure is justified. More than a 50 percent reduction in patient dose is possible by appropriate choice of technical parameters, attention to quality control and application of diagnostic reference levels.

4. What new equipment features would help manage patient dose?

CT doses are relatively high and have not decreased over time as they have in conventional radiography. Further improvements in CT equipment could help the operator substantially reduce unnecessary patient dose. The most important of these features will be anatomical based on-line adjustment of exposure factors.

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MAIN POINTS

1. The doses to tissues from computed tomography (10-100 mSv) can often approach or exceed the levels known to increase the probability of cancer
2. Radiologists are responsible for managing the dose in collaboration with imaging staff and medical physicists
3. CT examinations are increasing in frequency
4. Newer CT techniques have often increased doses when compared to standard CT
5. Referring physicians and radiologists should make sure that the examination is indicated
6. Many practical possibilities currently exist to manage dose. The most important is the reduction in mA.
7. Paediatric patients should have specific protocols with lower exposure factors (especially mAs)
8. Automatic exposure control would be the most helpful improvement in CT equipment for dose management

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What is the motivation for this report?

The motivation for this report is the relatively high radiation dose to the patient in CT examinations and the increasing frequency and variety of examinations. This report aims to provide radiologists with the means to successfully manage the patient doses.

1.1 General introduction

(1) Computed tomography (CT) was introduced into medical imaging in 1972 and since then has rapidly evolved in terms of both technical performance and clinical use. Although initial experiences readily predicted widespread implementation of the technique, it could hardly have been foreseen how rapidly CT would become one of the most important of all x ray procedures worldwide. Spiral CT and in particular the latest-generation of scanners with multi-slice capability in subsecond time frames have allowed improvements in speed of acquisition and image quality. This has resulted in highly reliable information about every part of the body, without motion artefacts from peristalsis and breathing. This consequence has been further unexpected growth of the modality. Thus, completely new indications for CT are being reported, as well as completely new methods for performing and reading the studies. Twenty years ago, a standard CT examination of the thorax took several minutes to conduct, while today similar information can be accumulated within a single breathhold period. This makes it more comfortable for patients and also easier for physicians to refer patients for examination, since the investigation is fast, well tolerated, accessible and, last but not least, regarded as highly reliable in its outcome.

(2) Shortening data acquisition time does not necessarily lead to reduction in patient radiation dose. The benefit to patients from properly directed CT scanning is beyond any doubt in relation to a extensive list of indications, from the use of cranial CT in unclear neurological status to orthopaedic investigations, as a preparation to the planning of surgical procedures. Various therapeutic regimens are directed by the results of CT investigations for staging disease and treatment planning in oncology patients. In modern medicine, where the evaluation of cost effectiveness plays a dominant role, an expensive examination like CT scanning can save money by excluding patients from inappropriate and even more expensive therapeutic procedures. Patient

management has changed in relation to a multitude of emergency cases as well as in diagnostic routine, with CT often being the initial investigation in a diagnostic work up. Some clinical investigations are postponed until after the results from CT scanning have been obtained in order to save time and money.

(3) In view of the known risk for radiation-induced cancer at dose levels reached by CT examinations, there is a continuing need to balance the benefits and risks to patients. In principle, this means the elimination of an unnecessary exposure. In practice, it requires the prior clinical justification of all CT examinations so as to ensure a net positive benefit for each patient, followed by the adoption of imaging techniques that will maximise the benefit relative to harm, by keeping the patient dose as low as reasonably practicable to meet defined clinical needs (ICRP, 1996 (Report 73)).

(4) In the early 1990s, when magnetic resonance imaging (MRI) had emerged and safety considerations concerning radiation exposure from medical imaging were gaining special importance in the western world, CT applications reached a short plateau and were expected to decline. However the pendulum has recently swung back towards CT due to technical innovations. Increasing numbers of CT scanners per million population observed in the last decade are the consequence of the high acceptance of the method in clinical imaging. Three-dimensional display of body regions like the abdomen, chest, intracranial and osseous structures is very useful. Online reconstructions in coronal, sagittal or any oblique plane help clinicians to understand better the underlying pathoanatomy of a disease.

(5) Greater implementation of CT in routine patient management has concomitantly increased the radiation burden from CT. In addition, requirements for improved image quality has led to higher patient doses. While new low-dose CT examinations are being proposed for a number of screening investigations, such as for lung cancer, patient doses have risen overall due to the steadily increasing requirements for adequate spatial and contrast resolution in the majority of diagnostic CT examinations. In conventional CT scanning, patient exposure is restricted to a thin slice of the body during each rotation of the x-ray tube with the possibility of an inter-slice gap. However, in spiral CT and more so in multi-slice CT the cumulative radiation dose from each complete investigation can be relatively high and gives rise to concern. Accordingly, CT is specifically addressed by several guidelines or regulations, mainly in the European Union (EC, 1997 (Directive); EC 1999 (Quality Criteria)). The latest EC Euratom Directive classified CT, together with interventional radiology, as a high-dose radiological procedure.

(6) Substantial variations in the dose to the patient for similar imaging protocols can result when applying different imaging protocols or using different CT scanners. Even when considering an identical clinical problem, the imaging procedure employed at two different imaging centres may be completely different. Comparison of the final diagnosis is not a measure for quality assessment or of dose comparison. Up to a certain point image quality usually increases with radiation dose. Past a certain level the dose continues to increase but the impact on patient care remains independent. Multiple factors like diagnostic uncertainty, "more-is-better" philosophy, or even competition, can produce CT protocols that are too extensive, too long and repetitive. The frequency of repeat investigation, examinations in paediatric patients and during pregnancy must be

undertaken with special care. The problem of high radiation dose from CT needs to be acknowledged, guidelines for quality control and CT dose measurements need to be promulgated, and there needs to be optimization of CT with respect to radiation protection.

1.2 Statistics

(7) In 1989, the UK National Radiological Protection Board (NRPB) reported that 20% of the national collective dose from all medical x-ray examinations was derived from CT alone, although it represented only 2% in terms of the total number of such examinations. Following further increases in the number of scanners available in the UK and growing implementation of the technique, subsequent reviews have suggested that the contribution from CT to collective dose had risen to approximately one third in 1995 and about 40% in 1998.

(8) Worldwide CT constitutes 5% of radiological examinations and makes 34% contribution to the collective dose (figure 1.1). In those countries with the highest levels of health care (classified by UNSCEAR as level I countries), the corresponding contributions are 6% and 41%, respectively. These data have increased relative to comparative analyses for frequency and collective dose for the period 1985 – 1990: 3% and 14%, respectively, for the entire world, and 4% and 18%, respectively, for developed countries. Such trends should of course be regarded not only in the light of increasing CT application, but also with regard to a decline in conventional x ray exposures following initiatives for optimizing the protection of patients. The worldwide total number of CT scanners is approximately 34,000 (UNSCEAR, 2000), with 80% operating in the western world where one quarter of the world's population lives. Annually, there is a global total of about 93 million CT examinations, corresponding to a frequency of 16 per 1000 inhabitants worldwide; 90% of all these procedures are conducted in the western world (UNSCEAR level I countries), at a rate of 57 examinations per 1000 population, with about 6% involving children (0-15 years). Although there is a remarkable variation in the numbers of CT scanners and investigations between different countries, the tendency towards increasing collective radiation dose is similar.

1.3 Trends

(9) Clinical application of CT for already established procedure has greatly increased in frequency in recent years due to technical advances in equipment leading to much faster acquisition and processing capability. A recent paper from USA (Mettler 2001) indicates that in a department with typical referral pattern CT scans now constitute 11% of the examinations and contribute 67% of the collective dose. Eleven percent were done in children below the age of 15 and most people had more than one scan sequence on the same day. The contribution from CT examinations to population exposure has steadily increased over the years. In radiological protection terms, the significance of this lies not merely in the absolute magnitude of the collective dose, but more in the increased potential for unnecessary patient exposures and the potential for dose reduction.

(10) New opportunities provided by CT fluoroscopy and angiography have given impetus to interventional radiology wherein dynamic and continuous imaging is now possible. Even though clinically useful, these developments are contributing to larger

radiation dose to the patient. Interventional procedures using CT expose specific parts of the body for an extended period of time adding to localised dose. In CT fluoroscopy, staff have to be present inside the CT room, near the gantry and their hands may be in the primary beam increasing the exposure of the staff.

1.4 Objectives of the report

(10) This report gives advice on managing the problem of increasing radiation doses from CT by technical means, training and justification of individual examinations. It is addressed to radiologists, radiographers, physicists and referring physicians, as well as to manufacturers, professional bodies and national authorities.

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(a) Contributions to frequency

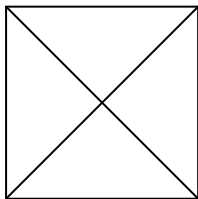
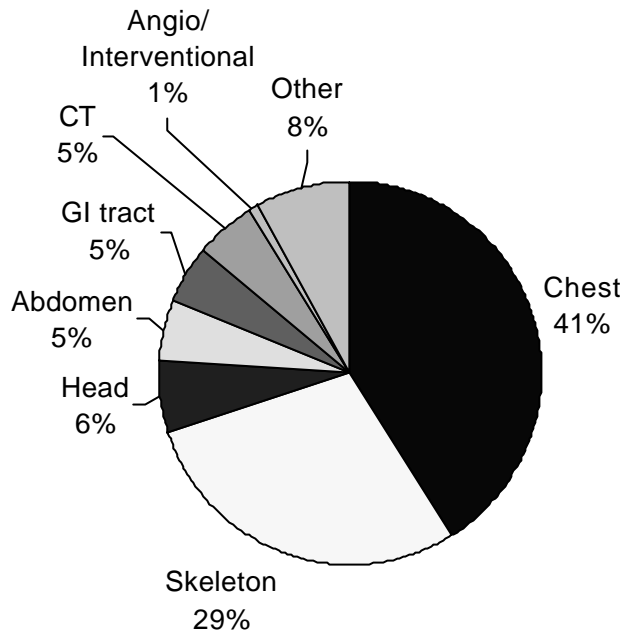


Figure 1 Analysis of annual global practice with medical x rays by examination category (UNSCEAR, 2000)

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How high are the doses?

Absorbed dose in tissues from CT are among the highest observed from diagnostic radiology (i.e. 10-100 mGy). These doses can often approach or exceed levels known to increase the probability of cancer.

2.1 Introduction

1) The conditions of exposure in CT, in which thin slices of the patient are irradiated in rotational geometry by a fan beam of x-rays, are quite different from those in conventional x ray examinations. Therefore specific techniques of dosimetry have necessarily been developed both to assess patient doses and to allow monitoring of performance for different types of CT examinations. Patient dose should not, of course, be considered in isolation from image quality (European Commission, 1999). The quantities used in this text are summarised below:

Absorbed dose in tissue: Energy deposited in tissue/organ per unit mass measured in Gy (gray). The basic quantity used for assessing the relative radiation risk to the tissue/organ.

Effective dose: a calculated quantity that takes into account the difference in radio-sensitivity of tissues. It is used as an index to compare relative radiation risk from different radiological procedures and is expressed in Sv (sievert),

Collective dose: The sum of effective doses in a patient population. Measured in man-Sv.

CTDI_w and DLP: Computed tomography dose index (weighted) and dose length product respectively. These are directly measured in phantom and represent dosimetric quantities for determining relative performance of equipment and technique used in CT. CTDI_w is measured in mGy and DLP in mGy cm. Either quantity can be used for the diagnostic reference levels.

2.2 Which quantities should be used to assess patient dose?

2) X-ray exposures of patients are best characterised by the absorbed radiation doses to each organ or tissue of the body (UNSCEAR, 2000). Such an assessment represents the most complete, risk-related summary of the patient dose, although the approach is rather unwieldy and difficult for routine use. The weighted-summation of organ doses to yield the quantity effective dose (ICRP, 1991) provides a convenient index of overall exposure that is useful for broad comparison of different CT techniques and other types of radiological examination.

3) Since the direct measurement of absorbed dose is impractical for most organs, comprehensive dose assessment necessarily involves the simulation of clinical CT practice, utilising physical or mathematical representations of the patient (anthropomorphic phantoms). Distributions of absorbed dose in such phantoms may be

determined by either measurements (Mini et al, 1995; Nishizawa et al, 1995) or, with greater utility, computational modelling (Zankl, 1998). The latter approach has provided dose coefficients, normalised to a free-in-air axial dose, that allow the estimation of organ and effective doses in a standard adult (Jones and Shrimpton, 1993; Shrimpton and Edyvean, 1998; Zankl et al, 1991; Kalender et al, 1999) and paediatric patients (Zankl et al, 1993; Zankl et al, 1995) for particular scanning protocols.

4) Building on initial experience with geometrical mathematical phantoms, computational methods of dosimetry are advancing steadily with the development of more realistic (voxel) phantoms based on digital images of humans (Veit et al, 1989; Caon et al, 1999; Jones, 1997; Xu et al, 2000). Differences in the results from calculations for different anthropomorphic phantoms under similar conditions of exposure underline the limitations and uncertainties in such computed dose coefficients. Accordingly, results determined for standard phantoms should not be applied to examinations of individual patients (Zankl, 1998), although patient-specific Monte Carlo calculations are also becoming a reality. In general, there is also reasonable agreement between sets of organ doses derived from measurements or calculations for a given CT examination technique when account is taken of differences in the exposure conditions being modelled (Calzado et al, 1995; Geleijns et al, 1994; Seifert et al, 1995). Some very general values for effective dose in particular scanning technique are shown in Tables 2.2 and 2.3.

2.3 Which quantities should be used to monitor performance?

5) Notwithstanding the need for some assessment of effective dose, good practice in CT demands periodic measurements of dose to characterise and monitor performance as an essential part of routine quality assurance. It is inappropriate to impose limits on the doses received by patients for medical purposes and the concept of diagnostic reference levels (DRLs) is increasingly recognised as a useful and practical way of promoting the fundamental requirement for optimisation of patient protection (ICRP, 1996). Diagnostic reference levels seek to characterise clinical practice in terms of quantities that allow comparisons within and among clinical facilities. Such measurements are intended to facilitate, where needed, improvements in patient protection during the regular process of review of equipment and techniques. In particular, diagnostic reference levels can be set for different types of examinations on the basis of wide-scale survey data and used to help identify potentially inadequate performance (Wall and Shrimpton, 1998). This approach has already proved effective for reducing unnecessary irradiation from conventional x ray examinations (Hart et al, 1996).

6) The quantities commonly used for monitoring patient doses during conventional x ray examinations, such as entrance surface dose, are less useful in CT. In practice, dosimetry in CT is based principally on measurements of the computed tomography dose index (CTDI), most conveniently quantified by using a pencil ionisation chamber with an active length of 100 mm and calibrated in terms of absorbed dose to air (see Appendix A). Such measurements are made free-in-air on the axis of rotation. CTDI provides only a coarse indication of patient exposure, although together with dose coefficients from mathematical modelling, they can be used to estimate organ and effective doses for particular scanning techniques (Shrimpton and Wall, 1995).

However, measurements of CTDI made in a phantom are better able to reflect the influence of scanner design, particularly the use of beam shaping filters, upon the radial distribution of absorbed dose within the irradiated slice. In particular, a weighted sum of CTDI measurements ($CTDI_w$) made at the centre and 10 mm below the surface of standard CT head and body dosimetry phantoms provides a useful way of characterising exposure in CT (European Commission, 1999) (Appendix A). Values of $CTDI_w$ are recommended for display on the operator's console of the CT scanner (IEC, 1999), reflecting the parameters of operation selected. However, operators should understand the basis of the values displayed, particularly where these include a correction for the pitch, that is, table feed in one rotation relative to collimation ($CTDI_{w, eff}$) (Nagel, 1999; IEC, 1999).

7) Two reference dose quantities have been defined for the purpose of promoting the use of good technique in CT: 1) weighted CTDI ($CTDI_w$) per rotation and 2) dose-length product (DLP) which takes into account beam collimation and the number of rotations in a complete examination (European Commission, 1999) (Appendix A). These dose quantities relate to measurements in standard head or body dosimetry phantoms, for a specific type of examination and the exposure conditions used in clinical practice. The concept was initially developed for examinations on adult patients, although it has subsequently been extended to paediatric CT (Shrimpton and Wall, 2000). Monitoring of $CTDI_w$ per rotation takes account of the exposure settings selected, such as tube current and tube voltage. Monitoring of DLP for a complete examination takes account also of the volume of irradiation, as determined, for example, by the number of slices in serial scanning or the acquisition time in spiral scanning, and the number of such scan sequences conducted during the examination. Values of DLP may also be used to derive broad estimates of effective dose for CT procedures using region-specific coefficients (European Commission, 1999; Shrimpton and Wall, 2000).

8) In line with international recommendations, some initial diagnostic reference levels for CT have been proposed for common examinations on adults (European Commission, 1999) and paediatric patients (Shrimpton and Wall, 2000). Such levels are for comparison locally in CT facilities against the measured values of dose descriptors assessed during examinations on representative groups of patients and they should not be applied on an individual patient basis. Diagnostic reference levels are intended to act as guides that trigger internal investigations by departments to identify situations where improvements in dose management may be necessary.

2.4 What influences the patient dose?

9) Patient dose in CT is determined by the inherent characteristics of the scanner, the size of the patient, the anatomical region under investigation, the scanning protocol and technique. The absorbed dose should be sufficient to meet the particular clinical need. These issues are discussed more fully in Section 4.

10) The influence of changes in some key technical and operational parameters on absorbed dose in tissues are summarised in Table 2.1 (Kalender, 2000); these apply both for serial or spiral scanning. Patient dose depends strongly on the radiation quality of the x ray beam. Patient dose decreases, for a given level of image quality (and in particular noise), with increasing tube voltage or filtration. For a given scanner, dose is

linearly related to the product of tube current (mA) and examination time (s). A reduction in the mAs value, for example by a factor of 2, causes a similar reduction in dose, but with a corresponding increase by a factor of $\sqrt{2}$ in image noise. Comparison of mAs values for different models of scanners is unlikely to provide meaningful information on relative dose due to differences in their design. Finally, mean organ/tissue dose depends on the volume of the patient irradiated during an examination. Absorbed dose increases with the number of slices in serial scanning or the acquisition time in spiral scanning, and the number of such sequences performed during a complete examination (for example multi-phase contrast scans of the liver). The absorbed dose for a given body part will also depend inversely on the pitch (table travel per rotation relative to beam collimation) during serial or spiral scanning. Scan projection radiography, which is commonly conducted to aid localisation in CT scanning, typically contributes only a few percent of the total patient dose (Shrimpton et al, 1991; Mini et al, 1995). New technical developments for reducing patient dose, such as tube current modulation, are discussed in Section 4.

2.5 What are the typical levels of patient dose?

11) Patient doses in CT are typically higher than those associated with many other common types of diagnostic x-ray procedures. Some illustrative doses to selected organs are shown in Table 2.2, on the basis of mean values reported in one particular comprehensive survey of national practice (Shrimpton et al, 1991); other studies of organ doses in CT have been reviewed elsewhere (UNSCEAR, 2000). There is paucity of national data on the variety of CT procedures and which provide dose information in comparable dose quantities. The data from UK in this respect is comprehensive even though it may not be representative of the situation in all countries. Doses to individual patients may be significantly higher than such mean data. For example, uterine absorbed doses of up to 80 mGy have been reported during pelvic CT and particular care is therefore required when conducting such examinations on female patients of reproductive age in order to avoid unnecessary fetal exposures (Sharp et al, 1998). The relatively small doses to the thyroid, breast and testes from scattered radiation may be further reduced by the use of lead shielding (Beaconsfield et al, 1998; Hidajat et al, 1996; Price et al, 1999). Lower levels of patient dose are often possible in CT with attention to choice of scanning technique, particularly with regard to lower settings or dynamic modulation of tube current (UNSCEAR, 2000); (see sections 3 and 4).

12) Typical effective doses to adults from some routine CT and conventional diagnostic x ray examinations in the UK are shown in Table 2.3 (RCR, 1998). Such dose data are broadly comparable with practice reported in other countries (UNSCEAR, 2000). Effective doses in CT are in general relatively high (typically 1-30 mSv) and may be similar to those values observed for some complex angiographic and interventional radiological procedures (UNSCEAR, 2000). Values of weighted CTDI and DLP are typically in the ranges 10 -100 mGy and 50 – 2000 mGy cm, respectively (European Commission, 1999).

13) With the use of standard scanning techniques, the energy imparted to the patient in CT increases with patient size, although the calculated effective dose is somewhat higher for children than adults; for example, data from one particular institution indicated

values of 6.0 mSv (newborn) and 1.5 mSv (adult) during head examinations, and 5.3 mSv (newborn) and 3.1 mSv (adult) during abdomen examinations (Huda et al, 1997).

14) Typical values of patient dose in CT can be expected to change with developments in technology (spiral, multislice and fluoroscopic CT), and clinical practice. Studies in the UK,, suggest as an initial trend broadly increasing levels of exposure per examination; the overall mean doses per CT examination from regional surveys in Wales (1994) and Northern Ireland (1996) were 20% and 5% higher, respectively, than the level observed in a national survey for the UK in 1989 (Clarke et al, 2000).

15) On the basis of equivalent scanning parameters, doses from spiral scanning are broadly similar to those from serial scanning, although increases by 10-30% will occur with multislice detector-array scanners (Kalender, 2000). Such technology can provide reductions in dose by the use of an increased pitch (>1), yet could also stimulate increased complexity of the examination and overall increases in patient dose. CT fluoroscopy is conducted at lower tube currents than for conventional scanning, although patients may remain stationary in the x ray beam for significant periods of time. Absorbed dose rates to the skin are typically 2 - 8 mGy per second, with effective dose rates of 0.03 – 0.07 mSv per second when scanning at the level of the mid-abdomen (Keat, 2000). Typically, conventional CT imparts an absorbed dose of 20-50mGy to the surface of the body.

16) Use of electron beam CT (EBCT) has been primarily limited to cardiac application, however newer machines have increased the number of images available and applications outside the heart are feasible. Using 3 mm collimation, $CTDI_w$ is virtually identical (5.0 mGy) for EBCT and spiral CT, whereas for 1.5 and 6 mm collimation, EBCT has a 75% and 106% higher average dose in comparison to the 1 and 7 mm spiral CT collimation (Weisser 1999).

17) Notwithstanding the levels of dose in CT discussed above, surveys of clinical practice have also demonstrated wide variations in patient dose and potential for improvements in optimization of the examination. Typical doses for a given general type of procedure have been shown to vary between individual CT centres by factors of 10-40 in the UK (Shrimpton et al, 1991) and 8-20 in Norway (Olerud, 1997). Such variations were largely due to differences in the local scanning technique employed, such as the number and thickness of slices imaged in serial scanning, the use of contrast medium for additional scans and the exposure settings selected. There is thus a continuing need for critical review of current practice, more widespread assessment of dose, and the use of reference doses.

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Table 2.1 Influence of technical and operational parameters on patient dose during CT (Kalender, 2000)

Parameter	Influence on patient dose
High tube voltage (Higher kV advantageous (for constant image noise)
Filtration	Higher filtration advantageous
Tube current	Linear increase with mA
Scanning time	Linear increase with s
Slice thickness	Approximately linear increase in dose with thickness (valid for single slices)
Scan volume	Approximately linear increase in dose with volume

Table 2.2 Typical doses during CT on adults (Shrimpton et al, 1991)

CT Examination	Eyes (mGy)	Thyroid (mGy)	Breast (mGy)	Uterus (mGy)	Ovaries (mGy)	Testes (mGy)	Effective dose (mSv)
Head	50	1.9	0.03	* ¹	*	*	1.8
Cervical spine	0.62	44	0.09	*	*	*	2.6
Thoracic spine	0.04	0.46	28	0.02	0.02	*	4.9
Chest	0.14	2.3	21	0.06	0.08	*	7.8
Abdomen	*	0.05	0.72	8.0	8.0	0.70	7.6
Lumbar spine	*	0.01	0.13	2.4	2.7	0.06	3.3
Pelvis	*	*	0.03	26	23	1.7	7.1

¹ The symbol * indicates that the dose is < 0.005 mGy.

Table 2.3 Comparison of typical doses in UK from CT and conventional x-ray examinations (Royal College of Radiologists, 1998)

Diagnostic procedure	Typical effective dose (mSv)
Conventional x ray	
Limbs and joints	< 0.01
Chest (single PA film)	0.02
Skull	0.07
Thoracic spine	0.7
Lumbar spine	1.3
Hip	0.3
Pelvis	0.7
Abdomen	1.0
IVU	2.5
Barium swallow	1.5
Barium meal	3
Barium follow through	3
Barium enema	7
CT	
Head	2
Chest	8
Abdomen	10
Pelvis	10

What practical actions can be used to manage patient dose ?

The referring physician should have evaluated whether the result of the examination will affect patient management. The radiologist should be satisfied that the procedure is justified. More than a 50 percent reduction in patient dose is possible by appropriate choice of technical parameters, concern for quality control and application of diagnostic reference levels.

3.1 Introduction

1) Radiologists and referring clinicians have a critical role in ensuring that patients are not irradiated unjustifiably. This section reviews the steps that referring clinicians and radiologists should undertake to discharge their responsibilities satisfactorily. It should be noted that in some countries this concept may be embodied in national law. The observations made in this section assume that medical practitioners will be fully familiar with regulatory and advisory requirements in their country.

3.2 Justification

2) Requests for a CT examination should be generated only by properly qualified medical practitioners. The radiologist should be appropriately trained and skilled in computed tomography and radiation protection, and with adequate knowledge concerning alternative techniques. A fundamental principle of radiation protection is that of justification, under which no investigation is undertaken unless the radiation dose is deemed to be justified by the potential clinical benefit to the patient. Also to be considered in the justification process are the availability of resources and cost. Justification is a shared responsibility between clinician and radiologist.

3) Clinical guidelines advising which examinations are appropriate and acceptable should be available to clinicians and radiologists. Ideally these will be agreed at national level but where they are not, local guidelines are often developed within an institution. Where possible, clinically relevant examinations should be obtained with the lowest achievable radiation dose to the patient consistent with obtaining the diagnostic information. In CT, this requires consideration of whether the required information could be obtained by conventional radiography, ultrasound or magnetic resonance imaging (MRI) without unduly hindering clinical management.

4) Where CT is deemed to be justifiable clinically, consideration must be given to tailoring the examination to diagnostic needs of the patient. This is good practice and constitutes one of the most important protection roles of the radiologist. CT scanning in pregnancy often raises concern. CT scanning of pregnant females is not contra-indicated, particularly in emergency situations. For computed tomography scans with uterus in the field of view, the absorbed doses to the fetus are typically about 40 mGy. Fortunately, the primary radiation beam on CT scanners

is very tightly collimated and can be precisely controlled relative to location by using scout view (topogram). As with other examinations it may be possible to limit the scanning to the anatomical area of interest (ICRP 84). As mentioned earlier, CT examinations of the abdomen or pelvis in a pregnant female should be carefully justified.

4

5) As in all x ray procedures, CT examinations should not be repeated without clinical justification and should be limited to the area of pathology under request. Unjustifiable repetition of exposure may occur if the referring clinician or radiologist is unaware of the existence or results of previous examinations. The risk of repetitive examinations increases when patients are transferred between institutions. For this reason, a record of previous investigation should be available to all those generating or carrying out examination requests. The clinician who has knowledge that a previous examination exists has a responsibility to communicate this to the radiologist.

6) CT examinations for research purposes that do not have clinical justification at the level of immediate benefit to the person undergoing the examination should be subject to critical evaluation since the doses are significantly higher than conventional radiography. Additional information on this is available in ICRP Publication 62 (ICRP 1991).

3.3 Managing the patient dose

5

3.3.1 Optimisation

7) Once referral for CT examination has been justified, the radiologist has primary responsibility for ensuring that the examination is carried out conscientiously, effectively, and with good technique. This is usually described as the principle of optimisation. Within this process the radiologist has considerable scope for limiting the radiation dose to the patient. The objective is to provide sufficient diagnostic information to influence the clinical management of the patient. Clinical issues define the area to be examined and the extent of the examination required. However even when these conditions are met the radiologist has additional opportunity for limiting the radiation dose to the patient.

8) It is valuable to consider the role of contrast medium enhancement prior to commencing the examination. In some cases a single examination following enhancement may be adequate for clinical purposes and initial unenhanced images may therefore be avoided. In multiphase enhancement studies the examination should be limited to the number of phases which are clinically justified.

9) CT fluoroscopy and interventional CT pose particular challenges in radiation protection. Conventionally, biopsy procedures have often been performed with x ray fluoroscopic or ultrasonographic guidance. However x ray fluoroscopy supplies limited 3-dimensional information and ultrasound guidance may be impeded by bowel gas, lung or bone. For this reason, CT guided percutaneous biopsy is widely performed and has the advantage of operational ease and safety. However this involves a longer exposure and the patient and radiologist may be exposed to high doses of radiation.

10) A number of national surveys have indicated widespread variation in the radiation dose to patients for any particular radiological examination (Shrimpton et al. 1991; Conway

et al. 1992, Hart et al. 1996). In conventional radiography, higher exposure leads to increased darkening of the image, whereas in CT that is not the case and this can result in selection of unnecessarily high exposure factors (Rehani, 2000; Rehani and Berry 2000). There is much radiologist and radiologic technologist can do to keep radiation exposure low without compromising image quality. The operator has control over tube current (mA), scan length, slice thickness (collimation), table feed per 360°, pitch and applied potential (kVp). Commonly CT machines provide pre-set factors however the settings should be tailored for each patient according to body part and patient build. Protocols should be designed to include patient parameters.

3.3.2 Role of mA and mAs

11) The mAs is the single most important factor for managing patient dose. mAs should vary with patient size and body part. Reducing mAs significantly reduces patient dose and lengthens tube life. The mA controls the x ray intensity (the number of x ray photons per unit time). The mAs setting represents the number of x ray photons in the defined exposure time. The intensity is directly proportional to mA. For a given scanner, halving mA means halving radiation dose. Since its invention about 3 decades ago, the trend in all subsequent developments in CT has been to minimize scanning time. When the image of a defined region is to be acquired in seconds or even fractions of a second, high x ray intensity is a must. The shorter the exposure time, the higher the required x ray intensity. Accordingly, x ray tubes for CT are designed to give better radiation output, improved heat capacity and heat dissipation.

12) In addition to faster scanning times, another factor which has contributed to high dose in CT is the demand for higher spatial resolution, leading to the use of thinner sections which in turn necessitates even higher intensities of x ray beam in order to keep noise low. High resolution CT requires thin slices typically of 1 or 2 mm, which is only possible by increasing the mA. For a fixed value of mAs, decreasing exposure time (s) means proportionately increasing the tube current (mA). Reduction of mA leads to an increase in noise and thus a possible degradation in image quality. In good practice one should strike the balance between image quality and dose.

13) The degradation in image quality as a result of reducing mAs is not significant in high contrast situations. In the body there are some high contrast structures like the thorax and pelvis where the contrast between bony structures and soft tissue or air is high. In such situations, a significant decrease in mA is possible while keeping image quality acceptable. This strategy has been exploited by many investigators, particularly in relation to imaging of the thorax. For example, a low dose CT technique of the thorax was described in 1990 whereby scans of acceptable diagnostic quality were obtained with an mAs setting that was only 20% of that used for standard practice (Naidich et al. 1990). For chronic infiltrative lung disease, a high confidence level in diagnosis has been demonstrated in 61% of low dose CT scans compared with 63% of conventional dose CT scans (Lee et al. 1994). Study under simulated conditions using phantoms demonstrated that there is no decrease in detection of simulated plaques, nodes and effusions in a chest phantom when mA is reduced by 80%, typically from 400 to 80 mA (Mayo et al. 1995).

14) A similar reduction in absorbed dose in paediatric chest CT has been reported. The low dose technique using 25 mAs (in a typical case) has been shown to provide image

quality that has no loss of diagnostic information (Rogalla et al.1999). In an attempt to find minimum tube current for spiral CT, the subjective quality of images obtained at 20 mAs has been reported to be not significantly different from that assessed for images obtained at 50 mAs. Imaging of the middle zone of the chest requires still lower values of mAs (approx. 12 mAs), relative to the upper and lower zone which require around 20 mAs. (Itoh et al. 2000). It is possible to perform spiral CT of the maxilla and mandible with a radiation dose similar to that used for conventional panoramic radiography.

15) There are definite problems in achieving low doses in areas of low contrast in the body like the abdomen. Noise becomes a limiting factor in such circumstances. It is a common practice to use the same mAs whenever abdomen and pelvis are to be scanned. Substantial dose reduction, without any recognisable deterioration in diagnostic image quality, may be achieved if pelvic CT is performed at almost $1/3^{\text{rd}}$ the mAs for abdomen region. A surface dose reduction from 30 to 10 mGy has been documented. The rationale behind reducing the mAs for imaging of the pelvis relative to the abdomen is that the abdomen contains organs like the liver, where resolution is very important, whereas the pelvis does not have similar structures, but rather bones, bladder and opacified bowel. An increase in mAs does not significantly improve high contrast resolution, but leads to a major change in low-contrast areas. Thus lower mAs values may not create problems for imaging of the pelvis, but are not desirable for the abdomen.

3.3.3 Smart technique:

16) Recently attempts have been made to develop the so-called “*smart technique*” with the principal idea being to change technical factors during a 360° rotation according to the actual object attenuation, instead of keeping tube current constant for all projection angles as is usual practice today (Kalender et al. 1999). If this is implemented by the manufacturers, it will contribute in a large measure to reduction in patient dose and reduce the need for subjective adjustment of mA may be reduced. Further details are given in section 4

3.3.4 Scan length

17) This controls the volume of patient irradiated, Unfortunately, with the advent of fast scanners, there is a tendency to increase the scan length so much that examinations of the thorax + abdomen + pelvis are becoming much more common. Practice may soon include head-to-pelvis examinations (particularly for rapid assessment of patients with massive trauma). It is essential to draw the attention of referring physicians and radiologists to the dose consequences of such practices and efforts must be made to restrict the areas of examination to those clinically essential.

3.3.5 Collimation, table speed and pitch

18) In conventional CT, the latter two factors are absent. In spiral CT, all three factors have to be considered together. They are inter-linked in such a way that discussion of one in isolation is irrelevant. For example, pitch is table feed (mm) in one rotation relative to collimation (slice thickness and interslice separation). If the pitch is taken as 1, it can be achieved by 10 mm/rotation for 10-mm collimation. If the rotation time is one second for 360° , the table speed becomes 10 mm/sec. If one alters the collimation to 5 mm without

changing table speed, the pitch becomes 2. If the pitch is to be retained as 1, the table speed has to be adjusted to 5mm/sec. Pitch changes have different effects on image quality in different situations. For some situations, like in virtual CT colonoscopy, image quality and reconstruction artifacts are less affected by the pitch value than by beam collimation. Thus from an image quality point of view, one may prefer a higher pitch with narrow beam collimation. But the situation is different for small pulmonary nodules, which may require thin section CT (lower collimation) and where an increased pitch may affect detectability. Keeping a pitch of 1 while using thinner sections results in higher radiation dose.

19) There are two ways by which pitch can be increased: increase table travel speed or decrease collimation. These methods have different effects:

a) Increasing table travel speed for a given collimation and hence higher pitch is associated with lower radiation dose (due to lower effective exposure time) and predictably decreased detection of lesions like small pulmonary nodules.

b) Decreasing collimation (for a given table speed) results in unchanged scan time, decreased radiation dose, decreased signal-to-noise ratio and, depending upon the signal-to-noise ratio consideration, potentially superior detection of small pulmonary nodules.

20) Continuous spiral CT scans (pitch of 1) give approximately the same radiation dose as contiguous axial scans acquired with the same technical factors. For non-contiguous scans (pitch >1) at a given collimation, the radiation dose decreases as the pitch increases, specifically as 1/pitch. For a given table speed of 10 mm/s, the radiation dose from a 10 mm collimation scan at pitch of 1 is approximately double that of a 5 mm collimation scan at pitch of 2. Thus, for a given table speed, increasing the pitch reduces the radiation dose, while changing the collimation has little effect on dose. In addition, for a given collimation, increasing the table speed (increasing the pitch) reduces the radiation dose by 1/pitch. For example, going from 10 mm and pitch of 1 (10 mm/s) to 10 mm and pitch of 2 (20 mm/s) reduces the radiation dose by 50%. At smaller slice thickness, the radiation profile width (full width at half maximum) is greater than the nominal slice thickness, which results in extended radiation overlap between slices and no net change in radiation dose compared with thicker slices. While thinner collimation would normally be expected to yield a smaller radiation dose, the higher degree of overlap between adjacent scans offsets this expected decrease and ultimately results in little net effect on absorbed dose due to collimation. TLD measurements have been shown that for a pitch of 1.5, the radiation dose [effective] is approximately 67% of the radiation dose for a scan with a pitch of 1, while a pitch of 2 yielded a dose of about one half that for the pitch 1 scan. Studies aimed at high quality 3-D reconstruction led to the conclusion that there is no indication to apply a pitch smaller than one.

3.3.5 Role of combination of factors

3.3.6

21) kVp is normally not changed from patient to patient for a particular type of study, even though many machines make it possible to change the setting and it may be desirable to do so. Assuming that scan length and slice thickness have been judiciously chosen as per clinical need, we are left with mA, table feed/rotation and pitch. Table 3.1 gives a typical example of settings for spiral CT of the chest, in which mA has been reduced from 165 to 110, table feed increased from 5 mm to 10 mm per rotation and pitch changed from 1 to 2

(Kalender et al. 1999a). This results in the effective dose decreasing from 7.1 to 2.4 mSv (i.e. 34% of original or a 66% reduction) and lung dose decreasing from 24.3 to 8.2 mGy (66% reduction). A similar example for quantitative CT of the lumbar spine indicates a 92% reduction in absorbed dose by reducing kVp and mA (Table 3.1).

22) Facial CT is used for osseointegrated implants and can be performed with spiral CT and a dental software package. Reducing mAs from 165 to 35 and using a pitch of 2 rather than 1 has been reported to reduce the bone marrow dose by a factor of about 8 (e.g. from 24 mGy to 3 mGy). Similarly the eye lens dose is reduced by a factor of nearly 2 (e.g. 0.5 mGy to 0.3 mGy), thyroid gland dose by a factor of 5 (e.g. 2.5 mGy to 0.5 mGy), parotid gland by a factor of 6 (e.g. 2.4 mGy to 0.4 mGy). These reductions in dose did not lead to any significant loss of image quality or diagnostic information (Rustmeyer et al. 1999)

3.3.7 Shielding of superficial organs

23) Conventionally organ shielding has not been practised in CT. However, increased doses in CT have generated interest in this area. Shielding is particularly relevant in children. Use of shielding should not be an excuse to raise exposure parameters. Breast, thyroid, lens of the eye and gonads are seldom the organ of interest in a CT examination, although they incidentally are often in the beam. The radiation doses delivered to these organs are significant enough to be a matter of concern. A conventional diagnostic chest CT imparts a dose of 20-50 mGy to the breast of an averaged sized woman. This is equivalent to 10-25 two view mammographic examinations. Justification of CT examinations of the chest in girls and young females need to be justified in view of the higher risks of radiogenic breast cancer for this age group. Shielding of breast tissue by a breast garment of thinly layered bismuth impregnated radioprotective latex has been shown to reduce the radiation dose by over 50 % without affecting the display of other deeper structures (Hopper 1999). Whether to use bismuth or lead is to be decided on the basis of ease of manufacturing, versatility, fit and cost.

24) CT slices at the base of the skull impart high doses to the thyroid and shielding of this organ in children is very effective in such cases. The dose to the eye lens is typically around 30 mGy in general head CT, 70 mGy in scanning of sinuses and may be 10-130 mGy in CT of orbital trauma. Gonadal shielding during CT examinations is controversial. When the gonads are not included in the examination field, the small doses are due to internal scatter and thus external shielding is largely ineffective. When the gonads are within the direct CT beam shielding may be considered if they are not the organ of clinical concern and if shielding will not compromise the examination by producing significant artifacts or by directly obscuring a contiguous area of clinical interest. Shielding of the ovaries is difficult because their exact location is usually not clear and the expected pathology is often nearby.

3.3.8 Partial Rotation

25) In CT, the x ray tube rotates around the patient resulting in cross-sectional images. The speed of rotation and the scan parameters like kVp and mAs are constant throughout the 360° rotational path in the models currently available commercially. The dose at the surface of the patient thus depends upon the distance from the x ray target for the entrance beam, together with contributions from the primary and secondary x ray photons from the beams entering the patient from other points. The major contribution to the absorbed dose at any

point superficially located arises from the entrance dose. For the eye lens, the frontal beams thus contribute the major part of the absorbed dose. In head scanning, if the frontal 90° is omitted and the scan is performed with an angular rotation of 270°, then minimal dose is received by the eyes (Fig. 3.1), (Robinson A 1997). This partial rotation capability is currently available in some scanners.

3.4 Dose in CT Fluoroscopy

26) Unlike x ray fluoroscopic or ultrasound (US) guidance in which the biopsy needle and the lesion can be observed in real time, guidance with conventional CT does not permit imaging during the actual procedure, which remains “blind”. This limitation of conventional CT guided procedure has been overcome by the development of continuous imaging and CT fluoroscopy which permit CT images to be reconstructed and displayed with a reconstruction time of less than 0.2 sec. CT fluoroscopy allows tomographic images to be observed in real time as an animated sequence.

27) During conventional CT guided biopsy, the physician is not exposed to x rays during scanning. One major problem with CT fluoroscopy-guided procedures, however, is that the physician’s hands are exposed to high levels of radiation because various procedures are performed within the direct x ray beam when the interventional devices are manipulated manually. Direct beam exposure to the hands may reach 120 mSv per procedure if protection is not provided. This would limit the number of procedures which a physician could perform to 4 per year (ICRP dose limit of 500 mSv to hands). Since the beam in CT is finely collimated, then effective protection can be achieved by moving the hands slightly so as to be out of the collimated primary beam. This can be achieved with the use of holding instruments for the syringe, needle etc. The holder should be of acrylic so as to prevent the streak artifacts associated with a metal holder. The hands can thus be 5 cm or so away from the primary beam and are thus exposed to only scattered x rays. The exposure is reduced by over 98%. The success rate reported with the use of the holder is 100% and no significant increase in operating time has been observed (Kato et al. 1996). The absorbed doses to patients are high as indicated in Section 2. The most effective way to control the absorbed dose is to minimize the fluoroscopy time and attention must be focused on this parameter.

3.5 EC quality criteria

28) Recommendations concerning achievable standards of good practice in CT have been developed by the European Commission in the form of quality criteria (European Commission 1999). This concept seeks to provide an operational framework for radiological protection initiatives in which technical parameters for image quality are considered in relation to patient dose. Diagnostic and dose requirements for CT are specified in terms of the quality criteria considered necessary to produce images of standard quality for a particular anatomical region, without regard to specific clinical indications. The subjective image criteria include anatomical criteria that relate to the visualisation or critical reproduction of anatomical features. Criteria concerning patient dose are given in terms of reference dose values associated with the examination technique used for standard-sized patients. Quality criteria have been developed for 26 types of examinations within 6 broad anatomical groups, together with examples of technique parameters influencing the dose. The usefulness of this framework for detailed

audit of CT practice has been investigated and demonstrated in clinical trials (Calzado et al 2000, Jurik et al. 1998).

3.6 Diagnostic reference levels (DRL)

29) The diagnostic reference level is an essential element of quality assurance in CT. The implementation of DRLs is done through measurement of CTDI, performed both free-in-air and in standard dosimetry phantoms, using a pencil ionisation chamber with an active length of 100 mm and calibrated in terms of absorbed dose to air (see Section 2 and Appendix A). These measurements should be conducted as part of routine constancy testing (quality control) for each scanner (PEM 1997; IEC 1999). To avoid a potential source of confusion, it should be recognized that previous recommendations published in the literature have sometimes utilised subtly different definitions of CTDI involving, for example, different lengths of integration or reference materials. (IEC 1994, Edyeayn 1998).

30) Measurement of CTDI in the standard head and body dosimetry phantoms allows the derivation of the quantities $CTDI_w$ and DLP for any given clinical scanning protocol (European Commission, 1999). In the absence of measurements for an individual scanner, broad estimates of dose may be made using model-specific generic data from published compilations of CTDI data (European Commission, 1999). Assessments of typical CT practice should be based on local surveys involving the evaluation of scan details for representative samples of at least 10 patients for each type of procedure. Mean values of $CTDI_w$ and DLP for each patient group should be compared with appropriate diagnostic reference levels that have been set nationally or locally to promote optimisation of patient protection (Appendix A). Any technique for which doses (DRL) are above an investigation level should be critically reviewed and either clinically justified or revised so as to reduce patient doses without loss of clinical efficacy. Such assessments should be carried out periodically (for example, at least every 3 years) or whenever there are substantial changes to equipment or technique. There is also a need for CT facilities to know typical effective doses for the different common types of procedure in clinical use. Such doses can be estimated from values of DLP or calculated with knowledge of scanning technique using published dose coefficients and CTDI measurements made free-in-air (section 2).

Table 3.1 Examples for dose reduction in CT by changes in scan parameters from set 'a' to set 'b' (adapted from Kalender et al. 1999a)

Spiral CT of the chest		Quantitative CT of the lumbar spine	
a	b	a	b

Voltage (kVp)	140.0	140.0	120.0	80.0
Current (mA)	165.0	110.0	250.0	75.0
Scan range (cm)	31.0	31.0	3x1.0	3x1.0
Slice thickness (mm)	5.0	5.0	10.0	10.0
Table feed/360° (mm)	5.0	10.0	--	--
Pitch	1.0	2.0	--	--
Organ of interest	Lung		Stomach	
Organ dose (mGy)	24.3	8.15	4.4	0.4
Effective dose (mSv)	7.1	2.4	1.0	0.1

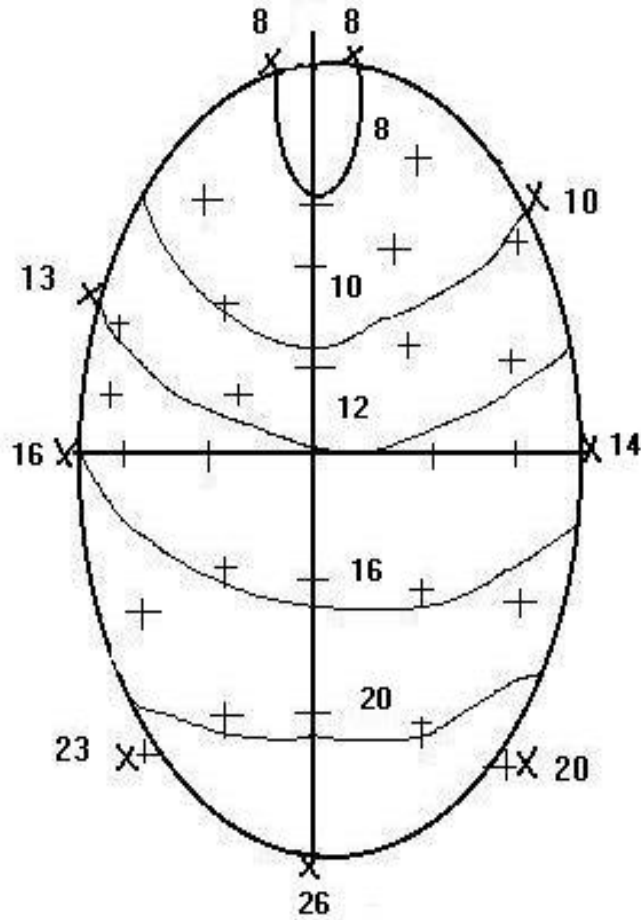


Fig 3.1, Dose distribution through the section of the skull (face-up) for 270° scan omitting the frontal 90°. Minimum dose occurs in the region of the eyes. The doses are slightly higher on left side since in this unit x ray tube rotates by an additional 20°c (clockwise) for patient movement (adapted from Robinson 1996).

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Table 3.3: Guidance on use of the interslice gap or pitch variation.

In general diagnosis , the interslice gap should not be more than one half of the diameter of the smallest lesion that may be detected in any clinical situation. For example, when examining for abdominal lymphadenopathy, the threshold of abnormality is a node of 10 mm diameter. An interslice gap of 5mm would imply that any lesion would appear on at least one section. In conventional CT any doubtful abnormality may be elucidated by obtaining a single section in that interslice gap.

In helical CT the above rule may still apply. However helical CT allows the operator to increase pitch - which will have a similar effect on radiation dose to increasing the interslice gap in conventional – but reconstruct images at contiguous locations. This results in images of lower spatial and contrast resolution and the operator must determine that the resulting images will be clinically acceptable.

Frequently the clinical evaluation of the patient allows sections to be limited, and interslice gaps or pitch to be increased. For example, if a patient is known to have a large mass on clinical examination, adequate diagnosis and evaluation may be achieved by large sections with large interslice gaps, or by large pitch in helical CT.

The localiser view should always be scrutinised for presence of disease at the start of the examination. If this shows extensive disease sections may be limited accordingly.

Sections may be limited in monitoring examinations during treatment of extensive lesions. In these circumstances the examination is planned to take account of clinical evaluation of progress; if clinical information suggests significant disease remains sections may be limited. Alternatively, if there is clinical evidence of good disease response, a detailed examination may be required to confirm that this is so.

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4

What new equipment features would help manage patient dose?

CT doses are relatively high and have not decreased as they have in conventional radiography. Further improvements in CT equipment could help the operator substantially reduce unnecessary patient dose. The most important of these features will be anatomically based on-line adjustment of exposure factors.

4.1 Introduction

(1) The frequency of CT examinations has continued to increase in recent years, in spite of the widespread availability of MR imaging. In view of the newest technical developments in CT, it is not expected that this trend will reverse in the foreseeable future. On the contrary, the very possibilities which multi-slice spiral CT offers will most likely lead to a further increase in the number of CT examinations performed. Consequently, it also appears likely that the collective dose to the general population from CT will remain at the present level or increase. The relative contribution of CT to the annual exposure of the population to ionizing radiation for medical diagnosis will continue to increase. A meaningful assessment of CT can take place only if, along with the discussion of possible risks, the clinical benefits, that is diagnostic reliability, patient comfort, costs, etc. are also taken into consideration. Such a discussion would go beyond the framework of this document. In general, the benefits of CT examinations are not questioned.

(2) During nearly 30 years of clinical use of CT, significant improvements have been observed in image quality and general scanning performance. Among the many parameters of performance, reductions in the scan times per slice, i.e. the rotation time per 360°, and the scan times per volume of examination have been the most impressive changes. CT now routinely offers sub-second rotation times and total examination times of 10 to 60 s. In comparison, the improvements in low-contrast resolution have been less

spectacular. The dose per slice for given levels of noise and resolution has not changed dramatically over the past years

(3) CT developments in the past always aimed at improving utility, i.e. at enhancing the diagnostic value of established CT applications and at providing new applications. Dose efficiency was not a primary goal to the same degree, and the “market“ did not demand that manufacturers pursue it. Consequently, there still appear to be a number of possibilities to optimize CT systems and their use with respect to dose efficiency. It has to be stressed that efforts have to be supported respectively by both the manufacturers and the users of the systems. Some important points are summarized in table 4.1.

4.2 Spiral CT

(4) Spiral CT offers specific possibilities for the reduction of dose. A very effective method for dose reduction is given by choosing a pitch factor of greater than 1. The specific use of the new possibilities which multi-slice CT systems offer, can also serve to limit the dose. The new approaches to z-interpolation and z-filtering, which allow for retrospective variation of the effective slice thickness, provide images both with high 3D spatial resolution or alternatively with low noise and excellent low-contrast resolution without the need for additional exposure to radiation.

4.3 Current, filtration and other technical factors

(5) Some technical measures to improve the dose efficiency of CT systems are known and have been partly tested. However, their use often creates a conflict in relation to other goals and requirements. Thus, for example, increasing the filtration, which reduces the patient dose, requires higher mAs values and thus leads to greater loading of the x-ray tube. This in turn can lead to limitation of the permissible scan duration for spiral CT. Multi-slice CT systems drastically reduce the scan duration, and the decreased loading of the tube can permit the use of additional filtration.

(6) The definition and preparation of low-dose scanning protocols for paediatric CT and for special indications should be studied further and be actively promoted by the manufacturers. The further development of noise-reducing reconstruction methods also appears to be promising, especially with regard to multidimensional adaptive filters for multi-slice CT systems, which offer considerable potential [Kachelrieß, 1999].

(7) A significant reduction in dose can be achieved through anatomy-adapted, attenuation-dependent, tube current modulation. The basic idea is that the pixel noise in a CT image is largely attributable to those projections in which the attenuation and therefore the quantum noise are greatest. This means that for cross-sections deviating significantly from a round shape the intensity of the radiation can be reduced in the projections with less attenuation, without any significant effect on the noise pattern. This offers considerable potential for the reduction of dose without a worsening of image quality, as has been shown clearly in several studies [Kalender, 1999b; Gies, 1999; Kalender, 1999c].

(8) Human anatomy practically always involves cross-sections which deviate more or less significantly from a circular or cylindrical shape. Accordingly, studies with tube current modulation show that the mAs product can be reduced typically by between 10% and 50% without any loss of image quality. For scans with extreme differences in the attenuation characteristics between the antero-posterior (AP) and lateral directions, such as in the shoulder region, absorbed dose reduction of even more than 50% is possible [Greess, 1999; Kalender, 1999c].

(9) With the use of tube current modulation, it is also possible to selectively influence image quality. Increasing the tube current in the lateral direction and reducing the current in the AP direction can improve the image quality and at the same time significantly reduce the dose. The actual patient dose is reduced even more than the mAs product. In hip examinations, for example, typical values of mAs reduction of around 40% were found. Phantom measurements and by Monte Carlo calculations, these corresponded to a reduction in patient dose of nearly 60 to 70% (figure 2 ?).

(10) Spiral CT is predestined for novel tube current modulation techniques, since the required reference data on attenuation for modifying the tube current are available in the shortest possible times and over the shortest possible distances. The currently used modulation parameters are determined in real-time from the immediately preceding values, taken from the oppositely located tube position, i.e. shifted by only 180° or half the table feed per rotation. This approach is generally applicable in spiral scanning. All manufacturers should be encouraged to implement and to offer it. A beneficial side effect is that tube life should go up or that the demands on the x-ray components may be relieved as total mAs per examination goes down.

Providing information on dose

(11) Establishing reference dose levels will help not only to control and optimize techniques, but also to make information on the orders of magnitude of patient dose more generally known.

(12) Indication of CTDI values and DLP information by the manufacturers on the operator's console is a valuable step in that direction and the radiologist should be familiar with the presentation and the meaning of the dose. There are established procedures and software to provide such values for a typical patient, i.e. for "standard man" [Zankl, 1991; Jones and Shrimpton, 1993; Kalender, 1999a]. There is also the possibility to calculate the dose distribution specific for the patient and scan protocol by Monte Carlo methods.

4.5 Automatic exposure control (AEC) for CT

(13) Optimization of CT systems and quality control have to ensure that a diagnostic quality image is obtained with a minimum of dose. For this existing measures must be supplemented by two further steps, which will require the close cooperation of manufacturers and users: development of an automatic exposure control for CT and objectively defined requirements for image quality. The combination of these two measures seeks to achieve and secure as its goal a definite level of image quality, attainable with minimum dose for the particular examination type. This would also include or define standards and diagnostic reference levels.

(14) The development of anatomy-dependent, attenuation-based methods of x ray tube current regulation have shown a high potential for dose reduction [Greess, 1999; Kalender, 1999b; Kalender, 1999c]. These methods should be used on a broad basis, since they do not entail any disadvantages in terms of image quality. Their introduction on a general basis, however, should only represent a first step, because they are so far limited to the optimum distribution of a predefined mAs product per 360° revolution. A further necessary step must be the development of an automatic exposure control for CT. Automatic exposure controls have long since been established in conventional x ray diagnostics, although less for the purpose of dose reduction than for the prevention of faulty exposures. In CT the idea of an automatic dose control has not yet been followed up because, as a result of the prevailing high dynamic ranges of the receptor systems,

faulty exposures in the classical sense can be ruled out and because certain technical questions remain to be clarified.

(15) In the meantime, technical possibilities, such as the example of anatomy-dependent tube current regulation, are available. The remaining technical problem for the implementation of an AEC lies in the fact that, along with the regulation of the tube current during a 360° revolution, the tube current - time product (that is, the mAs value per revolution) during a spiral CT examination continuously adapts to the changing body cross-section and the particular attenuation. This is technically feasible, provided that certain limiting conditions are considered, such as limitation of the maximum tube current. The essential problem is to arrive at an objective presetting to define the image quality, defined for example in terms of image noise and image sharpness, required for a specific examination type. The problem of calculating the required tube current values from the measured CT data in real time can be solved. The requirements for image quality must, however, first be defined by radiologists.

4.6 Image Quality

16) Objective measures of image quality are available. Nevertheless, experience shows that these cannot lay claim to a complete description of images. This refers, for example, to noise patterns, which can be influenced by both the dose and the choice of convolution kernel. The subjective assessment of image quality by the radiologist can very easily differ from an objectively determined order of ranking. In spite of this, it should be possible to arrive at a consensus with respect to the decisive parameters, above all for image sharpness and noise.

17) This image quality, which is to be seen as the “minimum necessary” or, in the sense of radiation protection, as the “optimum” image quality for a particular application, must be ensured for all patients and without exception for all slices of the volume to be examined, with minimum dose. The dose would then automatically be reduced for the examination of a slender patient. This of course applies in special measure to paediatric CT, where minimum dose with the assurance of acceptable image quality is a matter of greatest importance. The dose would likewise be automatically reduced when, in the course of an examination, thinner cross-sections are reached, which is almost never realized under the conditions prevailing today.

18) A consensus concerning the required image quality parameters for commonly

performed CT examinations would also improve the situation of different institutions working with substantially different parameters and consequently delivering different absorbed doses. Differences of more than a factor of four have frequently been reported [Shrimpton et al. 1998]. This would also simplify the comparison of different CT scanners with regard to their dose requirements and enable the definition of acceptance criteria for general use.

4.6 Potential for accidents

19) Accidents involving CT scanners that have resulted in high absorbed doses have been almost non-existent due to scanner design. The most obvious opportunity for accidental exposure in spiral CT would be if the table were mechanically jammed, did not move, and the tube continued rotational exposure. Mechanical jamming of tables is actually reasonably common with patient restraint devices, sheets, and tubes getting caught under the table. Fortunately the scanners are equipped with linear resistive potentiometers that sense the rate of change of table velocity and if there is a discrepancy of table velocity from that expected for the set pitch etc., the exposure is immediately terminated. In the design of new equipment manufacturers need to continue prospective assessment of accident potential.

Table 4.1 Possibilities for patient dose reduction with CT

Measures for the user	Measures for the manufacturer
Checking the indication and limiting the scanned volume	Increasing the prefiltration of the radiation spectrum
Adapting the scanning parameters to the patient cross-section	Attenuation-dependent tube current modulation
Pronounced reduction of mAs values for children	Low-dose scanning protocols for children and special indications
Use of spiral CT with pitch factors >1 and calculation of overlapping	Automatic exposure control for conventional CT and spiral CT

images in-stead of acquiring overlapping single scans	
Adequate selection of image reconstruction parameters	Noise-reducing image reconstruction procedures
Use of z-filtering with multi-slice CT systems	Further development of algorithms for z-filtering and adaptive filtering

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APPENDIX A

Reference dose quantities for CT

1) The principal dosimetric quantity used in CT is the computed tomography dose index (CTDI). This is defined as the integral along a line parallel to the axis of rotation (z) of the dose profile (D(z)) for a single rotation and a fixed table position, divided by the nominal thickness of the x-ray beam. CTDI can be conveniently assessed using a pencil ionisation chamber with an active length of 100 mm, so as to provide a measurement of $CTDI_{100}$, expressed in terms of absorbed dose to air (IEC, 1999):

$$CTDI_{100} = \frac{1}{nT} \int_{-50}^{+50} D(z) dz \quad (\text{mGy}) \quad (1)$$

where n is the number of tomographic sections, each of nominal thickness T, from a single rotation

2) Reference dosimetry for CT is based on such measurements made within standard CT dosimetry phantoms; these presently comprise homogeneous cylinders of polymethylmethacrylate (PMMA), with diameters of 16 cm (head) and 32 cm (body), although phantoms of water-equivalent plastic and with elliptical cross-sections are under development. The combination of measurements made at the centre (c) and 10 mm below the surface (p) of a phantom leads to the following two reference dose quantities (European Commission, 1999):

(a) Weighted CTDI in the standard head or body phantom for a single rotation corresponding to the exposure settings used in clinical practice

$$CTDI_w = \frac{1}{3} CTDI_{100,c} + \frac{2}{3} CTDI_{100,p} \quad (\text{mGy}) \quad (2)$$

where $CTDI_{100,p}$ represents an average of measurements at four different locations around the periphery of the phantom.

(b) *Dose-length product for a complete examination*

$$DLP = \sum_i n CTDI_w * T * N * C \quad (\text{mGy cm}) \quad (3)$$

where i is the number of scan sequences in the examination, each with N rotations of collimation T cm and exposure C mAs; $nCTDI_w$ is the normalised weighted CTDI ($\text{mGy mA}^{-1}\text{s}^{-1}$) appropriate for the applied potential and nominal beam collimation (number and width of slices per rotation).

1) These quantities can be applied to serial or spiral scanning, for both single- or multi-slice geometry scanners. Initial diagnostic reference levels have been published for some common procedures on the basis of surveys of practice for adult (European Commission, 1999) and paediatric (Shrimpton and Wall, 2000) patients; these values

are shown in Tables X.1 and X.2. Such investigation levels are for comparison locally with the mean values of dose descriptors assessed in a CT facility during examinations on representative groups of patients and should not be applied on an individual patient basis.

Table A..1. Initial diagnostic reference levels for CT examinations on adult patients (European Commission, 1999)

Examination	Diagnostic reference level*	
	CTDI _w (mGy)	DLP (mGy cm)
Routine head	60	1050
Face and sinuses	35	360
Vertebral trauma	70	460
Routine chest	30	650
HRCT of lung	35	280
Routine abdomen	35	780
Liver and spleen	35	900
Routine pelvis	35	570
Osseous pelvis	25	520

- same as ICRP reference levels

Table A.2. Initial reference dose values for CT examinations on paediatric patients (Shrimpton and Wall, 2000).

Examination	Patient age (years)	CTDI _w per slice or rotation (mGy)	DLP per examination (mGy cm)
Brain	< 1	40	300
	5	60	600
	10	70	750
Chest (general)	< 1	20	200
	5	30	400
	10	30	600
Chest (HRCT)	< 1	30	50
	5	40	75
	10	50	100
Upper abdomen	< 1	20	330
	5	25	360
	10	30	800
Lower abdomen & pelvis	< 1	20	170
	5	25	250
	10	30	500