Appendix MSCT Dosimetry, guidelines on radiation dose to the patient

OBJECTIVE

The conditions of exposure during CT examinations are quite different from those in conventional x-ray procedures and specific techniques are necessary in order to allow detailed assessment of patient dose from CT. National and international surveys of CT practice using such methods of dosimetry have established the increasing importance of CT as a significant source of medical x-rays for populations in developed countries (UNSCEAR, Brix, Imhof). Evidence from dose surveys has also indicated potential scope for improvement in the optimisation of protection for patients undergoing CT and the need for more widespread assessment of typical levels of patient dose as part of routine quality assurance. Inherent differences in the design of CT equipment lead to variations between scanner models by up to a factor of three in the values of effective dose calculated for a standard anatomical region and normalised to axial air kerma (Shrimpton and Edyvean, 1998). However, larger variations in dose are apparent in clinical practice, with a typical variation in patient effective dose for a given type of procedure by a factor 10 (European CT field survey of 2000-2003 (Appendix C)). This is largely as a result of differences in the local scanning technique typically employed for a particular type of examination, as determined by the number and thickness of slices imaged, the couch increment between tube rotations, the use of contrast medium for additional scans and the exposure settings selected.

The Examples of Good Imaging Technique given in the Lists of Quality Criteria are intended to help avoid unnecessary exposures in CT. The Criteria for Radiation Dose to the Patient indicate diagnostic reference dose values for general types of examination as a practical means of promoting strategies for optimisation of patient protection. The purpose of a reference dose quantity for a diagnostic medical exposure is to provide quantification of performance and allow comparison of examination techniques at different hospitals. Diagnostic reference dose values should not be applied locally on an individual patient basis, but rather to the mean doses observed for representative groups of patients. Reference dose values are intended to act as thresholds to trigger internal investigations by departments where typical practice is likely to be well away from the optimum and where improvements in dose-reduction are probably most urgently required. Typical levels of dose in excess of a reference dose value should either be thoroughly justified or reduced. In general, patient doses should always be reduced to the lowest levels that are reasonably practicable and consistent with the clinical purpose of the examination.

QUANTITIES AND UNITS

CT pitch factor

The CT pitch factor for a scan sequence is the ratio of the distance (Δd, mm) moved by the patient support in the z direction between consecutive serial scans or per 360° rotation in helical scanning, and the product of the nominal section thickness (T, mm) and the number (N) of simultaneous tomographic sections from a single rotation (IEC 2003).

$$CT\ pitch\ factor = \frac{\Delta d}{N \times T} \qquad (1)$$

Volume radiographic exposure (C_{vol})
The volume radiographic exposure (C_{vol}, mAs) describes in helical scanning the average radiographic exposure over the total volume scanned. The C_{vol} is defined as follows:

$$C_{vol} = \frac{C}{CT\ pitch\ factor} \qquad \text{(mAs)} \quad (2)$$

Computed Tomography Dose Index (CTDI)
The principal dosimetric quantity used in CT is the computed tomography dose index (CTDI, mGy). This is defined as the integral along a line z perpendicular to the tomographic plane of the dose profile (D(z)) for a single axial scan, divided by the product of the number of tomographic sections N and the nominal section thickness T (Shope):

$$CTDI = \int_{-\infty}^{+\infty} \frac{D(z)}{N \times T} dz \quad \text{(mGy)} \quad (3)$$

where:
D(z) is the dose profile along a line z perpendicular to the tomographic plane, where dose is reported as absorbed dose to air (mGy);
N is the number of tomographic sections produced simultaneously in a typically a 360° rotation of the x-ray tube;
T is the corresponding nominal tomographic section thickness (mm)

In practice, a convenient assessment of CTDI can be made 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 (mGy). Such measurements may be carried out free-in-air on, or parallel with, the axis of rotation of the scanner ($CTDI_{100(air)}$, or in abbreviation $CTDI_{air}$), or at the center ($CTDI_{100(center)}$) and 10 mm below the surface ($CTDI_{100(peripheral)}$) of standard CT dosimetry phantoms; in practice $CTDI_{100(peripheral)}$ is determined as the average of four values of $CTDI_{100}$ measured at evenly distributed positions around the dosimetry phantom:

$$CTDI_{100} = \int_{-50mm}^{+50mm} \frac{D(z)}{N \times T} dz \qquad \text{(mGy) (4)}$$

$CTDI_{air}$ is the $CTDI_{100(air)}$ measured at the isocenter (center-of-rotation) of the scanner in the absence of a phantom and patient support.

For the phantom measurements two homogeneous cylindrical phantoms with diameters of 160mm (standard CT head phantom) and 320mm (standard CT body phantom) are used. The height of the cylinders is at least 140mm and the material is PMMA. Holes with matching PMMA plugs are available in the phantoms for inserting a pencil ionisation chamber with an active length of 100 mm at the center and 4 equally spaced peripheral positions.

Measurements of CTDI in the standard head or body CT dosimetry phantom may be used to provide an indication of the average CTDI over a tomographic section produced with a single axial scan. On the assumption that dose in a particular phantom decreases linearly with radial position from the surface to the centre, then the average CTDI within a tomographic section (Leitz) is approximately the weighted $CTDI_{100}$ ($CTDI_w$):

$$CTDI_w = \frac{1}{3} \times CTDI_{100(center)} + \frac{2}{3} \times CTDI_{100(peripheral)} \qquad \text{(mGy) (5)}$$

The volume $CTDI_w$ ($CTDI_{vol}$) then describes the average dose over the total volume scanned in a sequential or helical sequence (IEC 2003):

$$CTDI_{vol} = \frac{CTDI_w}{CT\ pitch\ factor} \qquad \text{(mGy) (6)}$$

The subscript 'n' is sometimes used to denote when measurements of CTDI have been normalised to unit radiographic exposure (mAs):

$$_nCTDI = \frac{CTDI}{C} \qquad \text{(mGy/mAs)} \quad (7)$$

where C is the radiographic exposure (mAs). Values of $_nCTDI$ vary with tube voltage and beam shaping filter, and also section thickness due to the effect of overbeaming, most notably for the smallest section thickness and 4-slice scanners. The beam shaping filter in use might depend on the selected field-of-view (e.g. a dedicated filter for small field scanning) or the anatomy to be scanned (e.g. a dedicated filter for body or head scanning). Elevated values of $_nCTDI$ at narrow

section thickness, for a certain tube voltage and beam shaping filter, indicate a reduced geometric efficiency.

Dose Length Product (DLP)

Monitoring of the dose-length product (DLP, mGy.cm) provides control over the volume of irradiation and the overall exposure for an examination. The DLP depends on the $CTDI_{vol}$ and the length of the exposed range.

$$DLP = CTDI_{vol} \times L \quad \text{(mGy cm)} \qquad (8)$$

where:

L is the scan length (cm) limited by the outer margins of the exposed scan range (irrespective of pitch). For a helical scan sequence, this is the total scan length that is exposed during (raw) data acquisition, including any additional rotation(s) at either end of the programmed scan length that are necessary for data interpolation. Note that the DLP is derived from values of $CTDI_{vol}$ for either the standard head CT dosimetry phantom or the standard body CT dosimetry phantom. DLP's for different sequences are only additive if they refer to the same type of CT dosimetry phantom.

METHODS OF DOSE ASSESSMENT TO CHECK COMPLIANCE WITH THE CRITERIA

Comparison of performance against the criteria for each particular type of examination requires assessment of the values of the reference dose quantities associated with the technique typically used when scanning a standard-sized adult patient. In the absence of a well-defined scanning protocol, typical dosimetric practice should be determined on the basis of the mean results derived for a sample of at least 10 patients for each procedure. Despite the increasing attention on paediatric CT, specific tools for dose assessment for this particular application presently remain underdeveloped.

$CTDI_w$ may be assessed directly from Equation (5) using the results of measurements of $CTDI_{100}$ at the peripheral and central positions for either the head or body CT dosimetry phantom. Such measurements are typically carried out during routine performance testing and may be accomplished using thermoluminescent dosemeters (TLDs) or more conveniently using an appropriately calibrated 100 mm long pencil-shaped ionisation chamber. It is a requirement within the European Communities that new scanners are provided with an indication of patient dose (European Union). Furthermore, the International Electrotechnical Commission recommends that values of $CTDI_{vol}$ should be displayed on the operator's console of the CT scanner, reflecting the conditions of operation selected (IEC2003). Typical values of $_nCTDI_w$ for a wide range of scanner models are available both on the Internet (ImPACT) and in publications

(Nagel). Some standard dose data for a selection of MSCT scanners is given, for illustrative purposes, in the second part of this Appendix ($_nCTDI_w$). Measurements of $CTDI_{air}$ are easily accomplished with either the 100 mm pencil-shaped ionisation chamber or a shorter length of TLDs since the tails on the dose profiles in air are less significant than in a phantom in view of the lower amount of scattered radiation.

Estimates of DLP for an examination may be derived using Equation (8) with knowledge of appropriate values of $CTDI_{vol}$ (or $CTDI_w$) for the scanner and details of the particular scanning protocol used. Most modern MSCT scanners show values of DLP on the user interface. In the case of examinations involving separate scanning sequences in which different technique parameters might be applied (such as slice thickness or radiographic exposure, for example), the total DLP should be determined for the entire procedure as the sum of the contributions from each serial or helical sequence.

ASSESSMENT OF EFFECTIVE DOSE

In addition to comparison of performance against reference dose values, there is sometimes a need to assess effective dose (ICRP60) for CT procedures so as, for example, to allow comparison with other types of radiological examination. The effective dose for a particular scanning protocol may be estimated from a measurement of $CTDI_{air}$ utilising scanner-specific normalised organ dose data determined for a mathematical anthropomorphic phantom using Monte Carlo techniques (Jones, Zankl 1991). For specific types of scanner not included amongst these calculations, appropriate matching to an existing data set may be useful (ImPACT). Software for the calculation of effective dose based on results computed for mathematical phantoms representing adult patients is nowadays widely available (ImPACT (CT Dosimetry Calculator), Kalender (), Baadegard (CT Dose), Nagel (CT-Expo)).

Alternatively, broad estimates of effective dose (E) may be derived from values of DLP for an examination using appropriately normalised coefficients:

$$E = E_{DLP} \times DLP \qquad \text{(mSv)} \quad (10)$$

where DLP (mGy cm) is the dose-length product as defined in Equation (8) and E_{DLP} is the region-specific, DLP normalised effective dose (mSv mGy-1 cm-1).

General values of E_{DLP} appropriate to different anatomical regions of the patient (head, neck, chest, abdomen, pelvis or legs) are provided in the paragraph on clinical assessment of CT dose descriptors.

More realistic calculations of effective dose can be achieved using voxel phantoms (Kalender (1999)). Effective doses for paediatric CT can be assessed using Appendix B or data published by Zankl (1993) and Kuhrsheed (2002).

REFERENCE DOSE QUANTITIES

Two reference dose quantities are proposed for CT in order to promote the use of good technique: the CTDI, being either the weighted CTDI ($CTDI_w$) or volume CTDI ($CTDI_{vol}$), and the Dose Length Product (DLP), both quantities apply either to the standard head or body CT dosimetry phantom. They can be used for serial scanning as well as for helical scanning. Monitoring of $CTDI_w$ or $CTDI_{vol}$ for the head or body CT dosimetry phantom, as appropriate to the type of examination, provides control on the selection of exposure settings, such as mAs. Monitoring of DLP provides control on the volume of irradiation and overall exposure for an examination.

CLINCAL ASSESSMENT OF CT DOSE DESCRIPTORS

There are good arguments for users of CT scanners to assess CT doses from measurements of suitable dose descriptors. Motivations for CT dosimetry might be comparison of radiation exposure from different x-ray techniques and CT protocols, risk assessment and informing referring physicians and patients about dose issues. Assessment of appropriate dose descriptors should also be part of programmes for quality control of the CT scanner since dose measurements must be included in the acceptance and status tests of CT scanners [add appropriate IEC references on acceptance and status testing here?].

The need for practical CT dosimetry is nowadays formalised by European legislation. In the Directive 97/43/EURATOM the council of the European Union demands from manufacturers of CT scanners that their scanners provide an indication of patient dose. The same directive demands from the users of CT scanners that they implement quality assurance programmes, including patient dose assessment, and that they evaluate their clinical performance with regard to patient dose against diagnostic reference levels. The Directive also requires that a medical physicist is involved in the radiology department and that he carries responsibility for patient dosimetry, radiation protection and quality assurance. Thus nowadays, expertise for performing CT dose dosimetry should be available at any radiology department in Europe.

Currently there is general consensus concerning the main dose descriptors in computed tomography: the Computed Tomography Dose Index (CTDI), originally proposed by the FDA in the United States (Shope et al.); the weighted CTDI ($CTDI_w$), originally proposed as the practical CTDI by W. Leitz (Leitz et al.); the volume CTDI (CTDIvol) introduced by IEC (2003); and the Dose Length Product (DLP), as proposed by the European CT Working Group (Bongartz et al.). The manufacturers took this into account when they implemented the European Directive with

regard to CT dosimetry. Their current dosimetric framework is based on the dose descriptors weighted $CTDI_{100}$ or volume $CTDI_{100}$, and DLP. This means that users of modern multi-slice CT scanners have easy access to the dose descriptors volume CTDI and DLP after each clinical examination of each patient. Information on CT dose descriptors, including normalised values of the dose quantities, is also available in public databases, e.g. as part of the ImPACT CT Patient Dosimetry Calculator (version 0.99u, 2003) and as a table in the publications by the CT Working Group (Bongartz et al.) and Nagel et al. (4th edition).

During the concerted action a database of CT dose descriptors was established. This database served to validate subsequent reliance on the ImPACT database and the dose values displayed on the CT scanner.

Figure 1 shows the correspondence of the volume CTDI measured at a selection of CT scanners representing all major manufacturers that were on the market in Europe. The correspondence between the measured volume CTDI and the displayed value is good, indicating good accuracy of the displayed dose values for $CTDI_{vol}$ and DLP.
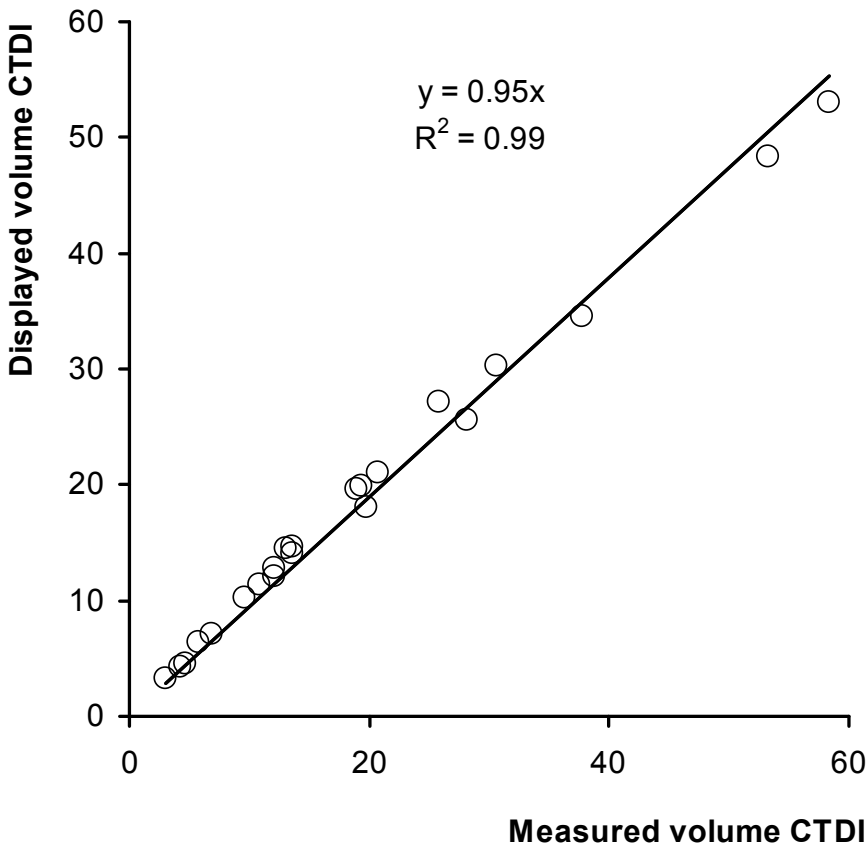

Figure 1. Correspondence between measured volume CTDI and the value displayed at the operators interface. Measurements correspond with scanners from all major manufacturers represented in Europe, i.e. GE Lightspeed; Philips Aura; Siemens: Somatom AR Star & Somatom Plus-4 and Toshiba Aquilion 16.

It is sometimes necessary to calculate, in addition to CTDI and DLP, other descriptors of patient dose such as organ dose (e.g. dose to the uterus when estimating the dose to the foetus of a pregnant patient), or effective dose (e.g. for comparison with other medical and non-medical exposures and for quantitative risk assessment).

An estimate of effective dose can easily be derived from DLP using a suitable effective dose conversion coefficient. As explained above, the DLP is displayed on the operators interface for all users of modern CT scanners. Table 1 provides suitable DLP conversion factors that allow a rough estimation of effective dose.

Table 1. Normalised effective dose per dose-length product (DLP) for adults (standard physique) over various body regions. Conversion factor for head and neck apply to the CT dose head phantom, all other conversion factors, including legs) apply to the CT dose body phantom.

Region of body	Normalised effective dose, E/DLP (mSv mGy-1 cm-1)
Head	0.0023
Neck	0.0054 *)
Chest	0.019
Abdomen	0.017
Pelvis	0.017
Legs	0.0008 **)

*) Conversion factor from previous document on CT Quality Criteria (CT study group 2000).
**) Calculated with CT Dose (version 0.6.7) National Board of Health, National Institute of Radiation Hygiene, Denmark).

Detailed assessment of effective dose and organ doses is more complex, and requires knowledge of CTDI free-in-air and weighted CTDI. The CTDI free-in-air is the dose descriptor that, in combination with dose conversion factors, yields average organ dose and effective dose. An extensive database of such conversion factors is available at NRPB (Jones et al.). Appropriate conversion factors should be selected from this database by means of 'scanner matching'; this process requires knowledge of tube voltage and $CTDI_{100}$ measured within standard CT dosimety phantoms, i.e. both central and peripheral $CTDI_{100}$. Ideally, users should measure CTDI free-in-air and $CTDI_{100}$ within the CT dosimetry phantoms themselves at their own CT scanner. This is however not always feasible or necessary. ImPACT, a CT scanner evaluation centre in the United Kingdom, provides at their website (www.impactscan.org) a practical spreadsheet (CTDosimetry: version 0.99u, 2003) with an extensive database of normalised CTDI free-in-air and normalised $CTDI_{100}$ (centre and periphery) values. In addition to this database, within the same spreadsheet, ImPACT provides an efficient interface for NRPB CT conversion factors. Other, but smaller, data bases of dose values have been established by for example the European CT Working Group (Bongartz et al.) and Nagel.

For comparison with the database included in the spreadsheet of ImPACT and with the table provided in the publication of Nagel, a large number of normalised CTDI free-in-air values were measured during the Concerted Action, as summarised in Table 2. This study included measurements for the following scanner models: General Electric LightSpeed & ProSpeed; Philips Secura and Tomoscan AVE; Siemens Somatom Sensation 16, Plus 4, Plus S & AR Star; Toshiba Aquilion 16 & Asteion. Figure 2 shows these measurements of CTDIair in comparison with similar values from the databases of ImPACT and Nagel. Excellent correspondence was found between the two sets of values, with a maximum deviation of 16%.
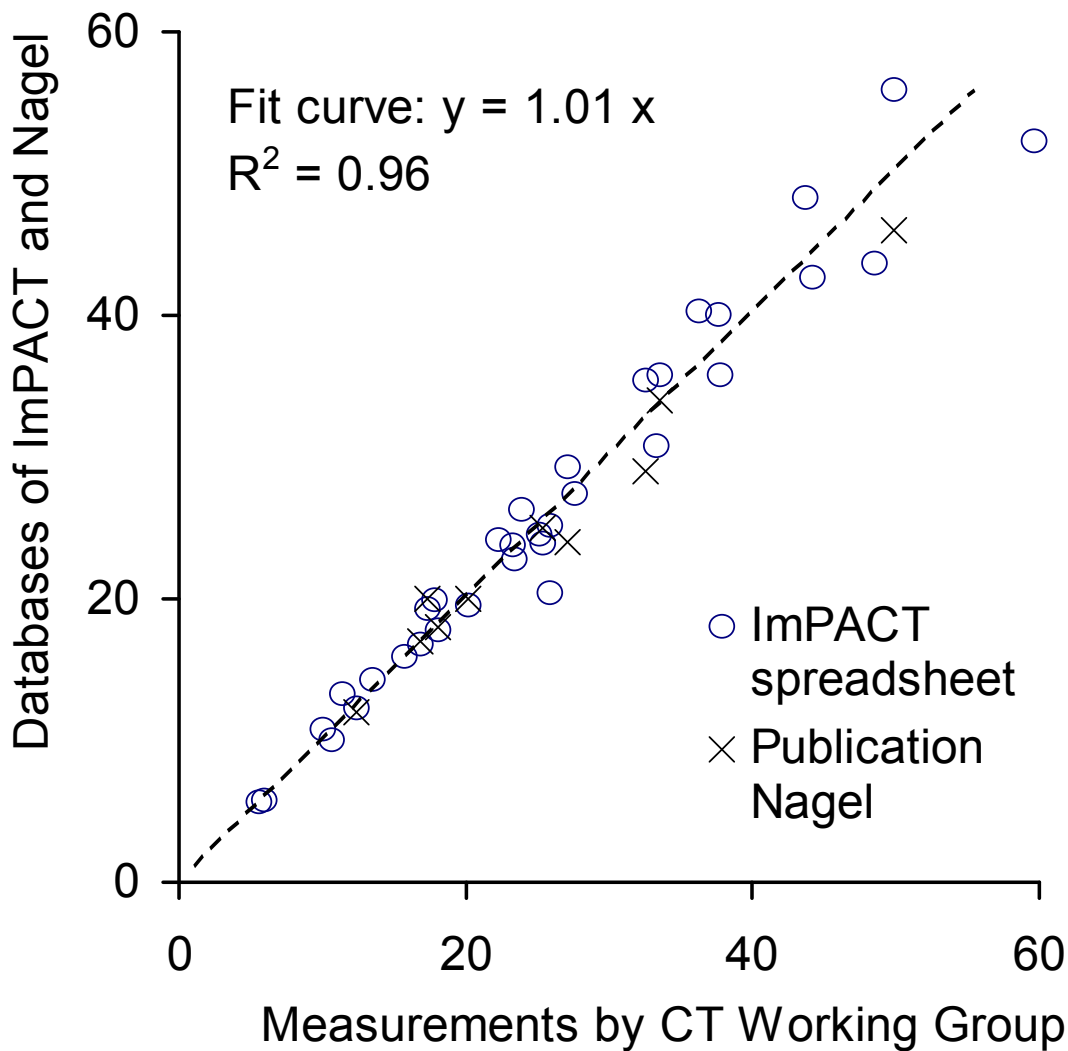

Figure 2.

Figure 2. Correspondence of measurements of CTDI_air by the CT Working Group with values taken from the ImPACT CT Patient Dosimetry Calculator (version 0.99t) and with values from the publication by Nagel et al. (4th edition) . The CTDI_air values refer to CT scanners from all main manufacturers, including single-slice, 4-slice and 16-slice CT scanners. All values are expressed as CTDI_air per 100 mAs.

Public databases on $CTDI_{100}$ free-in-air and $CTDI_w$ provide information that is sufficiently accurate for most purposes, e.g. for intercomparisons of patient dose at different CT scanners within one hospital or for assessment of patient dose at CT scanners within different hospitals. Under other particular circumstances, extensive dose measurements will have to be performed, often by the medical physicist. Accurate measurements are required, e.g. during acceptance testing of the CT scanner, and when accurate organ dose or effective dose values are required, e.g. in case of the dosimetric evaluation when an embryo or foetus of a pregnant patient was included in the scanned range.

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