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COMMENTARY

Radiation dosimetry for wide-beam CT scanners: recommendations of a working party of the Institute of Physics and Engineering in Medicine

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It is generally recognised that the CT dose index (CTDI) methodology developed for single-slice CT scanners [1] is flawed for wide-beam CT systems. In this commentary, the wide-beam CT dosimetry working party of the Institute of Physics and Engineering in Medicine (IPEM) appraises two alternatively published CT dosimetry protocols for wide-beam CT systems and presents its recommendations on the most practical method for wide-beam CT dosimetry in the UK.

BACKGROUND

CTDI has been used as a dose descriptor in CT since 1981 [1]. It is defined as follows:

$$\text{CTDI} = \frac{1}{NT} \int_{-\infty}^{+\infty} D(z) dz \quad (1)$$

where $D(z)$ is the absorbed dose profile parallel to the axis of rotation z , N is the number of active detector rows and T is the nominal width of each row. The NT term replaces the T used in the original definition, which applied to single-slice scanners. For practical measurement purposes, the integration length is limited to 100 mm and CTDI is then referred to as CTDI_{100} .

CTDI_{100} is generally calculated from measurements made free-in-air or in polymethylmethacrylate (PMMA) phantoms, 15 cm long and with standard diameters of 16 cm (head) or 32 cm (body), using a pencil ionisation chamber with an active length of 100 mm. In the case of phantom measurements, CTDI_{100} in the centre ($\text{CTDI}_{100,c}$) and periphery ($\text{CTDI}_{100,p}$) of the phantom are combined empirically to yield the dose descriptor CTDI_w as follows:

$$\text{CTDI}_w = \frac{1}{3}\text{CTDI}_{100,c} + \frac{2}{3}\text{CTDI}_{100,p} \quad (2)$$

CTDI_w is in turn used to calculate CTDI_{vol} and dose-length product (DLP), the dose metrics displayed on the scanner console.

CTDI_{100} and its derivatives are used for a variety of purposes. First, they are used as quick and reproducible measures of equipment performance during routine quality assurance tests; the UK guidance suggests a minimum requirement of annual in-air and 3-yearly phantom CTDI measurements [2]. Second, measurements of CTDI are necessary to confirm at acceptance the dosimetric performance of the scanner as specified by the manufacturer and to check the accuracy of displayed dose metrics (usually CTDI_{vol} and DLP), which are commonly used for setting and checking compliance with diagnostic reference levels. Third, the CTDI dose metrics are used for monitoring patient doses and optimising scan protocols. Finally, measurements of CTDI are essential on modern CT scanners in order to select the most appropriate Monte Carlo data set for the calculation of effective dose [3]. It is important to remember that CTDI_{100} was not formulated to provide an accurate measure of absorbed dose in the patient [4], although DLP is frequently used to estimate the effective dose. However, the technique is based on an empirical relationship between the two quantities rather than a robust derivation of effective dose from DLP.

LIMITATIONS OF THE CTDI_{100} METHODOLOGY

Measuring CTDI_{100} along a given axis in a particular medium is equivalent to measuring the average dose at the centre of the dose distribution along the same axis in the same medium from a 100 mm long contiguous scan. CTDI_{100} measurements made in PMMA phantoms will generally underestimate the absorbed dose in clinical situations because clinical scans are typically much longer than 100 mm (and the human body is neither homogeneous nor made of 16 or 32 cm diameter, 15 cm long PMMA cylinders).

Boone [5] has confirmed using computational techniques that, for an X-ray beam width of 40 mm or less, CTDI_{100} is within 1% of the expected value in the head and body phantoms. However, as the X-ray beam widens beyond

40 mm, an increasingly significant amount of scatter falls outside the 100 mm integration length, and as the X-ray beam widens beyond 100 mm, part of the primary beam falls outside it. Boone [5] has also shown that, for an X-ray beam width of 150 mm, $CTDI_{100}$ decreases up to 40% compared with its value for narrow X-ray beams. Approximately 33% of the drop is due to the loss of the primary beam and about 7% is due to the missed scatter, assuming a homogeneous beam profile. This breakdown of $CTDI_{100}$ with wide X-ray beams has prompted re-evaluations of $CTDI_{100}$ as the CT dose metric, which are summarised in the following section.

DOSIMETRY METHODOLOGIES SUITABLE FOR WIDE-BEAM CT SYSTEMS

The equilibrium dose approach

The American Association of Physicists in Medicine (AAPM) [6] presents a new method for measuring the radiation dose in CT and introduces a number of new dose metrics. These include equilibrium dose, D_{eq} , equilibrium dose–pitch product, $\hat{D}_{eq}$, single-scan dose, $f(0)$, planar average equilibrium dose, $\bar{D}_{eq}$, and integral dose, E_{tot} . Their reasoning for such a fundamental change is that $CTDI_{100}$ systematically underestimates patient doses and this underestimation varies with X-ray beam width. The term “integral dose” defined in report 111 [6] describes the total energy absorbed; this is not “dose” in its usual meaning, as this is normally expressed as energy per unit mass.

Measurement of the new dose metrics requires the use of longer phantoms to enable more complete scatter collection; a minimum length of 45 cm is recommended in the report. Although the report does not describe a specific phantom, it does provide examples. Suggested phantoms include a 50 cm long, 30 cm diameter water-filled phantom suitable for adult body measurements; a 20 cm diameter water-filled phantom suitable for adult head and paediatric body measurements; and another adult body phantom, 45 cm long, formed by joining three 32 cm diameter cylindrical PMMA phantoms together. All dose measurements are made using a thimble ionisation chamber, such as a 0.6 cm³ Farmer-type model.

Modified CTDI methodology

The International Electrotechnical Commission (IEC) describes a modified CTDI measurement method in Amendment 1 of the third edition of report 60601-2-44 [7], which enables the continued use of existing 100 mm pencil chambers and PMMA phantoms. This methodology has been adopted by the International Atomic Energy Agency in its Human Health Report no. 5 [8]. This approach will have the limitations of CTDI described earlier and will not be representative of patient dose. However, it will provide CTDI values that are equivalent to those on narrow-beam scanners.

The definition of CTDI [Equation (1)] is retained for in-air measurements with a modification to the dose integration length, which is now set to the X-ray beam width plus 40 mm or more, with a minimum total length of 100 mm. The definition of $CTDI_{100}$ is retained for in-phantom measurements with X-ray beam widths ≤ 40 mm. $CTDI_{100}$ for in-air phantom measurements with X-ray beam widths > 40 mm is defined as follows:

$$CTDI_{100,NT} = CTDI_{100,ref} \times \frac{CTDI_{in\ air,NT}}{CTDI_{in\ air,ref}} \quad (3)$$

where $CTDI_{100,NT}$ is the CTDI at the desired X-ray beam width NT , $CTDI_{100,ref}$ is the CTDI at the reference beam width, which is at or near 20 mm, and $CTDI_{in\ air,NT}$ and $CTDI_{in\ air,ref}$ are the CTDI in air for the desired and reference X-ray beam widths, respectively.

According to this methodology, CTDI in-air measurements can be carried out for X-ray beam widths up to 60 mm using established techniques and equipment. However, for X-ray beam widths > 60 mm, a new measurement technique, or a pencil chamber with a longer active length, is needed. $CTDI_{100}$ measurements in phantoms can be carried out for X-ray beam widths up to 40 mm using established techniques and equipment. Beyond 40 mm, $CTDI_{100}$ values in phantoms can be estimated from $CTDI_{100}$ measurements at the reference X-ray beam width scaled by the ratio of the respective CTDI in-air values. All the phantom measurements can be made using established techniques and equipment.

IMPLEMENTATION OF PROPOSED DOSIMETRY METHODOLOGIES

The equilibrium dose approach

The AAPM has set up Task Group 200 to provide practical solutions to the theoretical approach described in report 111, including phantom designs, and to formulate specific recommendations for which tests should be carried out at commissioning and during routine performance testing. The Group is yet to report. It is our belief that the adoption of the methods in report 111 will require investment in new phantoms for many medical physics departments and also introduce manual handling issues with the large heavy phantoms. The need for new equipment is confirmed by Descamps et al [9], who used the report 111 methodology to measure the dose from a two-slice CT scanner. They designed and built a 30 cm diameter, 50 cm long water phantom and used this in combination with a 0.6 cm³ Farmer chamber (PTW, Freiburg, Germany) that was calibrated for diagnostic CT beam qualities.

Modified CTDI methodology

The success of the modified CTDI methodology hinges on the availability of a reference beam width at or near 20 mm. The working party believes that such an X-ray beam width is available for all CT scanners.

CTDI in-air measurements for X-ray beams wider than 60 mm can be made using a pencil chamber of an appropriate length or alternatively by stepping the 100 mm pencil chamber through the X-ray beam, matching the table feed to the active chamber length and summing the readings obtained. The stepping technique is illustrated in Figure 1. It is an attractive solution as it allows implementation of the modified CTDI methodology without the need for new test equipment. However, it is important to ensure that contiguous measurements are obtained.

Manufacturers' specifications for table movement along the z-axis are typically ± 0.25 mm [10]. This error in table

Figure 1. Diagram showing a two-step, three-stage measurement process to measure CT dose index (CTDI) in air using extended integration length as required by the modified CTDI methodology. The z-axis is the axis of rotation.

movement can be systematic or random; it can be calculated by the propagation of error analysis assuming a rectangular dose distribution. These calculations show that systematic errors are greater than random errors, and the error is inversely proportional to beam width. For a two-position measurement, systematic errors are expected to be 0.9% and 0.2% for a 28.8 mm and 160 mm beam, respectively.

The working party has tested the stepping technique on a variety of CT scanners to identify and quantify sources of uncertainty. A comparison between measurements using the established single-position CTDI measurement and those made with the two-position 200 mm integration length technique showed an increased uncertainty of 1.3% for a 28.8 mm beam on a Definition AS scanner (Siemens AG, Erlangen, Germany). This is consistent with the errors expected from table motion accuracy. Results using a three-step measurement compared with two-step measurement showed differences of 2% using a 160 mm beam on an Aquilion One (Toshiba Medical Systems Europe BV,

Zoetermeer, Netherlands). This is greater than the error expected from table motion accuracy alone. The discrepancy can be attributed to scatter from the pencil chamber's support jig and/or the couch that is driven further towards or into the X-ray beam in the three-step technique than in the two-step technique.

RECOMMENDATIONS OF THE WORKING PARTY

In order to assess the relative merits of the two CT dosimetry methodologies outlined above, the working party has identified the features that, in its view, make a CT dosimetry protocol workable. These desirable features are listed in Table 1 in descending order of significance as determined by the working party. The two dosimetry methods have been assessed against these features and the outcomes are given in Table 1.

The working party recommends that the modified CTDI methodology be adopted in the UK by medical physicists involved in the routine quality assurance testing of CT systems with X-ray beams wider than 40 mm. The suggested methodology enables a dose index to be calculated that will reflect changes in system performance in the same way that conventional CTDI has done for narrow-beam systems in the past. The in-air- and phantom-based measurements can be carried out at frequencies recommended in IPEM report 91 [2]. As the recommended methodology is based on an IEC standard, it is likely that it will be adopted and used by manufacturers, e.g. displayed on the scanner console. It will therefore be possible to directly compare dose indices from routine quality assurance measurements with those displayed by the scanner. Furthermore, these measurements are possible using existing 100 mm pencil ionisation chambers and 15 cm long PMMA phantoms, avoiding the need to purchase new measurement equipment.

In order to minimise errors when making measurements for the modified CTDI methodology, the working party recommends that: (1) the couch is moved through a fixed distance between

Table 1. Evaluation of proposed CT dosimetry methodologies against the working party's desirable features

Desirable feature	Existing CTDI method	Modified CTDI method	Equilibrium dose method
Extension of existing method	n/a	Yes	No
Existing dose units used	Yes	Yes	No
Standard CT test equipment sufficient	n/a	Yes	No
In-air beam width range ^a	≤60 mm	≤∞	≤∞
In-phantom beam width range ^a	≤40 mm	≤∞	Phantom dependent
Measurement error at 160 mm under scatter-free conditions	n/a	1%	1%
Primary source of error	Chamber calibration	Varies with equipment: chamber calibration, cable irradiation or table motion	Varies with equipment: chamber calibration and the type of phantom used
HPA dosimetry/ImPACT dose calculator compatible	Yes	Yes	No

CTDI, CT dose index; HPA, Health Protection Agency; ImPACT, Imaging Performance Assessment of CT scanners; n/a, not applicable.

^aWhen measured to 1% accuracy (for consistency with Boone [5]).

measurements using the displayed couch position or by programming the table feed into the scan protocol; (2) the distance between the end of the couch and the edge of the active detector length is set to be greater than half the integration length in order to avoid scatter from the couch contributing to the signal; and (3) for systems where the couch motion cannot be controlled by the scanner, *e.g.* on some single-photon emission CT/CT systems, markings are used on the static and moving

parts of the couch to measure out a manual 100 mm table feed rather than moving the pencil chamber.

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