Applying three different methods of measuring $\text{CTDI}_{\text{free air}}$ to the extended CTDI formalism for wide-beam scanners (IEC 60601–2–44): A comparative study

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Abstract

**Purpose:** The weighted CT dose index ($\text{CTDI}_w$) has been extended for a nominal total collimation width ($nT$) greater than 40 mm and relies on measurements of $\text{CTDI}_{\text{free air}}$. The purpose of this work was to compare three methods of measuring $\text{CTDI}_{\text{free air}}$ and subsequent calculations of $\text{CTDI}_w$ to investigate their clinical appropriateness.

**Methods:** The $\text{CTDI}_{\text{free air}}$, for multiple $nTs$ up to 160 mm, was calculated from (1) high-resolution air kerma profiles from a step-and-shoot translation of a liquid ionization chamber (LIC) (considered to be a dosimetric reference), (2) pencil ionization chamber (PIC) measurements at multiple contiguous positions, and (3) air kerma profiles obtained through the continuous translation of a solid-state detector. The resulting $\text{CTDI}_{\text{free air}}$ was used to calculate the $\text{CTDI}_w$, per the extended formalism, and compared.

**Results:** The LIC indicated that a 40 mm $nT$ should not be excluded from the extension of the $\text{CTDI}_w$ formalism. The solid-state detector differed by as much as 8% compared to the LIC. The PIC was the most straightforward method and gave equivalent results to the LIC.

**Conclusions:** The $\text{CTDI}_w$ calculated with the latest CTDI formalism will differ most for 160 mm $nTs$ (e.g., whole-organ perfusion or coronary CT angiography) compared to the previous CTDI formalism. Inaccuracies in the measurement of $\text{CTDI}_{\text{free air}}$ will subsequently manifest themselves as erroneous calculations of the $\text{CTDI}_w$ for $nTs$ greater than 40 mm, with the latest CTDI formalism. The PIC was found to be the most clinically feasible method and was validated against the LIC.
INTRODUCTION

Computed tomography (CT) is associated with relatively high radiation doses. The accurate estimation of radiation exposure is therefore a major priority within the medical physics community. The CT dose index (CTDI) is a ubiquitous dose quantity used in CT. The CTDI represents an approximation of the average absorbed dose in a standard geometry (PMMA cylinder with a diameter of 32 cm for body scans or 16 cm for head scans and a length of approximately 14 cm) in a central rotation, including scatter contributions from adjacent rotations. Since the CTDI represents the average absorbed dose in a standard geometry, it should not be confused with patient dose; however, it does provide useful and comparative information about the output of CT scanners.

In practice, the CTDI is determined by integrating the dose profile from a single axial scan along the z-direction, \( D(z) \), and normalizing that integral with the nominal total collimation width (\( nT \)) of the scan. When the CTDI was first proposed in 1981 and subsequently became a standard dose quantity in CT, it was common with relatively narrow beam CT scanners. In 1999, the International Electrotechnical Commission (IEC) published the European Standard “Particular requirements for the safety of X-ray equipment for computed tomography” where the integration length of the CTDI was fixed to \( z = \pm 50 \text{ mm} \) (CTDI\(_{100}\)) and it also stated that \( D(z) \) should be measured in air kerma (\( K_{\text{Air}} \)). A 100-mm pencil ionization chamber is appropriate to use according to this definition of the CTDI. In that same European Standard, equations for calculating the weighted CTDI (CTDI\(_{w,100}\)) from central and peripheral CTDI\(_{100}\) measurements in the reference phantoms is given. The CTDI\(_{w,100}\) represents the average CTDI\(_{100}\) across a reference phantom in the axial plane.

Nowadays, there are CT scanners with wide-beam geometries that facilitate axial scans with a detector coverage up to 160 mm in a single rotation. This technique allows for entire organs to be scanned with a detector coverage up to 160 mm in the axial plane without a phantom. The advanced method was compared to more clinically feasible methods of determining the CTDI\(_{100}\) for nominal total collimation widths that exceed 40 mm, in a first amendment to the third edition of its European Standard. It should be noted that for nominal total collimation widths that are less than or equal to 40 mm, the definition of the CTDI\(_{100}\) remains the same as previous editions of the European Standard. The redefinition of the CTDI\(_{100}\) for wide beams utilizes the assumption that the ratio of CTDI\(_{\text{free air}}\) with appropriate integration lengths to capture \( D(z) \) between two nominal total collimation widths is equal to the ratio of CTDI\(_{100}\) with the same \( nT \). Using this relationship, the CTDI\(_{100}\), \( nT = 40 \text{ mm} \), is approximated by multiplying a measured CTDI\(_{100}\) at \( nT = 40 \text{ mm} \) with the ratio of CTDI\(_{\text{free air}}\) at \( nT > 40 \text{ mm} \) and CTDI\(_{\text{free air}}\) at \( nT < 40 \text{ mm} \).

To the best of our knowledge, no one has compared different methods of measuring CTDI\(_{\text{free air}}\) and their subsequent calculation of the CTDI\(_{w}\) per the extended formalism. The purpose of this work was to use three different methods of measuring CTDI\(_{\text{free air}}\) and apply those measurements to the latest amendment of the IEC Standard, for a range of \( nT \) up to 160 mm. The CTDI\(_{\text{free air}}\) was first determined using an advanced method, high-resolution step-and-shoot translation of a liquid ionization chamber, which is considered to be a dosimetric reference. The advanced method was compared to more clinically feasible methods of determining the CTDI\(_{\text{free air}}\), namely (1) using multiple contiguous positions to extend the integration length of a 100-mm pencil ionization chamber and (2) continuous translation of a real-time solid-state detector.

METHODS AND MATERIALS

2A CTDI formalism

When first proposed, the CTDI was defined as,

\[
\text{CTDI}_{100} = \frac{1}{nT} \int_{-\infty}^{\infty} D(z) \, dz.
\]  

where \( D(z) \) is a dose profile along the longitudinal axis, \( z \), centered at \( z = 0 \). The number of detector channels and the width of each channel are \( n \) and \( T \), respectively. Note that \( nT \) represents the nominal total collimation width of the scan and in the early days of CT it was common with single slice scanners \( (n = 1) \). In the first edition of IEC 60601–2–44, the CTDI was defined for an integration length of 100 mm as,
In that same edition of the IEC standard, the weighted CTDI was defined as,

\[
\text{CTDI}_{100,w} = \frac{1}{3} \text{CTDI}_{100,c} + \frac{2}{3} \text{CTDI}_{100,p}. \quad (3)
\]

where \(c\) and \(p\) denote measurements of the CTDI\(_{100}\) in the central and peripheral holes of the CTDI reference phantoms, respectively. In practice, the CTDI\(_{100,c}\) is the mean CTDI\(_{100}\) from the four peripheral holes in the reference CTDI phantoms. In the first amendment to the third edition of IEC 60601–2–44,\(^1\) the CTDI\(_{100}\) was redefined for \(nT\) that exceed 40 mm as,

\[
\text{CTDI}_{100,nT} > 40 \text{ mm} = \text{CTDI}_{100,\text{ref}} x \left( \frac{\text{CTDI}_{\text{free\ air, nt}}}{\text{CTDI}_{\text{free\ air, ref}}} \right). \quad (4)
\]

where the subscript \(\text{ref}\) represents a reference \(nT\) that is equal to or less than 40 mm. In that same European Standard,\(^1\) the CTDI measured in free air was defined as,

\[
\text{CTDI}_{\text{free\ air}} = \frac{1}{nT} \int_{-L/2}^{L/2} D(z)dz. \quad (5)
\]

where \(L\) is at least the \(nT\) of a single scan plus an additional 40 mm divided on both sides (\(nT + 40\) mm). Furthermore, it is stated that the CTDI\(_{\text{free\ air}}\) should not be calculated with an integration length below 100 mm.\(^1\)

Contemporary CT scanners are obligated to present the volume CTDI (CTDI\(_{\text{vol}}\)) in accordance with the first amendment to the second edition of IEC 60601–2–44.\(^1\) The CTDI\(_{\text{vol}}\) accounts for table translations that produce overlapping or gapped exposure(s). The CTDI\(_{\text{vol}}\) is calculated as \(\text{CTDI}_{\text{vol}} = \Delta\), where \(\Delta\) is the longitudinal table translation between scans divided by the nominal beam width for axial modes or the CT pitch factor for spiral modes. However, in the continuation of this work, only the CTDI\(_{\text{vol}}\) will be considered, which is equivalent to the CTDI\(_{\text{vol}}\) where \(\Delta = 1\) and an axial scan mode has been used.

To leverage a better understanding of how the first amendment to the third edition of IEC 60601–2–44 can be implemented in practice to measure the CTDI\(_{100,w}\) for \(nT\) greater than 40 mm, the following steps can be followed:

**1.** Measure the CTDI\(_{100,c}\) and CTDI\(_{100,p}\) for a reference (\(\text{ref}\)) \(nT\) equal to or less than 40 mm, resulting in CTDI\(_{100,\text{ref,c}}\) and CTDI\(_{100,\text{ref,p}}\).

**2.** Measure the CTDI\(_{\text{free\ air}}\) [Eq. (5)] with the same reference (\(\text{ref}\)) \(nT\) as step 1, resulting in CTDI\(_{\text{free\ air, ref}}\).

**3.** Measure the CTDI\(_{\text{free\ air}}\) [Eq. (5)] with an \(nT\) that is greater than 40 mm, resulting in CTDI\(_{\text{free\ air, nt}}\).

**4.** Calculate the ratio of CTDI\(_{\text{free\ air, nt}}\) and multiply with CTDI\(_{100,\text{ref,c}}\) and CTDI\(_{100,\text{ref,p}}\) respectively. This will result in CTDI\(_{100,\text{nt,c}}\) and CTDI\(_{100,\text{nt,p}}\).

**5.** Use Eq. (3) and the results from step 4 to calculate CTDI\(_{100,\text{nt,w}}\).

### 2.B CT scanner

All measurements were made on a Revolution CT (GE Healthcare, Waukesha, WI, USA). In addition to this scanner being able to perform volume scans with \(nT\) up to 160 mm, the CTDI is reported with the formalism from the first amendment to the 3rd edition of IEC 60601–2–44 in the scanner’s latest software releases (since version 15MW43.x). The technique parameters used in this study, Table 1, reflect parameters that are given in the acceptance testing section of the scanner’s Technical Reference Manual (TRM).\(^1\) All measurements were made in clinical mode. Note that the reference \(nT\) in Eq. (4) is 5 mm on this scanner.

### 2.C Determination of CTDI\(_{100,nT,w}\)

In this work, the CTDI\(_{100,nT=40,\text{ mm}}\), Eq. (4), is calculated using CTDI\(_{\text{free\ air, nt}}\) that is measured with three different measurement systems. The three different measurement systems used to obtain CTDI\(_{\text{free\ air, nt}}\) are subsequently used to determine CTDI\(_{100,nT,w}\).

#### 2.C.1 CTDI\(_{\text{free air, nt}}\) determined with high-resolution air kerma profiles measured with a liquid ionization chamber and a step-and-shoot methodology

A measurement rig, designed, and assembled by LonTech AB (Luleå, Sweden), was used to acquire air kerma profiles with a step-and-shoot methodology, see Fig. 1. A microLion (PTW GmbH, Freiburg, Germany) liquid ionization chamber (LIC) with a sensitive volume of 0.002 cm\(^3\) (cylindrical diameter of 2.5 mm and cylindrical height of 0.35 mm) was packaged into a minimally attenuating carbon fiber rod. The packaged LIC received an RQT-9 calibration (full field irradiation) from the National Metrology Laboratory (national secondary standards laboratory for the dosimetric quantity air kerma) at the Swedish Radiation Safety Authority. A Unidos Universal Dosemeter (PTW GmbH, Freiburg, Germany) was used to acquire LIC charge measurement readings. All LIC measurements were corrected for temperature with values that were obtained with a temperature sensor during the exposure at each step of the translation. The temperature sensor was positioned in proximity to the end of the patient table where the LIC was stepped through the gantry.

The packaged LIC was coupled to a linear actuator that provided a stepwise translation in the longitudinal direction with a positioning accuracy better than 0.2 mm. Prior to the air kerma measurements, the carbon fiber rod was extended fully (500 mm) and a 160-mm volume scan (256 images) was taken to ensure that the stepwise translation was centered (\(x = 0, y = 0\)) and was free from rotational pitch and yaw (rotation about the x- and y-axes of the scanner, respectively). Depending on the \(nT\), different profile lengths and step intervals were used (see Table 2). The profile measurements did not have equal step intervals, the interval was tighter at locations where the air kerma varied greatly, at, for example, step locations in the
penumbra of the radiation field where the air kerma rapidly increased or decreased. The $CTD_{free,air,nT}$, Eq. (5), was calculated for each $nT$ using the trapz function (numerical integration using the trapezoidal method) in MATLAB 2016b (The Mathworks Inc., Nat- tick, MA, USA) to integrate the air kerma profile, $D_z(\cdot)$. The type A uncertainty associated with this method was esti- mated by measuring 5 air kerma profiles using the technique parameters in Table 1 and a 5-mm $nT$. The number of measurement points was reduced to 40 and covered a length of 100 mm (−50 mm to 50 mm). The step interval was adapted to parts of the profile that increased or decreased rapidly. It would not have been feasible to estimate the type A uncertainty for all $nT$s.

**2.C.2 | $CTD_{free,air,nT}$ determined with pencil ionization chamber measurements at multiple contiguous locations**

In IAEA Human Health Reports No. 5,12 a method is provided to measure the $CTD_{free,air,nT}$ for $nT$s exceeding 40 mm. In our practical implementation of this method, a 100-mm pencil ionization chamber (PIC) is suspended in the longitudinal direction ($x = 0, y = 0$) using a minimally attenuating carbon fiber rod. Depending on the $nT$, the PIC is stepped into different contiguous locations between exposures to envelope the entire radiation field. The positions of the contiguous locations that are recommended by the IAEA to extend the integration length of the $CTD_{free,air,nT} > 40$ mm using a PIC are presented in Table 3. These recommended positions from IAEA are consistent with recommendations by Platten et al.16 Furthermore, GE states alternative PIC positions in the scanner’s TRM14 to extended the integration length of $CTD_{free,air,nT} > 40$ mm; these positions are also provided in Table 3. The GE positions differ greatly from the IAEA positions; however, the GE positions are based on recommendations from the IEC (personal communication with GE, December 2016). The CT scanner’s table translation was used to move the PIC into contiguous positions.

A carbon fiber rod was attached to the cable end of a 100 mm RC3CT PIC (Radcal Corporation, Monrovia, CA, USA), see Fig. 2. This pencil ionization chamber also received an RQT-9 calibration from the National Metrology Laboratory at the Swedish Radiation Safety Authority. The same electrometer that was used for the LIC measurements was used for the PIC measurements. The ambient temperature and pressure were measured during each exposure so that a standard air pressure and temperature correction to the measurements with the PIC could be made. The central marking of the PIC

### Table 1

| Scan mode | Tube Voltage [kVp] | Tube current [mA] | Focal spot size | Rotation time [s] | Shaped filter | Nominal total collimation width [mm] |
|-----------|--------------------|-------------------|----------------|------------------|-------------|-------------------------------------|
| Axial     | 120                | 400               | Large          | 1                | Large       | 5, 40, 80, 120, 160                  |

### Table 2

| Nominal total collimation width [mm] | Integration length [mm] | Steps |
|-------------------------------------|-------------------------|-------|
| 5                                   | 100 (−50 mm to 50 mm)   | 93    |
| 40                                  | 300 (−150 mm to 150 mm) | 124   |
| 80                                  | 300 (−150 mm to 150 mm) | 130   |
| 120                                 | 400 (−200 mm to 200 mm) | 153   |
| 160                                 | 490 (−245 mm to 245 mm) | 153   |

### Table 3

| Nominal total collimation width [mm] | Integration length [mm] | IAEA positions 12 [mm] | GE positions 14 [mm] |
|-------------------------------------|-------------------------|------------------------|----------------------|
| 5                                   | 100                     | 0                      | 0                    |
| 40                                  | 100                     | 0                      | 0                    |
| 80                                  | 200                     | −50, 50                | −10, 90              |
| 120                                 | 200                     | −50, 50                | −30, 70              |
| 160                                 | 300                     | −100, 0, 100           | −50, 50, 150         |

**Fig. 1.** A depiction of the rig that was developed to step a liquid ionization chamber so that high-resolution air kerma profiles could be measured to calculate $CTD_{free,air}$. In the lower left, the liquid ionization chamber has been cut out where the sensitive volume of the detector is represented by the imbedded dark disk. A US quarter dollar coin has been used as a size reference.
was positioned in isocenter \((x = 0, y = 0, z = 0)\) and a 160-mm volume scan (256 images) was used to ensure that the PIC was properly centered and free from rotational pitch and yaw. At each PIC location and \(nt\), five exposures were made. The mean value of the five exposures at each location was used in the continuation of this work. Additionally, the type A uncertainty of this method was analyzed.

### 2.C.3 | CTDI\(_{\text{free air,}nT}\) determined with solid-state detector system measurements during continuous longitudinal translation

All instruments and software used for the measurement of CTDI\(_{\text{free air,}nT}\) using a real-time solid-state detector and continuous translation are manufactured by RTI Electronics (Molndal, Sweden). A CT Dose Profiler (CTDP) is a real-time solid-state detector designed for CT dosimetry applications. The active length of the detector’s sensor along the longitudinal axis is 250 \(\mu m\) and it is packaged in an aluminum rod. The CTDP was connected to a Black Piranha electrometer. The CTDP received an RQT-9 calibration at RTI Electronics’ calibration laboratory.

A device called the Mover (manufactured by RTI Electronics) was used to translate the CTDP continuously along the longitudinal axis of the CT scanner. The Mover has a motor that drives a wire that is connected to the end of the CTDP. The CTDP is translated through a plastic tube that is placed along the longitudinal axis of the scanner. All measurements were made in the pull direction (toward the Mover’s motor) with a translation speed of 83.3 mm/s. The Mover’s translation speed was calibrated according to an application note (AN-034, June 2015) provided by RTI Electronics.

The Mover was centered in the CT scanner using the positioning lasers and a wide volume scan was used to ensure that the setup was centered and free from rotational pitch and yaw. Five air kerma profile measurements were made for all \(nTs\) presented in Table 1. The mean value of the five measurements was used in the continuation of this work and the type A uncertainty was calculated. The electrometer (Black Piranha) and the Mover were controlled using the accompanying software package Ocean 2014 version 2016.01.18.199. The measured air kerma profiles were exported from Ocean 2014 and MATLAB 2016b was used to determine the CTDI\(_{\text{free air,}nT}\) according to Eq. (5) in a similar manner to the measurements made with the LIC.

### 2.C.4 | Calculations of the weighted CTDI (CTDI\(_{100, nt,w}\))

A standard body CTDI phantom (model 007, CIRS Inc., Norfolk, VA, USA) with a diameter of 32 cm and a length of 14 cm was used to measure the CTDI\(_{100,nt,w}\) Eq. (3), with a reference \(nt\) of 5 mm. The CTDI phantom was placed approximately 1 m toward the middle of the patient table from the end that is closest to the gantry. The CTDI phantom was imaged with a volume scan to ensure that it was centered properly and was free from rotational pitch and yaw. The CTDI\(_{100.5\text{mm,w}}\) was measured five times in each of the central and peripheral holes using the same measurement system in section 2.3.2. A temperature and pressure correction was made for each measurement. The mean value of each set of five measurements was used in the determination of the CTDI\(_{100.5\text{mm,w}}\), Eq. (3). The CTDI\(_{100.5\text{mm,}p}\) is the average value of all measurements in the peripheral holes of the CTDI phantom.

Using the same measurement method that was employed for the CTDI\(_{100.5\text{mm,w}}\), the CTDI\(_{100.\text{nt},w}\) was measured for the remainder of the collimations according to the third edition of IEC 60601–2–44,\(^{10}\) where \(nt\) in Eq. (2) is equal to the \(nt\) or 100 mm, whichever is less. Measurements of the CTDI\(_{100.\text{nt},w}\) are compared using both the third edition and the first amendment to the third edition of IEC 60601–2–44.\(^{11}\)

### 3 | RESULTS

The air kerma profiles that were obtained using a step-and-shoot methodology with the LIC is presented in Fig. 3(a). Figure 3(b) presents air kerma profiles that were obtained using the continuous translation of the CTDP (solid-state detector). Note that the air kerma profiles in Fig. 3(b) are free from scatter tails. The scatter tails are removed in the Ocean 2014 software package since they are considered to have been caused by the aluminum rod in which the solid-state detector is packaged in (personal communication with RTI Electronics, December 2016).

The CTDI\(_{\text{free air,}nt\}}\) ratios for different \(nTs\) that were determined using the three different measurement methods considered in this work are presented in Table 4. Included in the table are expectation values that were greater than the \(nt\) or 100 mm, whichever is less. Table 5 presents calculations of the CTDI\(_{100.\text{nt},w}\) according to Eq. (2), where \(nt\) is set to 100 mm for \(nTs\)
that are greater than 100 mm. The measured values of CTDI_{100, nT} are consistently lower than the expectation values stated in the scanner’s documentation by 4–8%, depending on the nT.

The CTDI_{100, nT} was calculated with Eq. (4) using the CTDI_{free air, nT} ratios (Table 4) measured with the three different methods in this study. These results of the CTDI_{100, nT} are presented in Table 6. Equation (4) is intended for nTs greater than 40 mm. For that reason, CTDI_{100, nT} for nTs of 5 and 40 mm are not presented in Table 5. Take note that the CTDI_{100, nT} for an nT of 5 mm, (Table 5) is used as the CTDI_{free air, ref} for the calculations presented in Table 6. Alongside the CTDI_{100, nT} in Table 6, expectation values from the scanner’s TRM have also been included. There is a slight difference between the expectation values for CTDI_{100, nT} between the different revisions of the scanner’s TRM for nTs of 5 and 40 mm. In the scanner’s latest revision of the TRM, the expectation values for CTDI_{100, nT} are 44.5 and 27.2 mGy for the nTs of 5 and 40 mm, respectively.

The greatest difference between any of the PIC, LIC, and CTDP measurements in Table 6 to the scanner’s TRM is 7.5% for the PIC (IAEA Positions), with an nT of 120 mm. The greatest difference between any of the PIC results, both GE and IAEA positions, compared to the LIC results in Table 6 is 0.8%. However, the greatest difference between any of the CTDP results compared to the LIC results in Table 6 is 4.5% with an nT of 160 mm.

The relative standard uncertainty of CTDI_{free air, nT} for the PIC and CTDP measurements steadily decreased as the nT increased. Take note, the relative standard uncertainty of CTDI_{free air, nT} that required multiple PIC positions was calculated using a standard error propagation. The PIC measurement method, both the GE and IAEA positions, had a relative standard uncertainty between 0.04 and 0.01% for all nTs. The CTDP method had a relative standard uncertainty between 0.6 and 0.1% for all nTs. The relative standard uncertainty for the LIC method was estimated to be 0.2% for an nT of 5 mm. For nTs greater than 5 mm, the uncertainty is expected to be lower, since there are more measurement points along the air kerma profiles (better statistics).

### DISCUSSION

In this work, different methods of measuring CTDI_{free air,nT} have been investigated and subsequently used to calculate the CTDI_{w,nT} for
wide-beam CT dosimetry according to the CTDI formalism in the first amendment to 3rd edition of IEC 60601–2–44. As the amended wide-beam CT dosimetry formalism has recently been implemented on CT scanners, it necessitates that clinical Medical Physicists have a good understanding of how different methods of measuring CTDI free air may impact the accuracy of their results.

According to the investigated scanner’s TRM, the maximum allowed deviation for CTDI free air measurements is 40% from the stated expected values, which includes uncertainty contributions from variations in tube output, x-ray beam collimation, dosimetry methodology, and calibration errors. All methods that were investigated to measure the CTDI free air for different nTs are within the 40% tolerance stated by the vendor. However, in the scope of the work, the LIC was considered to be a dosimetric reference and not the CT scanner’s TRM. While the PIC methods yielded comparable results of the CTDI free air to the LIC (within 2%), the CTDP method consistently yielded results that were 6%–8% higher than the LIC for nTs greater than 40 mm.

Table 5 shows that for nTs that are less than 100 mm, the CTDI100, nT,w decreases as nT increases, which is consistent with the third edition of IEC 60601-2-44. When the nT is greater than 100 mm, the CTDI100, nT,w increases as the nT increases. This can be attributed to the CTDI phantom only having a length of 14 cm. As the nT increases, more and more scatter will contribute to the air kerma that the pencil ionization chamber measures. However, the normalization factor (nT) in Eq. (2) will remain constant (100 mm) for nTs greater than 100 mm. With the first amendment to the third edition of IEC 60601-2-44, the CTDI100, nT,w continues to decrease as the nT increases above 100 mm. Comparing the third edition with the first amendment to the third edition of IEC 60601-2-44 shows that there will be a slight increase in CTDI100, nT,w for an nT of 80 mm (+5%) and a decrease in CTDI100, nT,w for an nT of 160 mm (−19%) when using the latest definition of the CTDI100, nT,w with the LIC and PIC methods. However, the difference is +7% (80 mm) and −14% (160 mm) for the CTDP method. The values from the TRM for the different versions of the CTDI formalism yields +7% (80 mm) and −20% (160 mm). A difference of −20% between the measured CTDI100, nT,w and the CTDI100, nT,w displayed on the scanner’s console is considered to be a trigger to take remedial action by the Nordic Association of Clinical Physicists (NACP).

It is important to reflect upon that even though the CTDI100, nT,w may decrease by 19% using the latest CTDI formalism and an nT of 160 mm, the exposure to the patient (and image quality of the examination) will remain the same using the previous CTDI formalism. This should be considered when optimizing, for example, whole-organ perfusion protocols where the accumulated radiation doses can be high. In the context of patient dose, the CTDI metric has disadvantages in specificity with regard to characterizing the x-ray beam and the individual patient undergoing an examination. However, the evolution of applied CT dosimetry is built upon the CTDI, most notably in the form of size-specific dose estimates (SSDE). It is therefore important to continue discussing the theoretical and practical aspects of the CTDI. Further refinements of CT dosimetry, beyond the SSDE, where the x-ray beam characteristics and contributions from scattered radiation are completely taken into account will require new reference geometries and more detailed descriptions of exposure.

Each of the measurement methods was associated with a relatively low type A uncertainty (below 1% for the CTDP method, below 0.2% for the LIC method and below 0.05% for the PIC method). However, this uncertainty evaluation does not factor in uncertainties in, for example, air kerma calibration factors. In the scope of this work, the step-and-shoot method of acquiring air kerma profiles with the LIC is considered to be the most accurate method that was used to obtain CTDI free air,nT for the range of nTs, both dosimetrically and spatially. The LIC has appreciable energy dependence when compared to other instruments, such as pencil ionization chambers, over a range of radiation qualities. However, the LIC used a calibration (RQT-9), which closely matches the radiation quality that was used during the measurements. The HVL associated with the RQT-9 radiation quality is 8.7 mm Al and the HVL along the central ray of the Revolution CT for 120 kVp with the Large shaped filter is 7.6 mm Al. The downside to this method is that it is very labor intensive to produce the rig and measurements with this method are time consuming (as it requires many exposures to capture the air kerma profiles). For those reasons, it is not likely that this method could be employed in clinical routine. However, the LIC provided a good reference to which the other measurement methods could be compared.

The PIC measurement method(s) focus on extending the use of readily available instruments (100-mm pencil ionization chambers) so that they may be employed to measure CTDI free air,nT for wide nTs, in

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**Table 5** Values of CTDI100, nT,w (32 cm) that were calculated through measurements according to the third edition of IEC 60601–2–44. This table also shows expectation values of CTDI100, nT,w that were obtained from an older revision of the scanner’s technical reference manual.

| Nominal total collimation width [mm] | GE TRM 14 | Measured CTDI100, nT,w [mGy] |
|-------------------------------------|-----------|-----------------------------|
| 5                                   | 45.3      | 42.0                        |
| 40                                  | 27.3      | 26.2                        |
| 80                                  | 25.2      | 24.3                        |
| 120                                 | 27.3      | 25.9                        |
| 160                                 | 30.6      | 28.3                        |

**Table 6** The CTDI100, nT,w (32 cm) values that were calculated according to the first amendment to the third edition of IEC 60601–2–44 using different methods of measuring CTDI free air,nT.

| Collimation [mm] | GE TRM section 14 | PIC GE positions section 2.3.2 | PIC IAEA positions section 2.3.2 | LIC section 2.3.1 | CTDP section 2.3.3 |
|-----------------|-------------------|-------------------------------|----------------------------------|------------------|--------------------|
| 80              | 27.0              | 25.2                          | 25.3                             | 24.6             | 24.9               |
| 120             | 26.2              | 24.4                          | 24.4                             | 24.6             | 25.5               |
| 160             | 25.4              | 23.8                          | 23.8                             | 23.7             | 24.9               |
clinical routine. This was done by suspending a pencil ionization chamber free-in-air and moving the pencil ionization chamber into up to three contiguous positions. The measurements in each position are summed, and in effect extends the integration length to either 200 or 300 mm, depending on the number of positions used. This method is straightforward and easily practiced in clinical routine and for the most part gave results that were equivalent to the LIC (within the measurement uncertainty). It does however assume that the effective measurement length of the PIC is 100 mm. There could be a systematic uncertainty induced into the measurements if the effective length of the PIC diverges from 100 mm (overlap or gaps between measurements); however, it is outside of the scope of this work to investigate. There was no appreciable difference in the CTDI_{free \text{ air}} between the different (GE’s recommended and IAEA’s recommended) positions for the different contiguous locations of the PIC.

It was our intention to measure with the LIC, PIC, and CTDP during the same measurement session. However, after reviewing the results from the CTDP, it was concluded that the RTI Mover (continuous translation) device was not properly calibrated and inconsistent results between measurements were obtained. It was not until we could verify that the Mover was properly calibrated from RTI Electronics that another set of measurements were made. Between the different measurement times, the absolute dose of the CTDI_{free \text{ air}} differed appreciably (e.g., between 113 and 125 mGy for an nT of 5 mm). The reason for this difference between measurement times is uncertain. It is unlikely that this difference can be attributed to scanner output since similar measurements using the LIC were taken around the same time as the CTDP measurements and showed that the output had changed by no more than 1%. For wide (>40 mm) nTs, the CINE function (multiple continuous stationary rotations) was used to provide an exposure that was long enough in time so that the CTDP could be translated through the entirety of the radiation field. The fastest translation speed on the Mover is 83.3 mm/s and would require more than a 2 s exposure (2 rotations) to be able to measure the CTDI_{free \text{ air}} for an nT of 160 mm. We do not expect the CINE mode to have impacted the results compared to a axial mode. Furthermore, it was difficult to obtain values of CTDI_{free \text{ air}, nT} directly from the Ocean 2014 software. For that reason, air kerma profiles were exported from Ocean 2014 and calculations of CTDI_{free \text{ air}, nT} were made with MATLAB.

It should be noted that this study is limited by the fact that there are other instruments that could potentially be used to determine the CTDI according to its latest formalism for CT scanners with wide nominal total collimation widths. This includes instruments such as a 300-mm pencil ionization chamber or stepping a thimble chamber through the beam to acquire air kerma profiles. Furthermore, alternative methods of determining the weighted CTDI, such as using radiochromic film, has also not been investigated.

The measured value of CTDI_{free \text{ air}, nT} (and the ratio CTDI_{free \text{ air}, nT} for the 40 mm collimation using the LIC and CTDP methods is greater than the PIC method (see Table 4), as well as the expectation value in the scanner’s technical documentation.\textsuperscript{14} Note that the integration length of CTDI_{free \text{ air}, nT} for the LIC method was 300 mm compared to 100 mm (one position) using the PIC. Calculating CTDI_{free \text{ air}, nT} with the LIC, but using a 100 mm integration length (−50 to 50 mm) yields a value of 74.44 mGy or alternatively a ratio of 0.62 (the same ratio that was measured using the PIC). Extending the integration length of CTDI_{free \text{ air}} for the 40 mm collimation to 200 mm using 2 PIC positions (−50 and 50 mm) yields a value of 76.94 mGy or a ratio of 0.63 which is closer to the value that was obtained using the full integration length (300 mm) of the air kerma profile for the LIC measurement. This could possibly indicate that an integration length of 100 mm for CTDI_{free \text{ air}} measurements for a 40 mm collimation might not include the entire air kerma profile along the longitudinal direction. The additional contribution to the CTDI_{free \text{ air}} that was observed when using an air kerma profile integration length greater than 100 mm, for the 40 mm nT, can be caused by several factors including the geometric efficiency (actual beam width is wider than the nominal total collimation width), extra focal radiation, as well as penetration of radiation through the collimator edges.

5 | CONCLUSIONS

As CT is associated with relatively high radiation doses, it is therefore important for medical physicists to be able to accurately estimate the output from CT scanners. If the radiation output from a scanner is erroneously measured or reported, this could inadvertently lead to unnecessary radiation exposure or degraded image quality, both having unintended consequences. An amendment to the third edition of IEC 60601-2-44 has been made to further extend the concept of the CTDI\textsubscript{w} to CT scanners with nominal total collimation widths (nT) greater than 40 mm. This amendment has recently been implemented on certain CT scanners and clinical Medical Physicists need to update their measurement methodologies accordingly. The amendment relies on measurements of CTDI_{free \text{ air}} with integration lengths that exceed the length of a standard 100-mm pencil ionization chamber. In this work, three methods of acquiring air kerma profiles to calculate the CTDI_{free \text{ air}}, for a range of nTs, were implemented and subsequent calculations of the CTDI\textsubscript{w} were compared. The measurement methods consisted of:

1. high-resolution air kerma profiles using a step-and-shoot translation of a liquid ionization chamber (considered to be a dosimetric reference),
2. the sum of multiple 100-mm pencil ionization chamber measurements where the chamber is placed at different contiguous locations in the z-direction,
3. continuous translation of a real-time solid-state detector.

The liquid ionization chamber results suggested that the latest CTDI formalism should also be extended to a nTs of 40 mm. The CTDI\textsubscript{w} calculated with the latest CTDI formalism was found to differ by −20% compared to the previous CTDI formalism, for an nT of
160 mm (used in, e.g., whole-organ perfusion); however, it is important to consider that the radiation exposure to the patient and the image quality of the examination will remain the same, using the latest CTDI formalism. The real-time solid-state detector method provided results that differed by as much as 8% ($\text{CTDI}_{	ext{free-air}}$) compared to the liquid ionization chamber method. The pencil ionization chamber was considered to be the most clinically feasible method that was tested and provided results that closely matched, within 2%, the liquid ionization chamber method (dosimetric reference).

CONFLICT OF INTEREST

Love Kull is a majority shareholder in LoniTech AB. Mats Danielsson has a research collaboration with GE Healthcare and is a shareholder in Prismatic Sensors AB. The remaining authors have no conflicts of interest.

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