Updates on CT Dosimetry:
Free Falling: Measurements of Dose in Air

AAPM 2021
JULY 25–29 | VIRTUAL
63RD ANNUAL MEETING & EXHIBITION

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Disclosures

None

1 History and Background of performing in air measurements in CT

2 Measuring and Using $\mathrm{CTDI}_{\mathrm{free,air}}$

3 Measuring and using $\widehat{D}_{\mathrm{eq,air}}$

4 Advantages and limitations of measurements of dose in air

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1 History and Background of performing in air measurements in CT

Dose measurements are more than just Computed Tomography Dose Index variants

Tube Potential accuracy
Dose output with tube potential
Dose output linearity with mAs
Dose reproducibility
HVL

Both major AAPM Reports on CT testing have in Air measurements

ICRU report 87 contains extensive chapter on characterizing beam and dose in air

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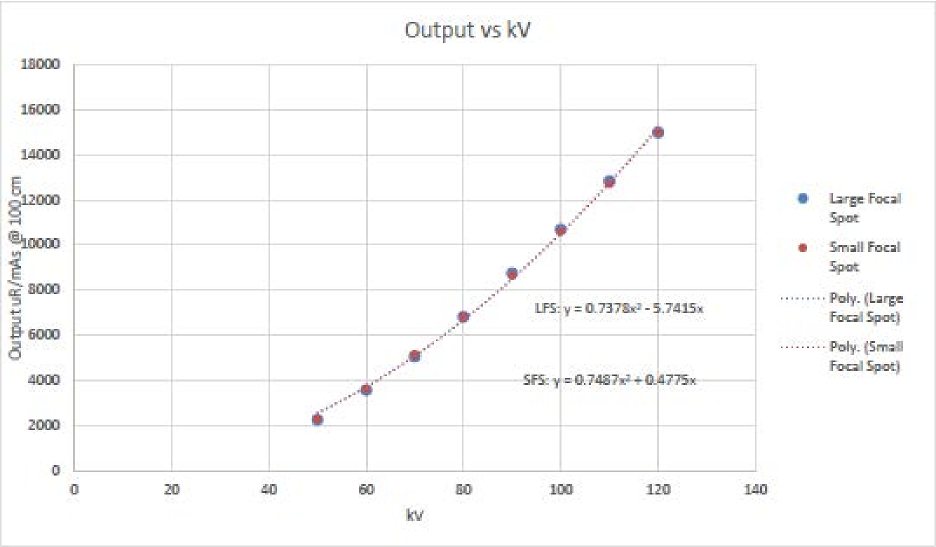

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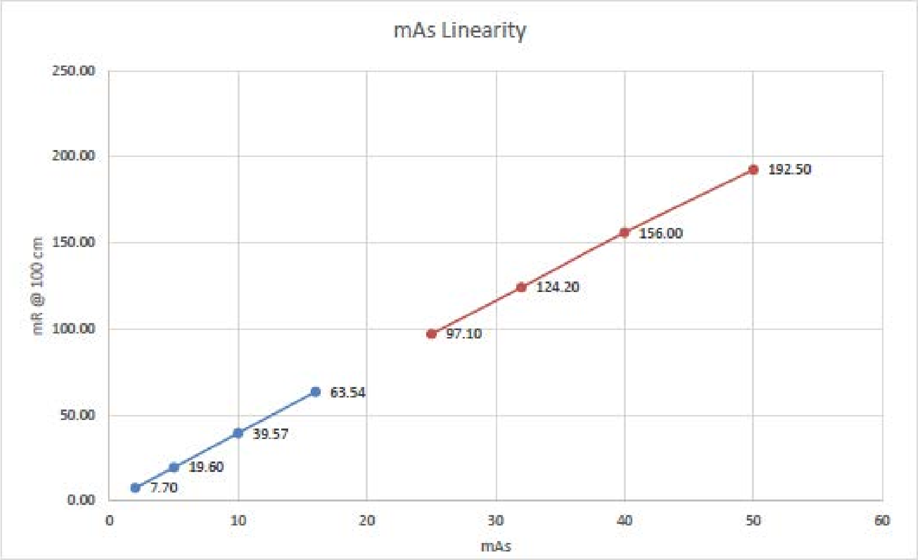

ICRU report 87 contains ext ose in air

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AAPM Report 39 (1993)

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Included tube potential accuracy measurement (non-invasive) in air

Specified measurement of dose linearity (with mAs) in air using ionization chamber

mA Linearity: Without specialized instruments (i.e., Hall Effect probes), tube current must be inferred indirectly using a mAs linearity measurement For a constant tube potential and slice width, the integral exposure should be a linear function of mAs.

Tools needed: CT ion chamber, electrometer with integral exposure and time duration capability and test tube stand or equivalent to hold ion chamber.

Method:

- Put tabletop just outside of scan field: place test stand on tabletop.
- Put ion chamber (without any attenuator) on stand and center parallel to rotational gantry axis. (Centering is critical if scan angle is variable, or if system has asymmetric fan beam). Ensure that chamber sensitive volume is within slice dimensions (not critical with CT chamber) and no other attenuator (including tabletop) is in scan field

AAPM REPORT NO. 39

SPECIFICATION AND ACCEPTANCE TESTING OF COMPUTED TOMOGRAPHY SCANNERS

AAPM

AAPM Report 233 (2019)

Includes multiple output dose measurements to be made in air:

HVL

Output Reproducibility

Output Exposure Linearity

Exposure time accuracy

Tube potential accuracy

Dose profile

Performance Evaluation of Computed Tomography Systems

The Report of AAPM Task Group 233

April 2019

AAPM Report 233 Measurements in Air

- HVL
- Output Reproducibility
- Output Exposure Linearity
- Exposure Time Accuracy
- Tube Potential Accuracy
- Dose Profile

Table 6a. Half-Value Layer (HVL)

Purpose	To measure the half-value layer of the CT system's x-ray source and ensure that it is within regulatory limits	
	Concentric Ring Method	**Stacked Sheet Method**
Testing Devices	CTDI ion chamber (pencil chamber with 10 cm active length) and electrometer; concentric 2 mm thick rings made of aluminum 1100.	CTDI ion chamber and electrometer; aluminum 1100 sheets.
Setup	CTDI ion chamber is placed at the gantry isocenter and centered along the z-direction. Axial CT scans are performed with the aluminum rings progressively nested to acquire CTDI data at increased filtration. The rings are placed on a low-attenuation stand such that the rings are centered about the chamber.	Park x-ray tube at a stationary position below isocenter. This could be achieved either using CT localizer radiograph scan, or with assistance of service engineer. The former requires a stationary support mechanism for the ion chamber other than patient table. CTDI ion chamber is placed at the gantry isocenter and centered along the z-direction. Aluminum sheets are gradually added on the CT gantry close to the x-ray tube.
Scan Protocol	Use relatively high mAs to ensure sufficient signal after several layers of aluminum are added. Perform measurements at each tube potential. Note that different bowtie filters could also be tested at each tube potential. Often the bowtie filter is determined by patient size selection for scan field of view.	
Measurements	Measure CTDI at each filtration level. HVL is calculated as the thickness of aluminum at which measured exposure is half of that without any aluminum filter (interpolation may be needed). Note that typical HVL range from approximately 4–8 mm aluminum and in some cases can be up to 10 mm aluminum.	
Qualitative Criteria	N/A	
Quantitative Criteria	CFR 21 specifies minimal HVL for general radiograph systems. HVL of CT system is usually higher than those specified in CFR 21. Recommend to use specifications from manufacturer.	
References	Kruger et al. 2000[66], IAEA Series No. 19, CFR 21	

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AAPM Report 233 Measurements in Air

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- HVL
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Table 6b. Exposure Reproducibility

Purpose	**To ensure the radiation output of the system is consistent across repeated identical exposures**
Testing Devices	CTDI ion chamber (pencil chamber with 10 cm active length) and electrometer
Setup	CTDI ion chamber is placed at the gantry isocenter and centered along the z-direction. Test procedure is the same as CTDI measurement, but can be done in free air if preferred.
Scan Protocol	Use axial scan protocol for the two typical kV and mAs settings, representative of typical head and body techniques.
Measurements	CTDI measurements for the two typical kV and mAs settings, representative of typical head and body techniques. Repeat scans with each parameter setting.
Qualitative Criteria	N/A
Quantitative Criteria	The output should also be reproducible within a coefficient of variation of <0.10 (AAPM report 74) <20% of mean value of measurements taken.[10] For $CTDI_{free\text{-}in\text{-}air}$, each value shall be within ±10% of the mean of a set of 10 measurements (IEC).
References	AAPM report 74, EC report 162, IEC standard 61223-3-5

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AAPM Report 233 Measurements in Air

- HVL
- Output Reproducibility
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Table 6d. Exposure Linearity

Purpose	To ensure the radiation output of the system is linearly proportional to mAs
Testing Devices	CTDI ion chamber and electrometer
Setup	Put patient table just outside of scan range, place ion chamber on top of patient table, parallel to the gantry axis and centered both laterally and vertically (use stand or support if patient table is too low).
Scan Protocol	Operate scanner in axial mode with no table translation.
Measurements	For each tube potential, mAs can be varied in two ways (1) fix rotation time and change mA, (2) fix mA and change rotation time. Measure exposure at a range of mAs settings corresponding to typical clinical ranges.
Qualitative Criteria	N/A
Quantitative Criteria	Calculated CTDI/mAs for each parameter setting. Coefficient of linearity of CTDI/mAs between the mean of all values and any single value (absolute difference divided by sum) should be within 0.05.
References	AAPM Report 39.

AAPM Report 233 Measurements in Air

AAPM 2021 JULY 25–29 VIRTUAL 63RD ANNUAL MEETING & EXHIBITION

HVL

Output Reproducibility

Output Exposure Linearity

Exposure Time Accuracy

Tube Potential Accuracy

Dose Profile

Table 6e. Exposure Time Accuracy

Purpose	To ensure the nominal exposure time is similar to the actual exposure time
Testing Devices	Dosimeters (ion chamber or other types) with time measurement capability
Setup	Place the chamber at the gantry center.
Scan Protocol	Use axial protocol with no table translation
Measurements	Take measurements and record the exposure time for each nominal rotation time that is available on the scanner model.
Qualitative Criteria	N/A
Quantitative Criteria	For generators that display the selected time prior to the exposure, accuracy should be within ±5% (AAPM Report 74) Radiation termination shall occur within an interval that limits the total scan time to no more than 110 percent of its pre-set value (CFR 21 CT). Deviation from set value ≤±20%.
References	AAPM Report 74, CFR 21 CT, IEC standard 61223-3-5

AAPM Report 233 Measurements in Air

- HVL
- Output Reproducibility
- Output Exposure Linearity
- Exposure Time Accuracy
- Tube Potential Accuracy
- Dose Profile

Table 6f. Tube potential Accuracy

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Purpose	To ensure the nominal tube potential is similar to the actual tube potential	
	Non-invasive Method	**Invasive Method**
Testing Devices	kV meter calibrated for CT	High voltage dividers.
Setup	Park the tube at top of the gantry, which can be achieved either in CT localizer radiograph mode or in service mode. Put table at lowest scan position, move tabletop into gantry opening, and place kV sensor on table. Align detector(s) to scan alignment light. If instrument detector is large or CT localizer radiograph mode is used instead of service mode, place the kV meter at bottom of gantry opening where the field size is greatest, with tabletop out of field.	Invasive test device (high voltage divider) directly measures the voltage of the generator. This is not recommended for routine test.
Scan Protocol	Set widest collimator setting and expose detector.	N/A
Measurements	Record kV values.	
Qualitative Criteria	N/A	
Quantitative Criteria	In absence of manufacturer's specifications, for both pulsed and non-pulsed generators, tube potential should be within ±2 kV of indicated values for all power levels.[9] ±5% nominal (Acceptable) and ±2% nominal (Achievable)[12].	
References	AAPM report 39 and AAPM report 74, IAEA Series No. 19	

AAPM Report 233 Measurements in Air

HVL

Output Reproducibility

Output Exposure Linearity

Exposure Time Accuracy

Tube Potential Accuracy

Dose Profile

Table 6g. Radiation Beam Profile

Purpose	To ensure the nominal radiation beam width is similar to the actual beam width
Testing Devices	External radiation detector. Area or long linear detectors such as CR plate, self-developing film, or optically stimulated luminescence (OSL) strip. Point detectors with temporal readout such as solid-state sensor or small ionization chamber with real time readout.
Setup	Preferred placement of radiation detector is in air at isocenter. However, this is not possible with all detectors: alternatively, a flat radiation attenuator shall be placed on the scanner table and then the radiation detector placed on top of the attenuator (e.g., CR plate placed on top of 15 cm acrylic sheet) and the table height adjusted to put radiation detector at isocenter.
Scan Protocol	Scan using each unique total beam collimation setting (N × T) available. • Area detectors (CR plate, film, long OSL) can be exposed with a single axial scan; • Point detectors (solid state sensor, small ionization chamber) require a helical scan through the entire beam width. • If necessary, available devices can transport small point detectors through the beam without having to move the table ("probe pullers"); consider their use for assessing scan modes/collimations with no helical scan option (e.g., a 320×0.5 mm beam width or other "volume scan" mode)
Measurements	From the radiation beam profile, calculate the full-width-at-half-maximum (FWHM) value.
Quantitative Criteria	Each manufacturer will have its own specifications for tolerances on FWHM of beam width at each collimation setting. Please consult manufacturer's documents. Generally narrower collimations require larger relative tolerances. ACR has suggested: FWHM should be accurate to within 3 mm or 30% of the total nominal collimated beam width (N × T), whichever is greater.
References	ACR CT QC manual
Notes	It is also possible to estimate the beam width using dosimetric measurements. For example, the CTDI pencil ion chamber can be used in conjunction with a radiopaque ring "mask" to estimate the dose per unit length for a given exposure setting (e.g., kV and mAs). A dose measurement at the collimation setting of interest is then divided by this dose per unit length to yield an estimate of the beam width.

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- HVL
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Table 6e. Exposure Time Accuracy

Table 6g. Radiation Beam Profile

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What about DOSE in air?

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IEC 60601-2-44 (Safety and Performance)defined $CTDI_{free,air}$

***CTDI*FREE AIR**
integral of the DOSE PROFILE produced in a single axial scan along a line perpendicular to the TOMOGRAPHIC PLANE from –50 mm to +50 mm, divided by the product of the number of TOMOGRAPHIC SECTIONS *N* and the NOMINAL TOMOGRAPHIC SECTION THICKNESS *T*, or divided by 100 mm, whichever is less

$$CTDI_{FREE\ AIR} = \int_{-50\ mm}^{+50\ mm} \frac{D(z)}{min\{N \times T, 100\ mm\}} dz$$

where

D(z) is the DOSE PROFILE along a line *z* perpendicular to the TOMOGRAPHIC PLANE, where dose is reported as ABSORBED DOSE in air and is evaluated free-in-air in the absence of a PHANTOM and the PATIENT SUPPORT;

N is the number of TOMOGRAPHIC SECTIONS produced in a single axial scan of the X-ray source;

T is the NOMINAL TOMOGRAPHIC SECTION THICKNESS.

Edition 3.0 2009-02

INTERNATIONAL STANDARD

NORME INTERNATIONALE

Medical electrical equipment –
Part 2-44: Particular requirements for the basic safety and essential performance of X-ray equipment for computed tomography

Appareils électromédicaux –
Partie 2-44: Exigences particulières pour la sécurité de base et les performances

Includes requirement of 10% reproducibility

$CTDI_{free,air}$ values shall be included in accompanying documents

Defined for: All beam collimations, All Tube Potential settings, all typical head conditions, and for all additional flat filters

What about DOSE in air?

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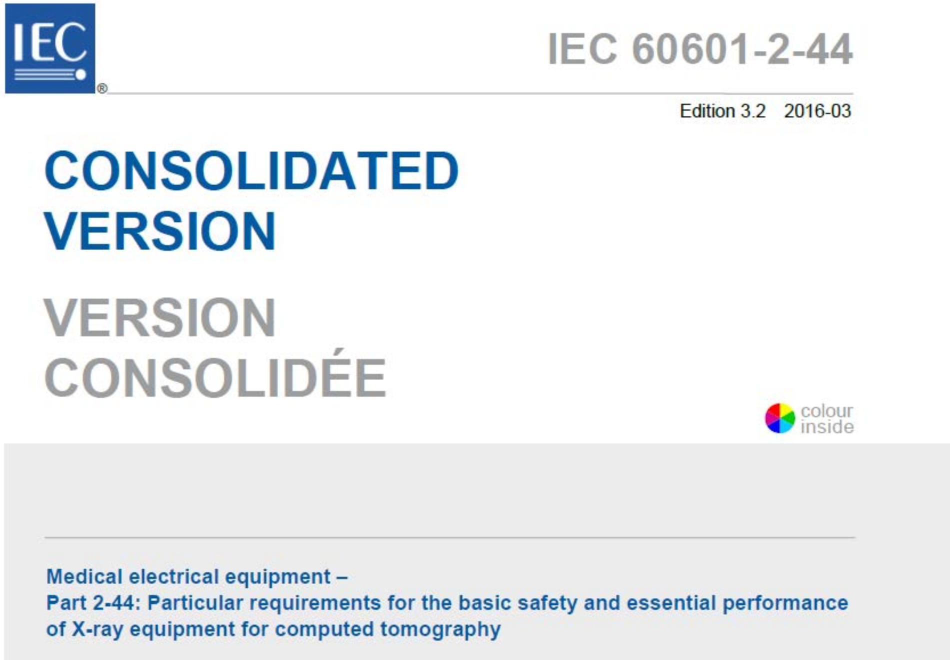
IEC 60601-2-44 updated with measurement procedure in 2016

Dose profile to be measured over at least 100 mm

Can be measured integrating profile with small dosimeter (meeting IEC 61674) or with long chamber stepped through isocenter

IAEA report referenced with details on testing

Includes $\text{CTDI}_{\text{free,air}}$ as part of definition of CTDI100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IEC 60601-2-44

Edition 3.2 2016-03

CONSOLIDATED VERSION

VERSION CONSOLIDÉE

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Medical electrical equipment –
Part 2-44: Particular requirements for the basic safety and essential performance of X-ray equipment for computed tomography

What about DOSE in air?

IEC 60601-2-44 updated with measurement procedure in 2016

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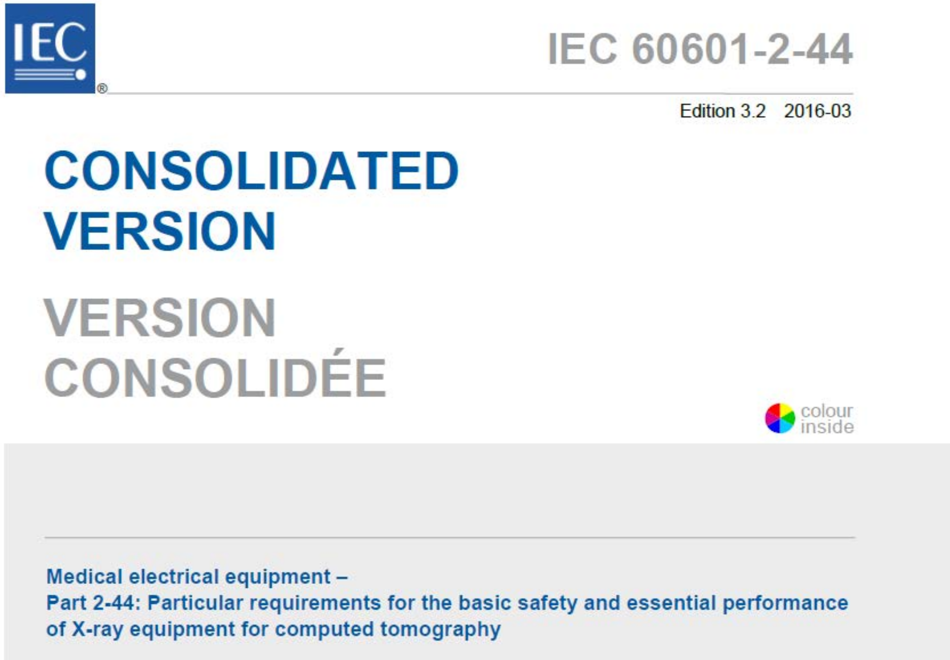
$$CTDI_{\text{free air}} = \int_{-L/2}^{+L/2} \frac{D(z)}{N \times T} dz$$

where

$D(z)$	is the DOSE PROFILE representative of a single axial scan along a line z through ISOCENTRE and perpendicular to the TOMOGRAPHIC PLANE, where dose is reported as ABSORBED DOSE in air and is evaluated free-in-air in the absence of a PHANTOM and the PATIENT SUPPORT;
N	is the number of TOMOGRAPHIC SECTIONS produced in a single axial scan of the X-ray source;
T	is the NOMINAL TOMOGRAPHIC SECTION THICKNESS;
L	is at least ($N \times T$) +40 mm, but not less than 100 mm

For $N \times T$ greater than 40 mm:

$$CTDI_{100} = \int_{-50\,\text{mm}}^{+50\,\text{mm}} \frac{D_{Ref}(z)}{(NxT)_{Ref}} dz \times \frac{CTDI_{\text{free air},N\times T}}{CTDI_{\text{free air},Ref}}$$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IEC 60601-2-44
Edition 3.2 2016-03
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Medical electrical equipment –
Part 2-44: Particular requirements for the basic safety and essential performance of X-ray equipment for computed tomography

What about DOSE in air?

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IEC 61233-3-5 Ed. 2 (2019) Acceptancy and Constancy

Further expansion of details for in air dose measurements

Acceptance testing shall include $CTDI_{free,air}$ at all nominal collimations and kVp settings

Constancy not to differ by more than 20%

Small detector, uniformly translated through radiation beam gives dose profile


IEC

IEC 61223-3-5

Edition 2.0 2019-09

INTERNATIONAL STANDARD

NORME INTERNATIONALE

Evaluation and routine testing in medical imaging departments –
Part 3-5: Acceptance and constancy tests – Imaging performance of computed tomography X-ray equipment

What about DOSE in air?

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Table 1 – Test pattern for $CTDI_{free\ air}$ for Adult Body PROTOCOL ELEMENTS

Variation of tube potential	Variation of the nominal beam collimation (N × T)				
	Collimation 1	Collimation 2	Collimation 3	Collimation 4 (typical Adult Body)	Collimation 5
kV 1				Yes	
kV 2 (typical Adult Body)	Yes	Yes	Yes	Yes	Yes
kV 3				Yes	

In addition to the test cases identified in Table 1, the $CTDI_{free\ air}$ shall also be tested using the kV and collimation for the typical Adult Head, typical Paediatric Head, and Typical Paediatric Body PROTOCOL ELEMENTS.

IEC

IEC 61223-3-5

Edition 2.0 2019-09

INTERNATIONAL STANDARD

NORME INTERNATIONALE

Evaluation and routine testing in medical imaging departments –
Part 3-5: Acceptance and constancy tests – Imaging performance of computed tomography X-ray equipment

Example of $CTDI_{free,air}$ measurements

1.1.11 $CTDI_{free\ air}$

The $CTDI_{free\ air}$ is stated in the following table for all collimations, tube voltage for shaped filter *Standard*. The $CTDI_{free\ air}$ for the typical head mode (acquisition 64 × 0.6 mm) and for the typical body mode (acquisition 192 × 0.6 mm) is marked as bold type. $CTDI_{free\ air}$ for shaped filter *Narrow* are in general approximately 5% lower.

$CTDI_{free\ air}$ in Gy/100 mAs		Tube voltage								
Acquisition	Collimation	70 kV	80 kV	90 kV	100 kV	110 kV	120 kV	130 kV	140 kV	150 kV
2 × 1 mm	2 × 1 mm	4.27	6.31	8.73	11.44	14.38	17.72	20.98	24.50	28.21
6 × 0.6 mm	6 × 0.6 mm	7.44	10.92	15.18	19.82	24.98	30.17	36.43	42.48	48.93
1 × 5 mm	1 × 5 mm	4.31	6.33	8.80	11.49	14.48	17.72	21.12	24.63	28.36
1 × 10 mm	1 × 10 mm	4.31	6.33	8.80	11.49	14.48	17.71	21.12	24.63	28.36

SOMATOM Force

Print No. C2-058.660.01.01.02

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What about DOSE in air?

AAPM Report 111 introduced another dose in air index $\hat{D}_{eq,air}$

Defined as: Equilibrium dose-pitch product (mGy), p*$D_{eq,air}$, where $D_{eq,air}$ is the equilibrium dose evaluated at pitch p in air.

$D_{eq,air}$ is inversely proportional to p, the product p* $D_{eq,air}$ is independent of p

$$\hat{D}_{eq,air} = \frac{1}{nT}\int_{-\infty}^{\infty} f_{air}(z')dz' \approx \frac{a}{nT} f_{air}(z=0),$$

AAPM REPORT NO. 111

Comprehensive Methodology for the Evaluation of Radiation Dose in X-Ray Computed Tomography

A New Measurement Paradigm Based on a Unified Theory for Axial, Helical, Fan-Beam, and Cone-Beam Scanning With or Without Longitudinal Translation of the Patient Table

**Report of AAPM Task Group 111:
The Future of CT Dosimetry**

February 2010

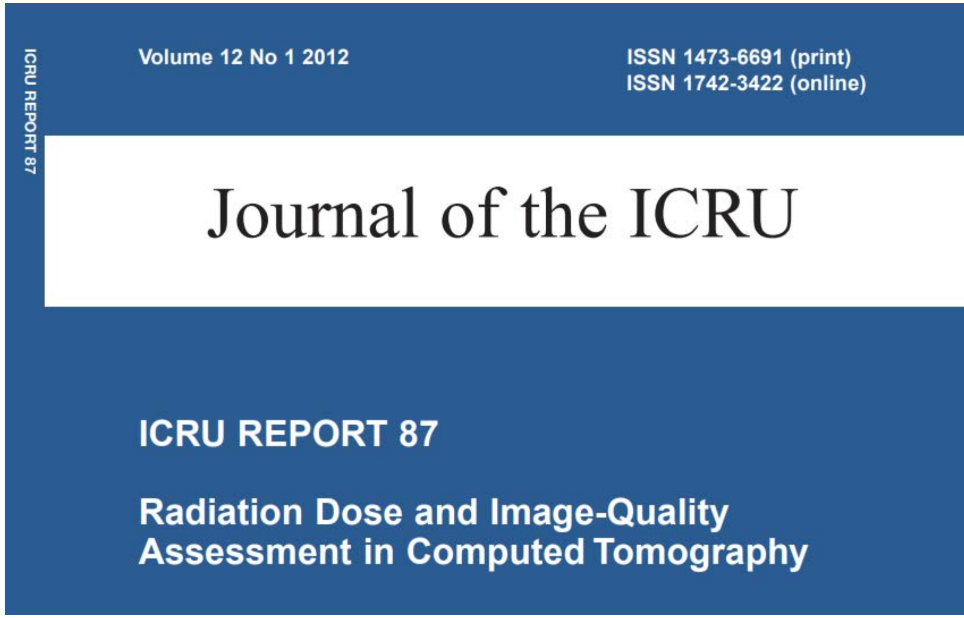
CT Output Characteristics Measured in Air

Options for measuring air kerma as function of z

Measurements of air kerma across field of view

- **Helpful for Monte Carlo Simulations**
- **Understand differences in bow ties**

Planar measurements of beam profile



CT Output Characteristics Measured in Air

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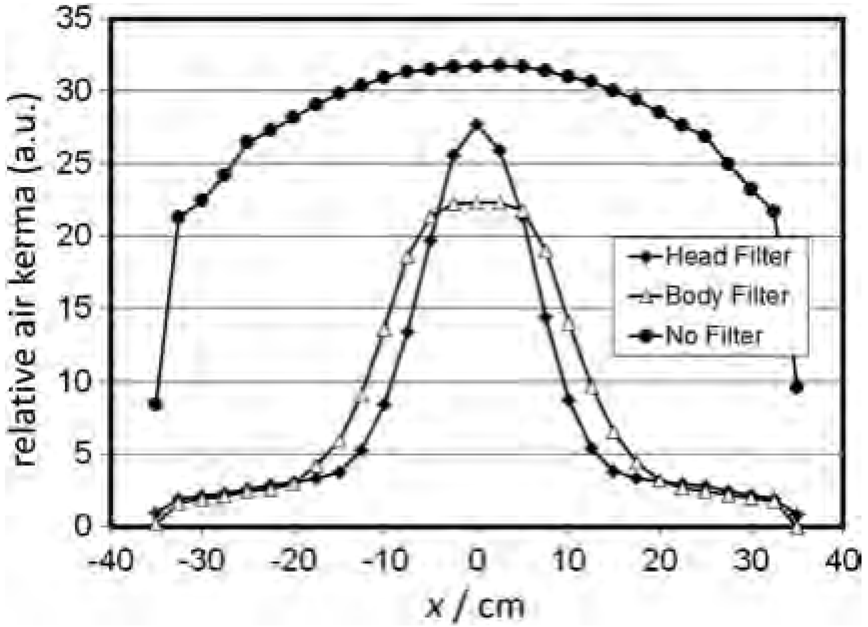
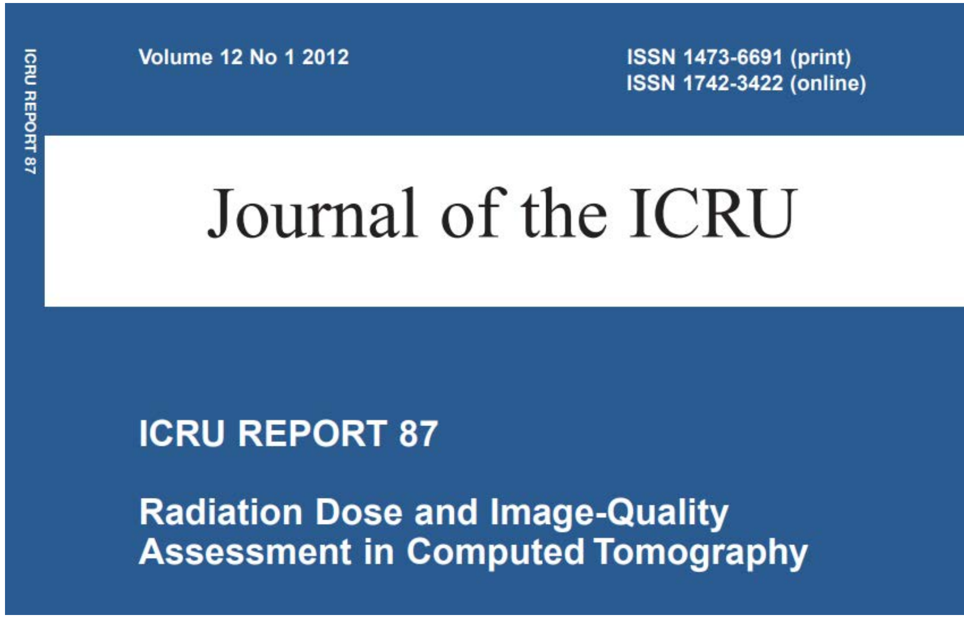


Figure 6.12. The x-ray-beam profile, $f_L(x)$, for a General Electric Lightspeed 16 scanner measured with a pencil chamber. The bow-tie filter function for both the head and body filters is shown, along with no filter (Huda, personal communication). The use of the pencil chamber results in a $1/r$ fall-off.



CT Output Characteristics Measured in Air

Options for ...

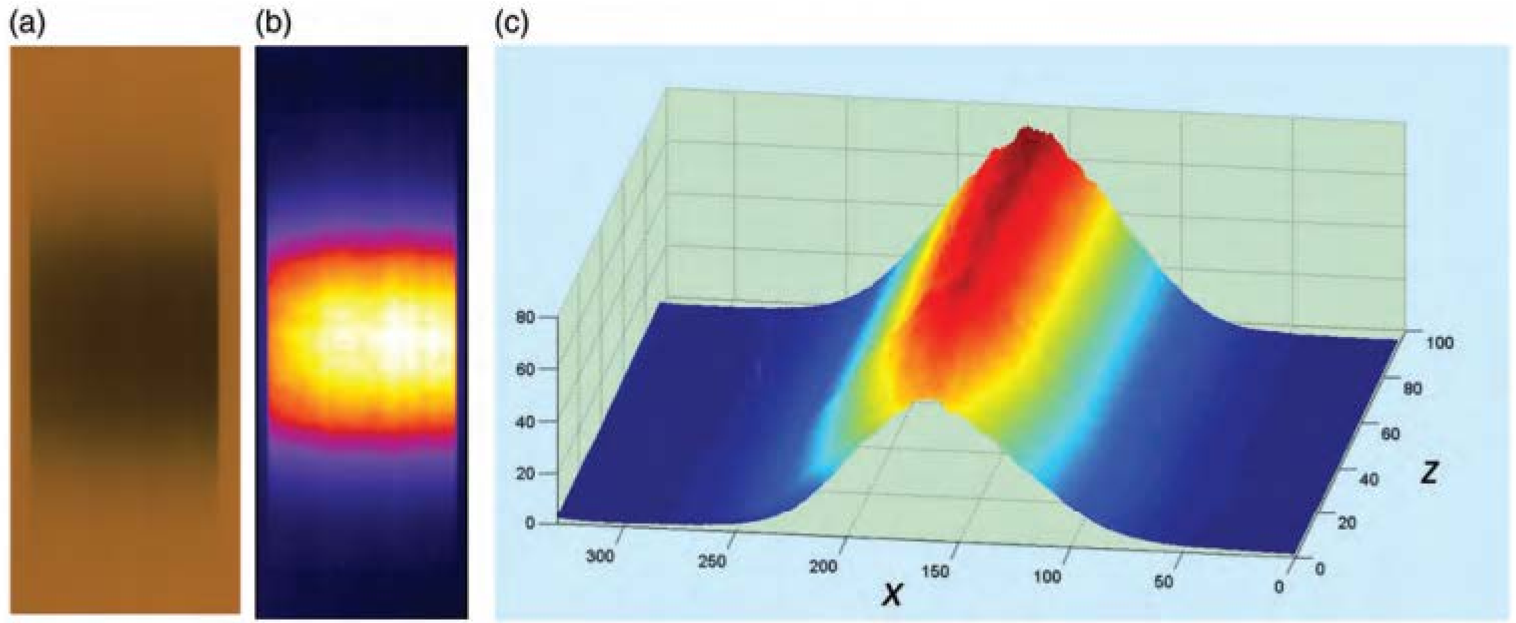


Figure 6.19. Use of radiochromic self-developing film to determine the relative two-dimensional distribution. A photograph of the self-developing film exposed at the isocenter of the CT scanner is shown in (a). The analog film was digitized, and the red channel was used with appropriate characteristic-curve normalization to determine the relative two-dimensional radiation-intensity distribution, shown in (b). An isometric plot of the distribution is shown in (c).

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shown, along with no filter (Huda, personal communication).
The use of the pencil chamber results in a 1/r fall-off.

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Journal of the ICRU

REPORT 87

ation Dose and Image-Quality
ssment in Computed Tomography

So why DO we need those phantoms?

RULES!

So why DO we need those phantoms?

20	For diagnostic computed tomography (CT) services: At least annually, a diagnostic medical physicist does the following: - Measures the radiation dose (in the form of volume computed tomography dose index [CTDIvol]) produced by each diagnostic CT imaging system for the following four CT protocols: adult brain, adult abdomen, pediatric brain, and pediatric abdomen. If one or more of these protocols is not used by the hospital, other commonly used CT protocols may be substituted. - Verifies that the radiation dose (in the form of CTDIvol) produced and measured for each protocol tested is within 20 percent of the CTDIvol displayed on the CT console. The dates, results, and verifications of these measurements are documented. Note 1: This element of performance is only applicable for systems capable of calculating and displaying radiation doses. Note 2: This element of performance does not apply to dental cone beam CT radiographic imaging studies performed for diagnosis of conditions affecting the maxillofacial region or to obtain guidance for the treatment of such conditions. Note 3: Medical physicists are accountable for these activities. They may be assisted with the testing and evaluation of equipment performance by individuals who have the required training and skills, as determined by the physicist. (For more information, refer to HR.01.02.01, EP 1; HR.01.02.05, EP 20; HR.01.02.07, EPs 1 and 2; HR.01.06.01, EP 1; LD.03.06.01, EP 4.)

So why DO we need those phantoms?

c) Radiation dose measurements shall be performed by a diagnostic imaging specialist on each CT x-ray system. The measurements shall be specified in terms of the computed tomography dose index (CTDI), for the head and abdomen, using a head or abdomen phantom, respectively, and the facility's technique factors most frequently used for a CT examination of the head or abdomen, respectively, and shall be performed:

1) At least annually by a diagnostic imaging specialist and after any change or replacement of components that could cause a change in the radiation output;

2) With a dosimetry system that has been calibrated within the preceding 12 months. The calibration of such system shall have no more than a three-step (tertiary) calibration, traceable to the National Institute of Standards and Technology; and

3) Using the computed tomography dose measurement protocol found in Report 111 of the American Association of Physicists in Medicine (AAPM), entitled "Comprehensive Methodology for the Evaluation of Radiation Dose in X-Ray Computed Tomography" published by AAPM, February 2010, exclusive of subsequent amendments or editions. A copy of this report is available for public inspection at the Illinois Emergency Management Agency, 1035 Outer Park Drive, Springfield, Illinois or may also be obtained directly from the AAPM, One Physics Ellipse, College Park MD 20740-3846.

AGENCY NOTE: The Agency recognizes that other phantoms and protocols are available to provide accurate dose measurements as specified in this Section. The Agency will consider use of such phantoms and protocols as satisfying this Section if the intent of the regulation is met.

So why DO we need those phantoms?

J. Dosimetry

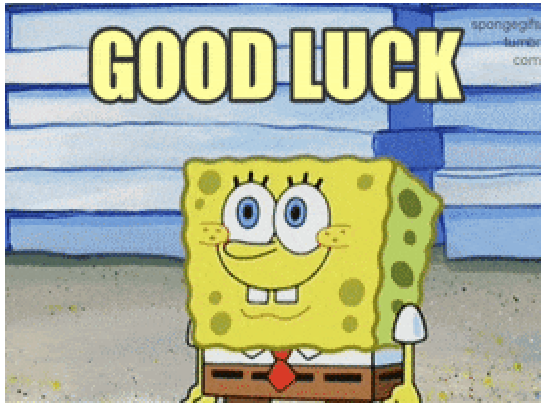
OBJECTIVE	To measure doses for verification of scanner performance and to allow for calculation of dosimetric quantities relevant to patient exam estimates.
FREQUENCY	Annually or after relevant service, including, but not limited to, x-ray tube replacement or alignment, collimator service, bowtie replacement, or alignment or generator service.
REQUIRED EQUIPMENT	1. Calibrated electrometer and CTDI pencil ionization chamber (10- or 15-cm long) 2. Head CTDI phantom: 16-cm diameter 3. Body CTDI phantom: 32-cm diameter

2 Measuring and Using $CTDI_{free,air}$

How do I measure $CTDI_{free,air}$?

How do I use it?

How do I find these “accompanying documents?!?!”



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Flavors of CTDI

D(z) is dose profile and nT is detector configuration

$CTDI_{\infty}$

$$CTDI_{\infty} = \frac{1}{nT}\int_{-\infty}^{\infty} D(z)dz.$$

$CTDI_{100}$

$$CTDI_{100} = \frac{1}{nT}\int_{-50\ mm}^{50\ mm} D(z)dz.$$

$CTDI_{100,w}$

$$CTDI_{100,w} = \frac{1}{3}CTDI_{100,c} + \frac{2}{3}CTDI_{100,p}$$

$CTDI_{free,air}$

$$CTDI_{free\ air} = \frac{1}{nT}\int_{-L/2}^{L/2} D(z)dz.$$

$CTDI_{100,nT>40mm}$

$$CTDI_{100,nT > 40\,mm} = CTDI_{100,ref} X \left(\frac{CTDI_{free\ air,\ nT}}{CTDI_{free\ air,\ ref}}\right)$$

Measuring $CTDI_{free,air}$

Bujila et al. examined 3 different dosimeters and methods for measuring $CTDI_{free,air}$ for use when NT > 40 mm

Liquid ionization chamber and step and shoot method

100mm Pencil chamber at contiguous locations (also described in IAEA Report #5)

Small real time dosimeter with continuous translation

Move dosimeter with stationary table

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MEDICAL IMAGING WILEY

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

Robert Bujila[1,2] | Love Kull[3] | Mats Danielsson[2] | Jonas Andersson[4]

Measuring $CTDI_{free,air}$

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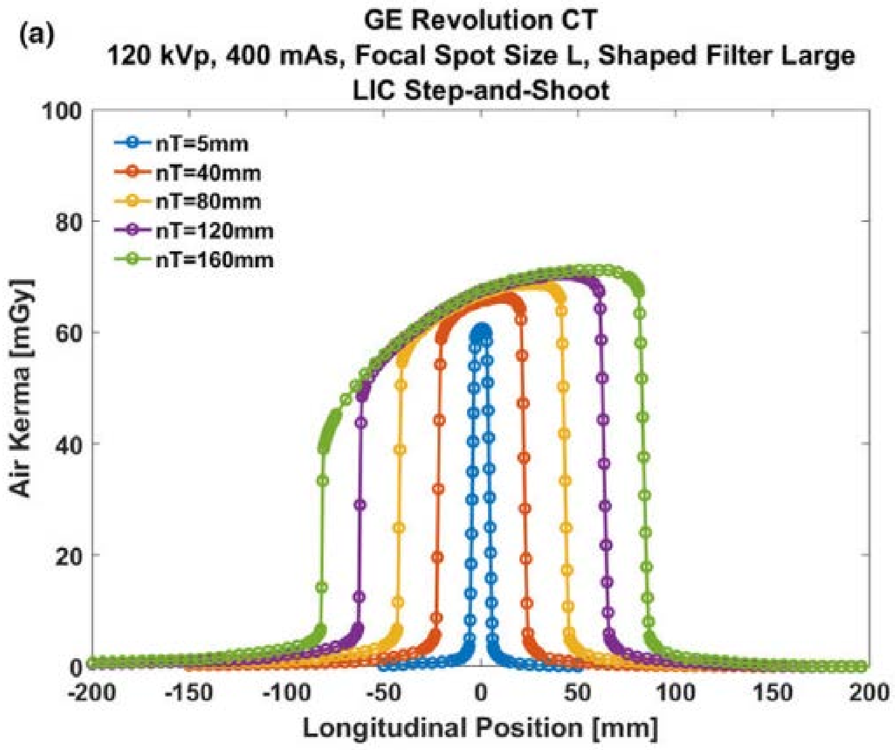
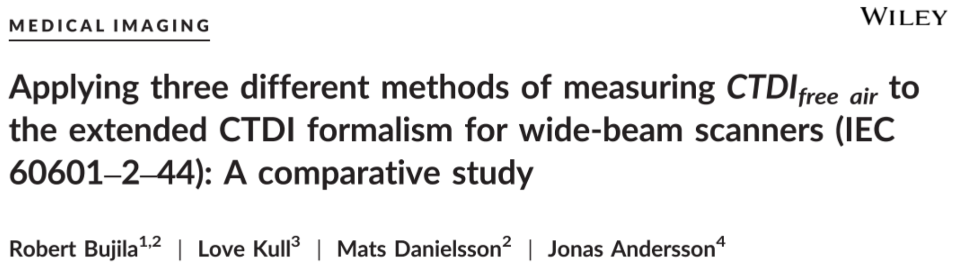
Integrate Results to determine $CTDI_{free,air}$




MEDICAL IMAGING

WILEY

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Measuring $CTDI_{free,air}$

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Contiguous measurements with ion chamber

Sum measurements to get $CTDI_{free,air}$

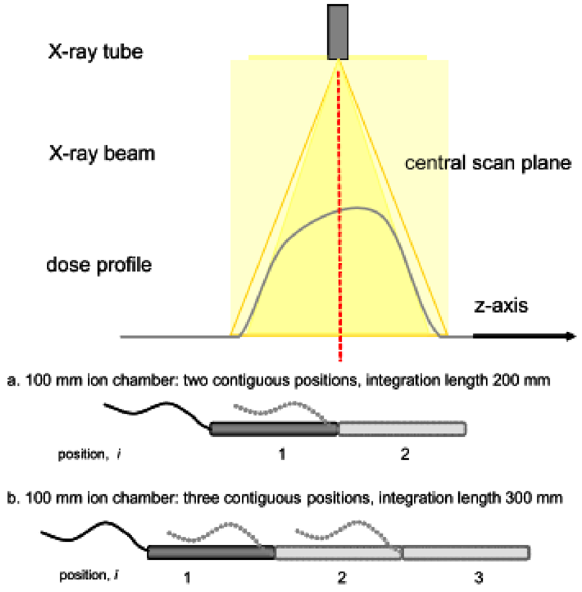
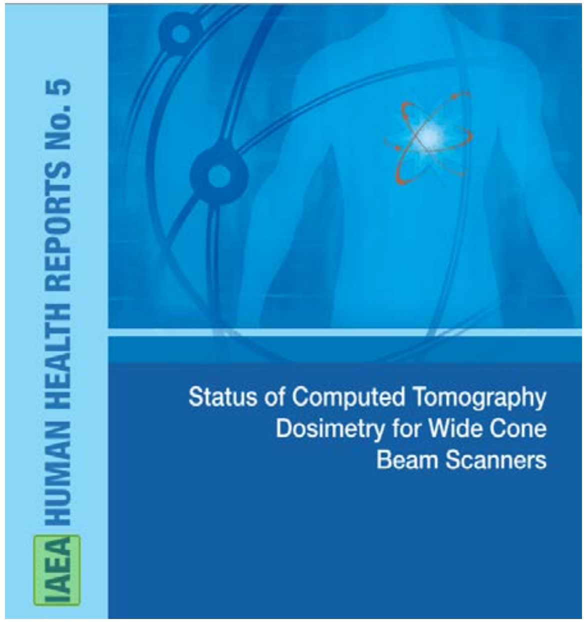


FIG. 10. Diagram demonstrating practical measurements of $CTDI_{free\text{-}in\text{-}air}$ for a beam width of 160 mm with a 100 mm ion chamber, and step increments equal to the ion chamber length. Two integration lengths are shown. The 200 mm integration length is sufficient according to the minimum requirement of IEC; however the 300 mm integration length can also be used.



$$CTDI_{free-in-air} = \frac{1}{N \times T} \times \sum_{i=1}^{i=n} \left[\int_{L_c} D_i(z)\, dz \right]$$

Measuring $CTDI_{free,air}$

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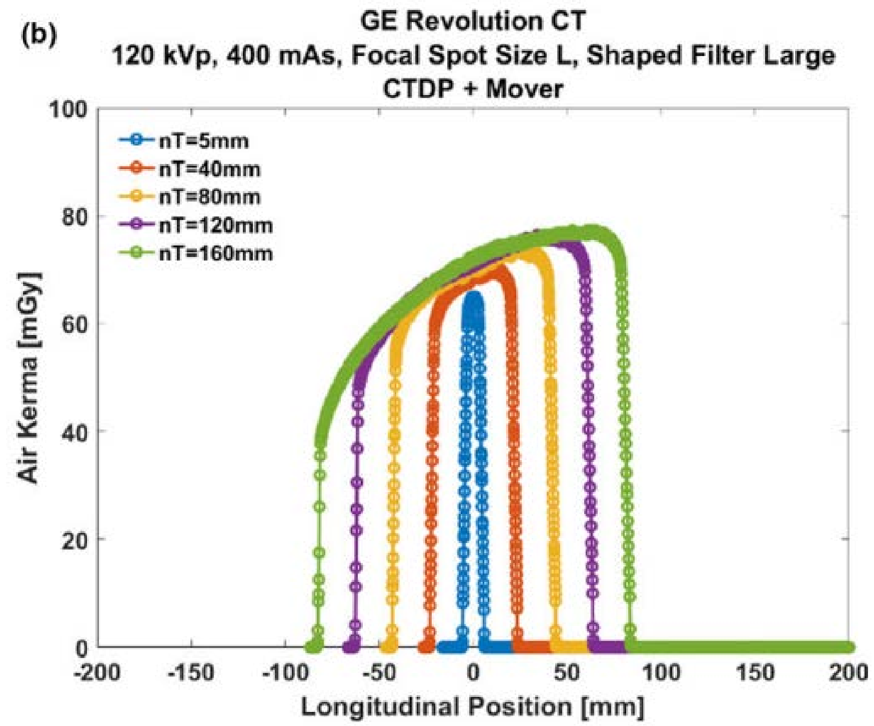
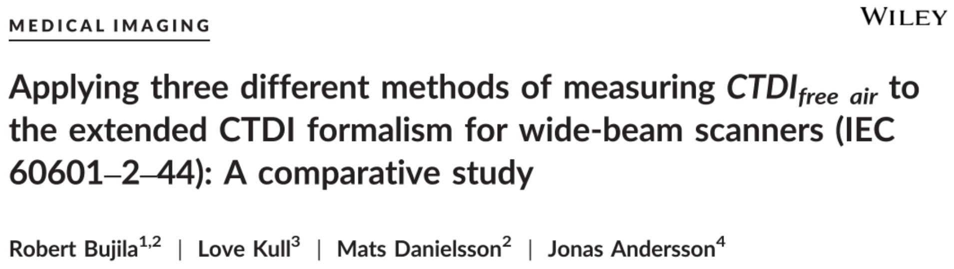
Integrate results to determine $CTDI_{free,air}$





MEDICAL IMAGING

WILEY

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

Robert Bujila[1,2] | Love Kull[3] | Mats Danielsson[2] | Jonas Andersson[4]

Small dosimeter translated through beam

Using $CTDI_{free,air}$

Must use $CTDI_{free,air}$ if NT > 40 mm to determine $CTDI_{100}$

Measure with continuous translation and integrate profile using small dosimeter

Measure using pencil chamber placed at contiguous positions and sum values

$CTDI_{free,air}$ values can be compared directly to Technical Reference Manual or accompanying documents (no CTDI phantom needed) IF not required by regulatory/accrediting body

Non-diagnostic scanner where allowed by state

Bi-annual constancy checks

After major service (if not ACR accredited)

Using $\text{CTDI}_{\text{free,air}}$

$\text{CTDI}_{\infty\text{free,air}}$ gives variation of penumbra with changes in *nT*

Measure one beam width *a* for a given *nT*

Measure $\text{CTDI}_{\infty\text{free,air}}$ for same *nT*

$$CTDI_{\infty} = \frac{1}{nT} \int_{-\infty}^{\infty} D(z)dz,$$

Repeat free in air measurements at different *nT* with all other conditions the same

Changes in $\text{CTDI}_{\infty\text{free,air}}$ at different *nT* are due to variation in contribution of the penumbra (or the total beam width, *a*)

Cone beam CT dosimetry: A unified and self-consistent approach including all scan modalities—With or without phantom motion

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Med. Phys. 37 (6), June 2010

What about those Accompanying Documents?

NOTE The definitions of $CTDI_w$ and $CTDI_{free\ air}$ are described below.

[Definition of $CTDI_w$ (Weighted $CTDI_{100}$)]

Based on the definitions of this standard, a 10-cm chamber dosimeter is used to measure the integrated dose for a single conventional scan at center and peripheral positions (0°, 90°, 180°, and 270°, 1 cm below surface) of the polymethylmethacrylate (PMMA) phantom with a diameter of 160 mm (head-equivalent phantom) and the acrylic phantom with a diameter of 320 mm (trunk-equivalent phantom). For each position the $CTDI_{100}$ is calculated using Equation A.

By using the obtained $CTDI_{100}$ values (center and four peripheral positions) for each phantom, the $CTDI_w$ is calculated according to Equation D.

$$CTDI_w = 1/3 \times CTDI_{100\ (center)} + 2/3 \times CTDI_{100\ (peripheral:\ average\ value)} \quad \text{(Equation D)}$$

[Definition of $CTDI_{free\ air}$]

$CTDI_{free\ air}$ is evaluated in the air without the use of a dose phantom or patient support. $CTDI_{free\ air}$ was defined in IEC 60601-2-44:2009 and revised in IEC 60601-2-44:2012 as follows.

Definition of $CTDI_{free\ air}$ specified in IEC 60601-2-44:2009

Assuming that the dose profile on a straight line perpendicular to the slice plane is D(z), $CTDI_{free\ air}$ is defined as the integrated dose within the range from -50 mm to +50 mm, assuming that the dose profile is centered on z = 0, divided by N × T, or divided by 100 mm, whichever is less.

$$CTDI_{free\ air} = \int_{-50\,mm}^{+50\,mm} \frac{D(z)}{\min\{N \times T, 100\,mm\}} dz \quad \text{(Equation E)}$$

Definition of $CTDI_{free\ air}$ specified in IEC 60601-2-44:2012

Assuming that the dose profile on a straight line perpendicular to the slice plane at the center of rotation without the use of a dose phantom is D(z), $CTDI_{free\ air}$ is defined as the integrated dose, assuming that the length (L) to be integrated for the dose profile is (N × T + 40) mm and the dose profile is centered on z = 0, divided by N × T.
Note that the length (L) to be integrated must be at least 100 mm.

$$CTDI_{free\ air} = \int_{-L/2}^{+L/2} \frac{D(z)}{N \times T} dz \quad \text{(Equation F)}$$

(2) Dose data (For $CTDI_{free\ air}$)

Table shows dose data ($CTDI_{free\ air}$) under typical scan conditions.

<Scan conditions>

Head mode : 120 kV, 300 mA, 1-s scan, scan field S, 4 mm × 4 slice thickness

Body mode : 120 kV, 300 mA, 1-s scan, scan field L, 4 mm × 4 slice thickness

$CTDI_{free\ air}$ under typical scan conditions

	Head mode	Body mode
$CTDI_{free\ air}$	114 (±20%)	100 (±20%)

Unit: mGy

What about those Accompanying Documents?

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NOTE

The definitions of $CTDI_w$ and $CTDI_{free\ air}$ are described below.

[Definition of $CTDI_w$ (Weighted $CTDI_{100}$)]

Based on the definitions of this standard, a 10-cm chamber dosimeter is used to measure the integrated dose for a single conventional scan at center and peripheral positions (0°, 90°, 180°, and 270°, 1 cm below surface) of the polymethylmethacrylate (PMMA) phantom with a diameter of 160 mm (head-equivalent phantom) and the acrylic phantom with a diameter of 320 mm (trunk-equivalent phantom). For each position the $CTDI_{100}$ is calculated using Equation A.

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$$CTDI_w = 1/3 \times CTDI_{100\ (center)} + 2/3 \times CTDI_{100\ (peripheral:\ average\ value)} \quad \text{(Equation D)}$$

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Definition of $CTDI_{free\ air}$ specified in IEC 60601-2-44:2009

Assuming that the dose profile on a straight line perpendicular to the slice plane is D(z), $CTDI_{free\ air}$ is defined as the integrated dose within the range from -50 mm to +50 mm, assuming that the dose profile is centered on z = 0, divided by N × T, or divided by 100 mm, whichever is less.

$$CTDI_{free\ air} = \int_{-50\,mm}^{+50\,mm} \frac{D(z)}{\min\{N \times T, 100\,mm\}} dz \quad \text{(Equation E)}$$

Definition of $CTDI_{free\ air}$ specified in IEC 60601-2-44:2012

Assuming that the dose profile on a straight line perpendicular to the slice plane at the center of rotation without the use of a dose phantom is D(z), $CTDI_{free\ air}$ is defined as the integrated dose, assuming that the length (L) to be integrated for the dose profile is (N × T + 40) mm and the dose profile is centered on z = 0, divided by N × T.
Note that the length (L) to be integrated must be at least 100 mm.

$$CTDI_{free\ air} = \int_{-L/2}^{+L/2} \frac{D(z)}{N \times T} dz \quad \text{(Equation F)}$$

(2) Dose data (For $CTDI_{free\ air}$)

Table shows dose data ($CTDI_{free\ air}$) u

<Scan conditions>

Head mode : 120 kV, 300 mA, 1-s thickness

Body mode : 120 kV, 300 mA, 1-s thickness

$CTDI_{free\ air}$ under typi

	Head
$CTDI_{free\ air}$	114

NOTE

This section describes how to measure CTDI for collimations greater than 40 mm. To measure CTDI for collimations less than or equal to 40 mm, refer to Collimations less than or equal to 40 mm (of Section 1.1)

For any scan technique with collimation greater than 40 mm (hereon referred to as "wide collimation"), the following measurements must be obtained, as indicated by the equation for $CTDI_{100}$ in CTDI.

1. $CTDI_{100,\ 5\ mm}$
2. $CTDI_{free\ air,\ 5\ mm}$
3. $CTDI_{free\ air,\ N \times T\ mm}$

where N x T mm represents the wide collimation for which the user wishes to measure CTDI.

Thus, for wide collimations, CTDI phantom measurements are required only at 5 mm collimation. CTDI free-in-air measurements are performed at both 5 mm collimation and the wide collimation, and then these CTDI free-in-air measurements are used to scale the $CTDI_{100}$ measurement taken at 5 mm to determine $CTDI_{100}$ for the wide collimation. See the equation for $CTDI_{100}$ in CTDI.

The following steps describe how to obtain each of the three CTDI measurements listed above for a given scan technique. In the following steps, N x T indicates the wide collimation for which the user intends to measure and calculate CTDI.

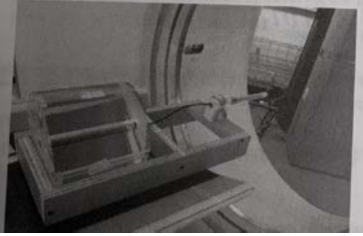
1. Measure $CTDI_{100,5mm}$

   Measure $CTDI_{100}$ using a 5 mm collimation. To do this, follow the instructions in Dose, but substitute your desired scan technique (kV, SFOV, etc.) for those listed in Typical CT Conditions of Operation (21 CFR 1020.33(c)(1). Note, however, that the scan must be axial and 5 mm collimation.

2. Setup for free-in-air measurements

   Remove the phantom from the cradle and set up the system for free-in-air measurements, as shown in Figure 66 on page 132. This will require a mechanism to position the ionization chamber unobstructed into the x-ray beam. Make sure the ionization chamber is centered in x-, y-, and z-axes using the laser alignment lights as a guide. Once the ion chamber is centered, landmark the system.

Figure 66 CTDIfree air measurement setup



3 Measuring and Using $\widehat{D}_{\text{eq,air}}$

$\widehat{D}_{\text{eq,air}}$ defined in AAPM Report 111 as the equilibrium dose-pitch product (free in air)

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$\hat{D}_{eq,air}$ and $\text{CTDI}_{\infty free,air}$ what's the difference?

$$\text{CTDI}_{\infty free,air} = \frac{1}{nT}\int_{-\infty}^{\infty} D_{air}(z)dz$$

$$\hat{D}_{eq,air} = \frac{1}{nT}\int_{-\infty}^{\infty} f_{air}(z')dz' \approx \frac{a}{nT} f_{air}(z=0),$$

D(z) and f_{air}(z') are both dose profiles

IEC only defines CTDI variants for axial acquisitions

$\hat{D}_{eq,air}$ is defined for acquisitions table motion and can be measured with table motion (rather than moving detector)

AAPM REPORT NO. 111

Comprehensive Methodology for the Evaluation of Radiation Dose in X-Ray Computed Tomography

A New Measurement Paradigm Based on a Unified Theory for Axial, Helical, Fan-Beam, and Cone-Beam Scanning With or Without Longitudinal Translation of the Patient Table

Report of AAPM Task Group 111:
The Future of CT Dosimetry

February 2010

Measuring $\widehat{D}_{eq,air}$

Position real time, small dosimeter so passes through isocenter

Set and record conditions of operations

Start dosimeter at least 15 mm outside useable beam

Acquire scan with table motion

$D_{eq,air}$ is total air kerma collected during scan (integral of dose profile)

$\widehat{D}_{eq,air}$ is simply $D_{eq,air}$ multiplied by the pitch used

$\widehat{D}_{eq,air}$ can also be measured at radial locations corresponding to phantom dose bore locations

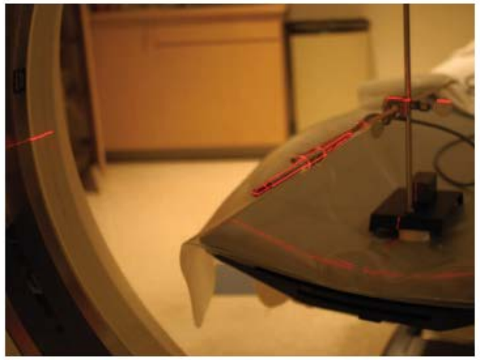
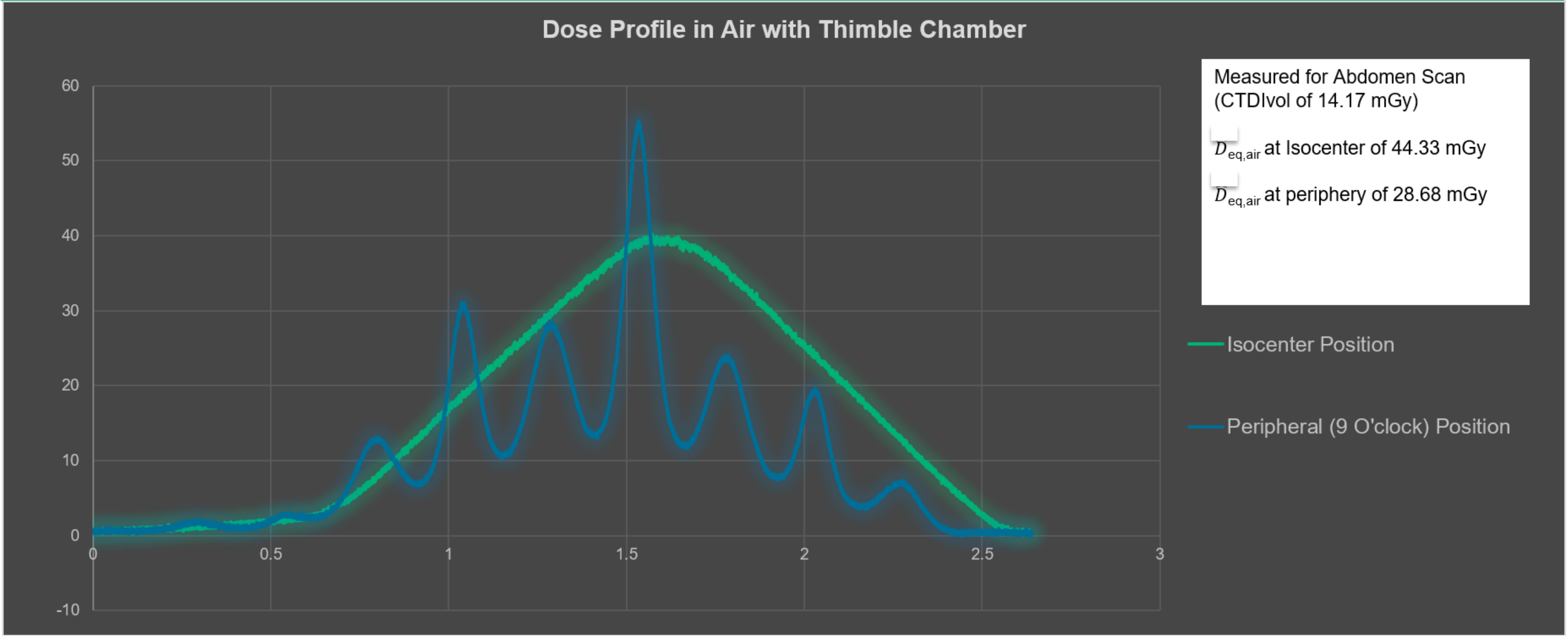


Figure 8. Thimble ionization chamber free-in-air and aligned along the axis of rotation. The chamber is attached to an extender rod from a lab stand, and the assembly is illuminated by the CT system alignment laser lights.

Image from AAPM Report 111

Measuring $\widehat{D}_{eq,air}$

Measuring $\hat{D}_{eq,air}$



Measured for Abdomen Scan (CTDIvol of 14.17 mGy)

$\hat{D}_{eq,air}$ at Isocenter of 44.33 mGy

$\hat{D}_{eq,air}$ at periphery of 28.68 mGy

Using $\widehat{D}_{\text{eq,air}}$

Like $\text{CTDI}_{\infty\text{free,air}}$, $\widehat{D}$eq,air provides a dose proportional to the overbeaming factor

$\widehat{D}_{\text{eq,air}}$ is a simple and quick constancy value to check without needing to move dosimeter

$\widehat{D}_{\text{eq,air}}$ is a near direct measurement of the primary radiation component of the beam (very little scatter)

$\widehat{D}_{\text{eq,air}}$ can be used with initial in phantom measurements of $\widehat{D}_{\text{eq}}$ to establish phantom factors to potentially eliminate need for constancy tests with phantoms

AAPM REPORT NO. 111

Comprehensive Methodology for the Evaluation of Radiation Dose in X-Ray Computed Tomography

A New Measurement Paradigm Based on a Unified Theory for Axial, Helical, Fan-Beam, and Cone-Beam Scanning With or Without Longitudinal Translation of the Patient Table

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February 2010

4 Advantages and Limitations of Dose in Air

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Limitations

Doesn't provide information on scatter contribution to dose

Doesn't approximate patient attenuation or dose deposited

Regulatory and accrediting bodies require phantom measurements

100 mm pencil chamber requires contiguous positioning and can't be used with table translation

Advantages

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Eliminates need for constancy testing with phantoms

Can be performed with axial or helical acquisitions

Comparable results for multiple measurement approaches

Most accompanying documents/technical reference manuals already contain reference values

Direct measurement of variation of penumbra contribution to dose for different detector configurations

Direct measurement of air kerma for conditions of operation

Can be used to fully map dose profile

Thank You!

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