Imaging Educational Course - Calculating Dose (Dose I + II): Estimating Radiation Dose in CT SAMS course

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AAPM Annual Meeting 2011

This Session is "Joint" with Education Track

- Tuesday 10:30 to 12:30
- Room 110

"Patient Dose in CT:
Calculation Patient Specific Dose in CT"

Background

- **NCRP 160 and (Mettler et al, Health Physics, Nov 2008)**

Estimated US averages	1980	2006
Estimated Average Annual Radiation Dose (whole body eff. dose in mSv)	3.6 mSv/yr	6.0 mSv/yr
From Medical Radiation	0.54 mSv/yr 15% of total	3.0 mSv/yr 50% of total
From CT	---	1.5 mSv/yr 25% of total

Background

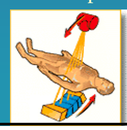
- CT procedures
  - Estimate 18.3 million in 1993
  - Estimate 62.0 million in 2006
  - 10% annual growth
    - Slightly higher since introduction of MDCT (1994-1998)
  - Could be over 100 million per year by now

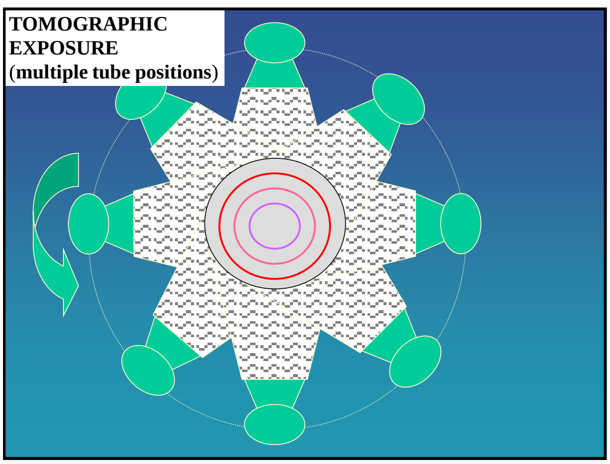
CT –Specific definitions

- CTDI
  - – $CTDI_{100}$
  - – $CTDI_w$- weighted
  - – $CTDI_{vol}$
- Problems with CTDI (100 mm chamber) and proposed solutions:
  - – TG 111
  - – TG 200
  - – IEC(Amend 1, Ed. 3)

CT –Specific definitions (See AAPM report 96)

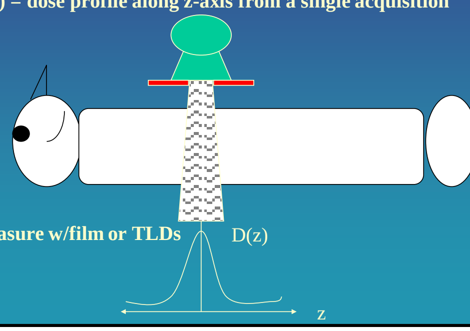
- What is unique about CT?
  - – Geometry and usage
  - – Exposure is at multiple points around patient
  - – Typically thin? (0.5 - 40 mm) beam widths
    - Some beam widths up to 160 mm nominal
  - – Multiple Scans (Series of Scans)





CT Dose Distributions

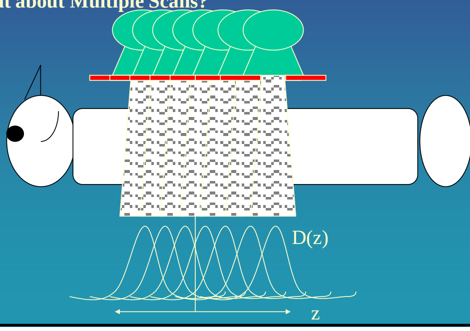
- **D(z) = dose profile along z-axis from a single acquisition**



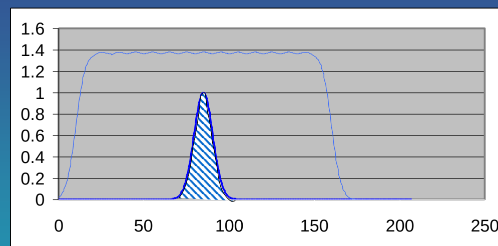
- **Measure w/film or TLDs**

CT Dose Distributions

- **What about Multiple Scans?**

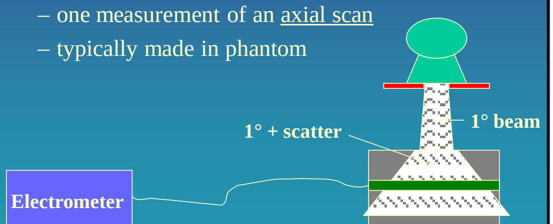


CT Dose Distributions



(CTDI) – defined

- How to get area under single scan dose profile?
  - Using a 100 mm pencil ion chamber
  - one measurement of an axial scan
  - typically made in phantom



(CTDI) – defined

- CTDI Represents
  - **Average dose** along the z direction
  - at a given **point (x,y)** in the scan plane
  - over the **central scan of a series of scans**
  - when the series consists of a **large number of scans**
  - **separated by the slice thickness** (contiguous scanning)

CTDI Phantoms

- Body (32 cm diam), Head (16 cm diam)
- Holes in center and at 1 cm below surface

$CTDI_{100}$

- Measurement is made w/100 mm chamber:
- $CTDI_{100} = \mathbf{(1/NT)} \int_{-5cm}^{5cm} \mathbf{D(z)\,dz}$

  $\mathbf{= (f*C*E*L)/(NT)}$

  f = conversion factor from exposure to dose in air, use 0.87 rad/R

  C = calibration factor for electrometer (typical= 1.0, 2.0 for some)

  E = measured value of exposure in R

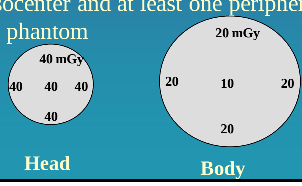
  L = active length of pencil ion chamber (typical= 100 mm)

  N = *actual* number of data channels used during scan

  T = nominal width of one channel

$CTDI_{100}$

- $CTDI_{100}$ Measurements are done:
  - In Both Head and Body Phantoms
  - Using ONLY AXIAL scan techniques
    (CTDI = Area under the single scan dose profile)
  - At isocenter and at least one peripheral position in each phantom



$CTDI_w$

- $CTDI_w$ is a **weighted average** of center and peripheral $CTDI_{100}$ to arrive at a single descriptor
- $\mathbf{CTDI_w = (1/3)CTDI_{100,center} + (2/3)CTDI_{100,peripheral}}$

CTDI $_{vol}$

- Calculated, not measured directly
- Based on $CTDI_w$
- Measured from a single axial acquisition but calculated with a pitch value.
  - Think of this as the pitch that you *would have used* if you were performing a helical scan.
- (NOTE: CTDI not defined for helical acquisition)

CTDI $_{vol}$

- **$CTDI_{vol} = CTDI_w/Pitch$**

DLP – defined

- Dose Length Product is:
  - $CTDI_{vol}$* length of scan (in mGy*cm)
- Found in most "Dose Reports"
- Includes any overscan (extra scanning for helical scans)

Effective Dose

- Most CT scans are partial irradiations of body
- How to compare the effects of different exposures to radiosensitive organs?
- Effective Dose takes into account
  - Absorbed Dose to specific organs
  - Radiosensitivity of each organ
- NOTE: Eff. Dose is NOT intended for dose to an individual; intended for populations

Effective Dose

- $E = \Sigma_T(w_T{*}w_R{*}D_{T,R})$
- w_T= tissue weighting factor (next page)
- w_R= radiation weighting coefficient (1 for photons)
- $D_{T,R}$= average absorbed dose to tissue T
- Units are: SI - Sieverts (Sv); English -rem
- 1 rem = 10 mSv; 1 Sv = 100 rem

Effective Dose

Tissue	ICRP 60 Tissue weights (w_T)	ICRP 103 weights
Gonads	0.20	0.08
Red Bone Marrow	0.12	0.12
Colon	0.12	0.12
Lung	0.12	0.12
Stomach	0.12	0.12
Bladder	0.05	0.04
Breast	0.05	0.12
Liver	0.05	0.04
Esophagus	0.05	0.04
Thyroid	0.05	0.04
Skin	0.01	0.01
Bone Surface	0.01	0.01
Brain	(part of remainder)	0.01
Salivary Glands	(part of remainder)	0.01
Remainder	0.05	0.12

Estimating Effective Dose

- To estimate effective dose accurately, you would need to ESTIMATE DOSE TO EACH RADIOSENSITIVE ORGAN !!!

$(E = \Sigma_T\,(w_T{*}D_{\,T,R}))$; $w_R = 1$

- Difficult to do accurately

Estimating Effective Dose

- Computer Software
  - Based on Monte Carlo simulations
  - ImPACT calculator
  - Impactdose calculator
- K Factors (Jessen) based on DLP
  - E = DLP * k (k in mSv/(mGy*cm))
  - k= .0023 for head exams , k =0.015 for abdomen
  - See AAPM report 96 for all k factors

What is a typical reference?

- 3 mSv per year background radiation
  - Natural sources such as radon and cosmic rays
- Mettler et al now estimate 3 mSv per year from medical procedures as well
- 6 mSv **total** average annual exposure to US Population

Allowable Dose levels

- What is allowed for patient?
  - In US, No limit….yet.
  - Some recommended limits.
  - Whatever is diagnostic for that patient
- What is allowed for workers?
  - Technologists, radiologists 50 mSv/year whole body dose

ACR CT Dose Reference Values

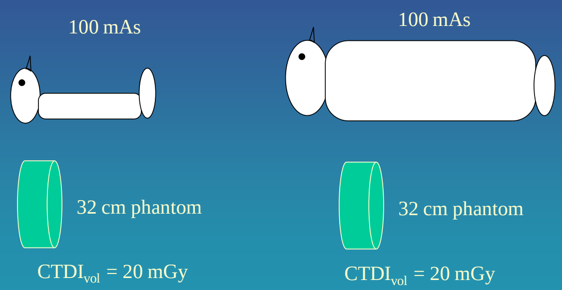
- $CTDI_{vol}$
- Two levels:
  - Reference level and Pass/Fail level
  - If Reference Level is exceeded, then sites will be asked to consider some dose reduction
  - If Exceed Pass/Fail level, then Fail

Exam	Ref Level	Pass/Fail Level
Adult Head	75 mGy	80 mGy
Adult Abdomen	25 mGy	30 mGy
Pediatric (5y/o) Abd	20 mGy	25 mGy
Pediatric Head	45 mGy	

$CTDI_{vol}$ and DLP

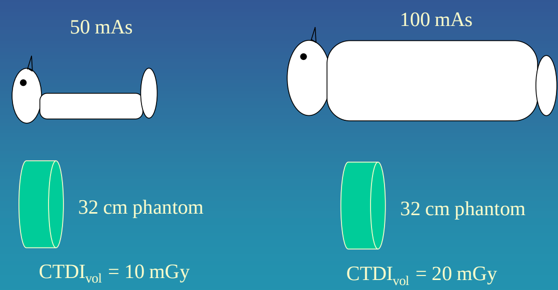
- $CTDI_{vol}$ reported on the scanner
  - (though not required in US)
- Is Dose to one of two phantoms
  - (16 or 32 cm diameter)
- Is NOT dose to a specific patient
- Does not tell you whether scan was done "correctly" or "Alara" without other information (such as body region or patient size)
- MAY be used as an index to patient dose with some additional information (later)
- See McCollough et al "CT Dose Index and Patient Dose :They Are Not the Same Thing. Radiology 2011; 259:311–316

Scenario 1: **No adjustment** in technical factors for patient size



The CTDI$_{vol}$ (dose to phantom) for these two would be the same

Scenario 2: **Adjustment** in technical factors for patient size



The CTDI$_{vol}$ (dose to phantom) indicates larger patient received 2X dose

Did Patient Dose Really Increase ?

For same tech. factors, smaller patient absorbs more dose

- Scenario 1:
  - CTDI is same but smaller patient’s dose is higher
- Scenario 2:
  - CTDI is smaller for smaller patient, but patient dose is closer to equal for both

CTDI$_{vol}$

- Not patient Dose
- By itself can be misleading
- CTDI$_{vol}$ should be recorded with:
  - Description of phantom size (clarify 16 or 32 cm diameter)
  - Description of patient size (lat. Width, perimeter, height/weight, BMI)
  - Description of anatomic region

CTDI$_{vol}$ can be correctly interpreted as:

0%	1. Scanner output measured in phantoms
0%	2. Patient Dose from CT exams
0%	3. Scanner output adjusted for patient size
0%	4. Effective Dose from CT exams
0%	5. Patient Dose to radiosensitive organs

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Correct Answer

- 1 – Scanner output as measured in either one of two standardized phantoms
- (AAPM Report 96)

The Legal Limit on Patient Radiation Dose in the US is:

0%	1. 1.5 mSv
0%	2. 3 mSv
0%	3. 6 mSv
0%	4. 50 mSv
0%	5. As much as needed to obtain the necessary Diagnosis

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Correct Answer

- 5 – There is no legal limit for radiation dose from a CT exam in the United States
- (Reference Slide 25 and Code of Federal Regulations; 10 CFR 20 addresses occupational exposure and exposure to the public, but there is no CFR that addresses patient dose)

If Tube Current Modulation or Size Adjusted Technical Factors are used for Patient Scans, then which of the following is true:

0%	1. $CTDI_{vol}$ accurately reflects patient dose
0%	2. $CTDI_{vol}$ reflects change in scanner output due to patient size
0%	3. $CTDI_{vol}$ is always dose to 32 cm phantom
0%	4. $CTDI_{vol}$ can indicate whether scan was performed correctly or "ALARA"
0%	5. $CTDI_{vol}$ accurately reflects dose for scans with no table motion (eg. perfusion)

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Correct Answer

- 2 – $CTDI_{vol}$ reflects change in scanner output due to patient size
- (McCollough et al. CT Dose Index and Patient Dose :They Are Not the Same Thing. Radiology 2011; 259:311–316)

How to Calculate mSv?

- One approach (actually an approximation):

  E= DLP * k

  Where

  E = Effective Dose in mSv

  DLP = Dose Length Product in mGy*cm

  k = conversion coefficient in mSv/mGy*cm
- Formula is based on a curve fit for several scanners (circa 1990) between E and DLP
- k values are based on ICRP 60 organ weights

DLP Approach to Calculate mSv

- DLP approach
  - DLP comes from scanner
    - CTDIvol x length of scan
  - k's are known
    - (e.g. .0021 for adult head, .015 for abdomen, etc.)
    - Different k factors for peds
- Can be calculated for each patient….right?

DLP Approach to Calculate mSv

- Any assumptions here?
  - Standard Sized (70 kg) Patient for adults
  - Based on scanner reported CTDIvol
    - Dose to homogenous acrylic cylinder
    - (NOTE: for pediatric, some scanners currently report dose to 16 cm , others to 32 cm phantom)

DLP Approach to Calculate mSv

- A few examples

Patient Protocol Page from Siemens Sensation 64

UCLA

[redacted] M, 3Y

Sensation 16
CT 2006G

16-Oct-2009 13:44

Ward:
Physician:
Operator:

Total mAs 3048 Total DLP 122

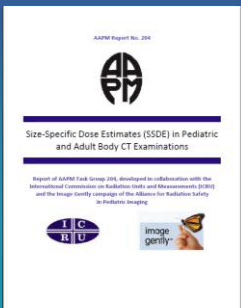
	Scan	kV	mAs / ref.	CTDIvol	DLP	TI	cSL
Patient Position F-SP							
Chest/ab Topo	1	80				5.3	1.0
Chest	2	80	77 / 55	1.71	39	0.5	1.5
PreMonitoring	3	80	25	1.47	1	0.5	1.5
I.V. Bolus							
Monitoring	4	80	25	4.40	4	0.5	1.5
Arterial	7	80	78 / 55	1.73	38	0.5	1.5
Venous	8	80	73 / 55	1.90	40	0.5	0.8

E = (39*.022) + (83*.025) = 2.9 mSv

Limitations to CTDI

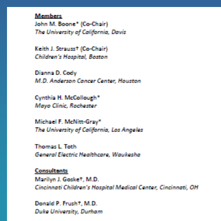
- Is CTDIvol Organ Dose?

AAPM TG 204


AAPM Report No. 204

Size-Specific Dose Estimates (SSDE) in Pediatric and Adult Body CT Examinations

Report of AAPM Task Group 204, developed in collaboration with the International Commission on Radiation Units and Measurements (ICRU) and the Image Gently campaign of the Alliance for Radiation Safety in Pediatric Imaging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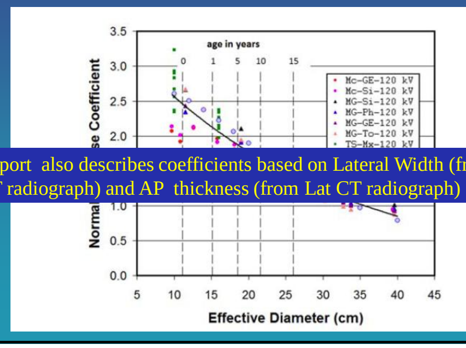
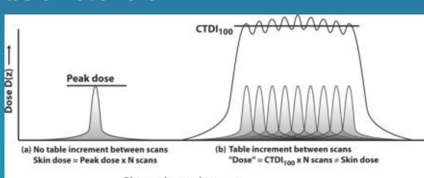
AAPM TG 204



Report also describes coefficients based on Lateral Width (from PA CT radiograph) and AP thickness (from Lat CT radiograph)

Does $CTDI_{vol}$ Indicate Peak Dose?

- $CTDI_{vol}$ is a weighted average of measurements made at periphery and center of cylindrical phantom
- Defined to reflect dose from a series of scans performed w/table movement



Does $CTDI_{vol}$ Indicate Peak Dose?

- $CTDI_{vol}$ is a weighted average of measurements made at periphery and center of cylindrical phantom
- Defined to reflect dose from a series of scans performed w/table movement
- Is not patient dose (not even skin dose)
- Typically OVERestimates skin dose in cases where scan is performed with no table movement (e.g. perfusion scans)

- BTW, AAPM TG 111 dose metric will do a better job here (specifically defines a measure with no table motion);
  - But still not patient dose (Dose to phantom)

CA Senate Bill 1237

(http://info.sen.ca.gov/pub/09-10/bill/sen/sb_1201-1250/sb_1237_bill_20100929_chaptered.html)

- Three sections:
- Section 1- Recording dose from CT by 7-1-12
  - CTDIvol, DLP
  - Or "The dose unit as recommended by the AAPM"
- Section 2- Accreditation by 7-1-13
- Section 3 Reporting "Events" to Dept. Pub Health (and patient and physician).

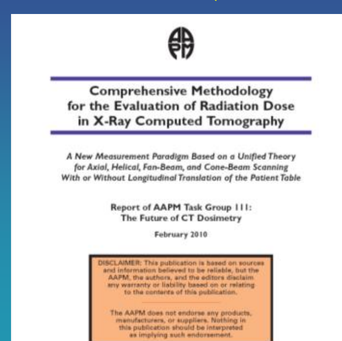
CA Senate Bill 1237 Section 3

- Section Requires a facility that uses Computed Tomography (CT) to ***report to DPH any scan that is repeated, or a scan of the wrong body part(s)***
  - An Effective Dose (E.D.) that exceeds 0.05 Sv (5 rem)
  - A dose in excess of 0.5 Sv (50 rem) to any organ or tissue
  - Shallow dose to the skin of 0.5 Sv (50 rem)
- ***UNLESS***:
  - Repeat due to movement or interference of patient.
  - Ordered by a physician

S.B. 1237 Section 3 (continued)

- Requires facilities that use CT to report to DPH:
  - ***Unanticipated*** permanent damage to organ, hair-loss, or erythema.
  - **Dose to fetus that is greater than 50 mSv (5 rem) *for known pregnancies* "*unless the dose to the embryo or fetus was specifically approved, in advance, by a qualified physician*"**
  - DPH FAQ http://www.cdph.ca.gov/certlic/radquip/Documents/RHB-SB1237-FAQ.PDF

AAPM TG 111
CT Dose Measurement (Small Chamber)



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

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Coming Attractions – TG 111/200

- Basic ideas
  - CTDI underestimates dose from contiguous scans (e.g. helical) by not capturing scatter tails.
    - Some scanners have beam widths larger than 100mm now, so not even all primary is captured.
  - CTDI overestimates dose from axial scan with no table motion because scatter tails included
- Replace CTDI w/ small chamber measurement
- Measure Deq w/long phantom and long scan
  - capture all scatter tails

Coming Attractions – TG 111/200

- Helical scan or axial scan, however scan is performed clinically
  - Perform measurement w/table motion or no motion
- Three phantom lengths or one phantom length
  - Full characterization of Deq
  - Or a reference measurement for QA
- TG 111 report on AAPM website
- TG 200 working out phantom and protocol

Other Coming Attractions
Proposed IEC Standard (Amend 1, Ed. 3)

- Modify CTDI measurement, based on beam width (NT)
  - NT≤ 40 mm, conventional CTDI w/single axial scan

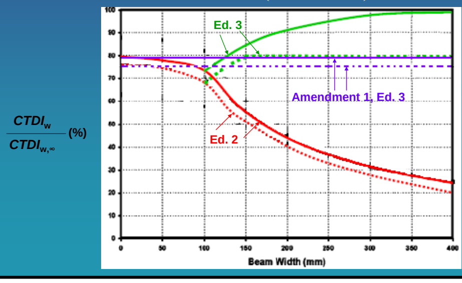
$$CTDI_{100}(N \times T) = \frac{1}{N \times T}\int_{-50\,mm}^{+50\,mm} D(z)dz$$

  - NT > 40 mm, first
    - conventional CTDI w/single axial scan at ref. NT (≤ 40 mm)
    - Then scale by ratio of measurements made free-in-air at desired NT and reference NT

$$CTDI_{100}(N \times T) = \frac{1}{(N_{ref} \times T_{ref})} \times \left(\int_{-50\,mm}^{+50\,mm} D_{ref}(z)dz\right) \times \left(\frac{CTDI_{free-in-air}(N \times T)}{CTDI_{free-in-air}(N_{ref} \times T_{ref})}\right)$$

Coming Attractions

- Proposed IEC Standard (Amend 1. Ed. 3) provides consistent offset from ideal (CTDIw,∞)



$CTDI_{vol}$ can be adjusted for patient size using:

0%	1. Scanner output measured in anthropomorphic phantoms
0%	2. Factors described in TG 204 Report
0%	3. Patient Age factors
0%	4. Head Size
0%	5. Scanner make and manufacturer

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Correct Answer

- 2 – Factors described in TG 204
- These factors include:
  - Water equivalent diameter
  - AP thickness (from scan radiograph)
  - Lateral Diameter (from scan radiograph)
  - Sum of AP thickness and Lateral Diameter if two scan radiographs are performed
- (AAPM TG Report 204)

TG 111 and TG 200 Seek to :

0%	1. Adjust CTDI for Tube Current Modulation
0%	2. Adjust CTDI for patient size
0%	3. Replace CTDI with measurements made from either helical, axial or no table movement scans
0%	4. Adjust CTDI for wider collimations
0%	5. Balance Image Quality and Radiation Dose

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Correct Answer

- 3 – Replace CTDI with measurements made from either helical, axial or no table movement scans
- (Reference: AAPM TG 111 report which describes theory of D_{eq} (Equilibrium dose) and how to deal with wider beam widths and single rotation scans. TG 200 has not issued a report, but is discussing desired phantom)

As an Interim Measure, the IEC has described:

0%
0%
0%
0%
0%

1. An early version of TG 111's D_{eq}
2. A version of $CTDI_{vol}$ that reflects change in scanner output due to patient size
3. A version of $CTDI_{vol}$ that reflects changes due to tube current modulation
4. Modifications to $CTDI_{vol}$ that account for both narrow and wide beam widths.
5. A version of $CTDI_{vol}$ that reflects effects of radiosensitivity of children

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Correct Answer

- 4 – Modifications to $CTDI_{vol}$ that account for both narrow and wide beam widths
- (IEC Standard draft (Amend 1. Ed. 3); this draft standard defines conventional CTDI for beam widths <= 40 mm.
- For beam widths > 40 mm, this standard describes adjustments to CTDI made at a reference collimation (~20mm) and which uses ratio of $CTDI_{air}$ of desired Nominal beam width to reference beam width)

Summary of CTDI

- Summary of CTDIvol
  - Is not patient dose
  - Is dose to a reference sized phantom (reference can vary from Peds to Adult or it might be same)
  - Underestimates dose to small patients
  - Overestimates dose to very large patients
  - Is not skin dose (overestimates skin dose for perfusion scans)
  - TG 111 measurements (small chamber) will do a better job when that is standardized

Summary

- CT Dose
- CTDI and DLP
- Organ dose and Effective Dose
- Future Methods/Challenges
- "Patient Dose in CT:
  Calculation Patient Specific Dose in CT"
  Tuesday 10:30 to 12:30, Room 110