TomoTopics – Focus on the Clinical Plane

CT SSDE – Body, Head, and Beyond

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Michael McNitt-Gray, PhD, DABR, FAAPM, FACR
Professor, Department of Radiology
Director, Physics and Biology in Medicine Graduate Program
David Geffen School of Medicine at UCLA
mmcnittgray@mednet.ucla.edu
Disclosures

• UCLA Department of Radiology has a Master Research Agreement (MRA) with Siemens Healthineers
• I currently receive grant support from MRA with Siemens Healthineers
• I am a Member of the Advisory Board, Hura Imaging, Inc.
CT Dosimetry - Background

• Current clinical CT dosimetry metrics typically used are CTDI_{vol} and DLP.
• These have substantial limitations, which motivated the development of Size Specific Dose Estimates (SSDEs) that account for patient size.

• This presentation will describe several key elements related to SSDE including:
  (a) Water Equivalent Diameter, as described in AAPM Report 220
  (b) SSDE for body originally described in AAPM Report 204 and updated with AAPM report 220 and
  (c) SSDE for head described in AAPM Report 293.

• This presentation will focus on how these metrics were developed, how they are expected to be calculated and how they might be used clinically in the future.
CT Dosimetry

Learning Objectives

• Review current radiation dose index metrics used in CT Dosimetry and their limitations

• Explain how the Size Specific Dose Estimates (SSDEs) for Body and Head overcome some of these limitations and how they can be used in clinical practice
CT – Specific definitions

- What is unique about CT?
  - Geometry and usage
  - Exposure is at multiple points around patient
  - Typically thin-ish (1 - 160 mm) beam widths
  - Multiple Scans (Series of Scans)
RADIOGRAPHIC EXPOSURE
(single tube position)

Dose Gradient

Entrance Skin Exposure (ESE)

Exit Skin Exposure
TOMOGRAPHIC EXPOSURE
(multiple tube positions)
TOMOGRAPHIC EXPOSURE
(multiple tube positions)

32 cm Diameter (Body) Acrylic Phantom
TOMOGRAPHIC EXPOSURE
(multiple tube positions)

16 cm Diameter (Head) Acrylic Phantom
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

• What about Multiple Scans?
  • They can overlap and create higher dose profiles
CT Dose Distributions
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$\text{CT Dose Distributions} = \text{total from central + adjacent + 2 slices away + 3 slices away, etc.}$
The average dose in central slice is the sum of contributions from all slices to that small width; if one rearranges the contributions from each slice, they are just different portions of the single scan dose profile.
CT Dose Distributions

To sum their contributions, just take the area under the curve of that single slice dose profile.
(CTDI) – defined

- How to get area under single scan dose profile?
  - Using a pencil ion chamber
  - one measurement of an axial scan (no table motion)
  - typically made in phantom
(CTDI) – defined

Figure 3 from Bauhs, RadioGraphics, 2008
(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\textsubscript{100}

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

\[ = \frac{(f\times C \times E \times L)}{(NT)} \]

- \( f \) = conversion factor from exposure to dose in air, use 0.87 rad/R
- \( C \) = calibration factor for electrometer (typical= 1.0 or close to this)
- \( E \) = measured value of exposure in R
- \( L \) = active length of pencil ion chamber (typical= 100 mm)
- \( N \) = \textit{actual} number of data channels used during one axial scan
- \( T \) = nominal slice width of one data channel
- \( NT \) = nominal total beam collimation width (e.g. 32 x 0.6 mm)
$\text{CTDI}_{100}$

- $\text{CTDI}_{100}$ 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
$\text{CTDI}_w$

- $\text{CTDI}_w$ is a weighted average of center and peripheral $\text{CTDI}_{100}$ to arrive at a single descriptor

- $\text{CTDI}_w = \frac{1}{3} \text{CTDI}_{100, \text{center}} + \frac{2}{3} \text{CTDI}_{100, \text{peripheral}}$
CTDI$_{\text{vol}}$ – accounts for table motion

- Based on CTDI$_{w}$
- Hence measured from an axial acquisition; EVEN THOUGH a pitch value is used.
  - Think of this as the pitch that you would have used if you were performing a helical scan.
CTDI\textsubscript{vol} - EXAM-related performance

- Exam parameters such as thickness, spacing between slices (axial) or table speed (helical)
- CTDI\textsubscript{vol} = CTDI\textsubscript{w} * NT/I
- where 
  \( N \) = number of data channels used,
  \( T \) = thickness of each data channel
  \( l \) = spacing or tablefeed/rotation for helical

\textbf{Note:} NT = total collimated width of beam
Also pitch = \( l/NT \), so

\[
\text{CTDI}_{vol} = \frac{\text{CTDI}_{w}}{\text{pitch}}
\]
Dose Length Product (DLP) – defined

- Dose Length Product is:
  - $C_{TID\text{vol}} \times \text{length of scan (in mGy}\cdot\text{cm})$
CT Dosimetry – $\text{CTDI}_{\text{vol}}$ and DLP

- $\text{CTDI}_{\text{vol}}$ and DLP are reported on all scanners
- Used for Dose Notifications and Dose Alerts (XR-29)
- Used for ACR accreditation (and ACR’s Dose Index Registry)
CT Dosimetry: Are $\text{CTDI}_{\text{vol}}$ and DLP enough?

- What do $\text{CTDI}_{\text{vol}}$ and DLP tell us?
- And what do they **not** tell us?

- Do they tell us about scanner output? (Yes)
- Can they be used to tell us about CT system performance? (Yes)
- Can they be used for acceptance testing? (Yes) Ongoing QC? (Yes)
- Can they be used for ACR accreditation (and ACR’s Dose Index Registry)? (Yes)
- Can they tell us about Patient Dose? ...well.....
Can they tell us about Patient Dose? ...well.....

The CTDI values are included in ... a screen-captured ‘patient dose report’... which reinforces the incorrect belief that CTDI is a measure of patient dose.”

“The CTDI\textsubscript{vol} is a standardized measure of the radiation output of a CT system...”

McCollough et al, Radiology, 2011
CT Dosimetry: Are CTDI$_{vol}$ and DLP enough?

• Can they tell us about the effects of Patient Size? Like for Peds Patients? (well...kind of...)
  • If a scanner is adjusting for patient size, we can see lower CTDI$_{vol}$ values for smaller patients and higher CTDI$_{vol}$ values for larger patients.

• However, we found that different scanner manufacturers were using different schemes for reporting CTDI$_{vol}$ values:
  • One manufacturer reports CTDI$_{vol}$ for 32 cm for all body scans regardless of patient size (even for pediatrics and neonates)
  • Another manufacturer reports CTDI$_{vol}$ for 16 cm phantom for small body sizes and used 32 cm phantom for larger body sizes (Depends on Scan Field of View).

• So if a peds patient underwent a scan on a CT from manufacturer A for one scan and then had a scan on a CT from manufacturer B, it could be difficult to compare relative dose levels.
Size Specific Dose Estimates (SSDE) from AAPM Report 204

https://www.aapm.org/pubs/reports/rpt_204.pdf (it’s free!!)
Size Specific Dose Estimates (SSDE) from AAPM Report 204

“The dose received by a patient from a CT scan is dependent on both the patient size and scanner radiation output. \(\text{CTDI}_{\text{vol}}\) provides information regarding only the scanner output. “

“This task group was charged with developing conversion factors that can be applied to the displayed \(\text{CTDI}_{\text{vol}}\) dose index to allow practitioners to be able to estimate patient dose. These factors take into account patient size, and hence are especially important for pediatric CT or when small adults are scanned”

(BTW, “…Other differences between the current scanner radiation output indicates and patient dose estimates due to the use of “short” phantoms …are not addressed by this task group”…in other words, this does not address issues of “approach to equilibrium” or TG 111 or TG 200 related issues).

https://www.aapm.org/pubs/reports/rpt_204.pdf (it’s free!!)
Size Specific Dose Estimates (SSDE) from AAPM Report 204

- Methodology
  - 2 Groups did measurements on various sized phantoms
  - 2 Groups performed simulations

- John Boone overlaid the results (Amazing consistency!)

https://www.aapm.org/pubs/reports/rpt_204.pdf (it’s free!!)
Size Specific Dose Estimates (SSDE) from AAPM Report 204

- Our group’s contribution (Adam Turner’s paper)
  - Organ Dose normalized by CTDI$_{vol}$ vs. Patient Size (we used perimeter)

Figure 2 from Turner et al, Medical Physics, 38(2), 2011.
Size Specific Dose Estimates (SSDE) from AAPM Report 204

Size Metric for Report 204 - Effective Diameter (AP and Lateral dimensions)

Figure 2. The anterior posterior (AP) and lateral dimension, along with effective diameter are illustrated in this figure. The lateral dimension can be determined from a PA or AP CT radiograph, and the AP dimension can be determined by a lateral CT radiograph. The effective diameter corresponds to a circle having an area equal to that of the patient’s cross section on a CT image. Some investigators have also used patient perimeter (circumference) as a metric of patient size.

Figure 2 of AAPM Report 204 (page 3)

https://www.aapm.org/pubs/reports/rpt_204.pdf (it’s free!!)
Size Specific Dose Estimates (SSDE) from AAPM Report 204

- "f" factors
  - Normalized Dose Coefficient vs. patient size (effective diameter)

Figure 4 of AAPM Report 204 (page 8)
Conversion factors for 32 cm phantom

Figure 6 of AAPM Report 204 (page 12)
Conversion factors for 16 cm phantom
Size Specific Dose Estimates (SSDE) from AAPM Report 204

- Calculating SSDE

- \[ SSDE = f_{\text{sie}}^{32X} \times CTDI_{\text{vol}}^{32} \] \hspace{1cm} \text{equation 8a}

  for 32 cm diameter CTDI phantom

- \[ SSDE = f_{\text{sie}}^{16X} \times CTDI_{\text{vol}}^{16} \] \hspace{1cm} \text{equation 8b}

  for 16 cm diameter CTDI phantom

In each case, the superscript X refers to the S (sum of Lat+AP), L(Lat only), A (AP only) and D (effective diameter) and identifies which Table is to be used for conversion factors.
Table 1 (A, B, C, D) for 32 cm phantom

Table 2 (A, B, C, D) for 16 cm phantom
Size Specific Dose Estimates (SSDE) from AAPM Report 204

• Appendix A (formulae to represent data in figures and tables)

  • \[ y = a \times e^{-bx} \] \(x = \text{patient size}\) \hspace{1cm} \text{equation A-1}

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Size Specific Dose Estimates (SSDE) from AAPM Report 204

• Summary of AAPM Report 204 in one line:

$$SSDE = (a \times e^{-bx}) \times CTDI_{vol}$$

• Scanner reports CTDI_{vol}
• a and b are known (depends on phantom)
• Estimate patient size
Patient Size (v2) – Water Equivalent Diameter

https://www.aapm.org/pubs/reports/rpt_220.pdf (it’s free!!)
Water Equivalent Diameter - Motivation

• For the task of calculating SSDE, geometric size was used as a surrogate for a patient’s x-ray attenuation.

• However, x-ray attenuation is the fundamental physical parameter affecting the absorption of x-rays and is thus more relevant than geometric patient size in determining patient dose.

• For example, the thorax and abdomen could have the same external physical dimensions, but have different composition and hence different attenuation (and absorption) properties.
Water Equivalent Diameter - Motivation

- So, this thorax and abdomen have approximately the same area and effective diameter
- But they have different attenuation properties (due to air in lung)

https://www.aapm.org/pubs/reports/rpt_220.pdf (it’s free!!)
Water Equivalent Diameter - Motivation

• The charge of AAPM Task Group 220 was to develop a ...metric for automatically estimating patient size in CT that would account for patient attenuation and allow routine determination of SSDE for all patients, with little or no user intervention.

• TG had a specific goal of developing a practical, standardized approach to estimating patient size that could be implemented by CT scanner manufacturers and others using CT localizer radiographs, axial CT images, or other data derived from the scanning process (e.g., projection data).
Water Equivalent Diameter - Motivation

• While CT operators can measure a patient’s AP or lateral width, they currently have no practical way to measure attenuation. Both a CT localizer radiograph and CT projection data are measurements of the integrated x-ray attenuation along a ray path, and a CT image is a cross-sectional map of the linear attenuation coefficients of the materials in the image.

• Therefore, the CT localizer radiograph, the CT projection data, and the CT image all contain information that can be used to estimate patient attenuation.

https://www.aapm.org/pubs/reports/rpt_220.pdf (it’s free!!)
Water Equivalent Diameter

- **Water Equivalent Diameter** ($D_w$)
- Express the x-ray attenuation of a patient in terms of a water cylinder having the same x-ray absorption.
- The area and diameter of such a cylinder of water are referred to as the water equivalent area ($A_w$) and water equivalent diameter ($D_w$), respectively.
- This can be done:
  - From CT image data (after scan is performed)
  - From CT localizer radiograph (scout, topogram, planning scan) – after localizer is performed, but before CT scan is performed.

[https://www.aapm.org/pubs/reports/rpt_220.pdf](https://www.aapm.org/pubs/reports/rpt_220.pdf) (it’s free!!)
Water Equivalent Diameter ($D_w$) From CT image

- $A_w = \frac{1}{1000} \overline{CT(x,y)_{ROI}} \times A_{ROI} + A_{ROI}$
  
  - Where $\overline{CT(x,y)_{ROI}}$ is the mean CT number in the ROI (Region of Interest) and $A_{ROI}$ is the total Area of that ROI (which encompasses the body).

- $D_w = 2\sqrt{\frac{A_w}{\pi}} = 2\sqrt{\left[\frac{1}{1000} \overline{CT(x,y)_{ROI}} + 1\right]\frac{A_{ROI}}{\pi}}$

Equation 3d (Page 8)

Equation 4b (Page 8)
Water Equivalent Diameter ($D_w$) From CT Localizer Radiograph (Scout, Topogram, Pilot)

- $A_w = \sum L_w \times S$  
  - Where $L_w =$ the water equivalent length and $S =$ detector spacing at isocenter and the sum is taken over a horizontal line of a CT localizer radiograph

- Note: Siemens estimates the (water equivalent) attenuation for both AP and Lat directions and stores it in a private field w/in DICOM header of topogram.

- From McMillan et al, Medical Physics, 2017
Use of Water Equivalent Diameter for Calculating Patient Size and SSDE in CT AAPM Report 220

- Summary of AAPM Report 220:
  - Water Equivalent Diameter accounts for patient attenuation in patient size metric
  - Can be estimated from either CT Image Data or CT localizer radiograph
  - Can be used to estimate SSDE
  - “No additional corrections are required when substituting $D_w$ for effective diameter” from AAPM report 204.
  - Can use the same equations and figures shown previously

$$SSDE = (a \times e^{-b\lambda}) \times CTDI_{vol}$$

- Scanner reports CTDI_{vol}
- $a$ and $b$ are known (depends on phantom)
- Patient size ($x$) uses $D_w$
Size Specific Dose Estimate (SSDE) for Head CT - AAPM Report 293

https://www.aapm.org/pubs/reports/RPT_293.pdf (it's free!!)
SSDE for Head - Motivation

• The size-dependent conversion factors provided in Report 204 were developed specifically for CT imaging of the abd/pel
  • although use in thorax was acceptable since the errors were expected to be below 20%.

• Purpose of Report 293 was to extend the development of SSDE concepts to the head

• Particular interest was variation of head size and scan length across age (and specifically for pediatric patients)

• TG sought to develop conversion factors for 1 y/o to adult (though variation is small after 7 y/o)
SSDE for Head - Motivation

• SSDE represents the *absorbed dose* to the center section along the z-axis of a typical clinical CT scan.

• For head scans, the absorbed dose in this thin center section includes dose from scattered radiation from the tissues above (superior to) and below (inferior to) the center section.

• It is recognized that the dose to the center section (along z) of the CT scan represents a *near-maximum absorbed dose* to the tissues within the scan volume and, consequently, the *average absorbed dose to the entire scan volume will be lower in virtually all cases*.

• The principal outcome of this report is a set of CTDI$_{vol,16}$-to-SSDE conversion factors for CT examinations of the head as a function of water-equivalent diameter ($D_w$) and will use same form of conversion equation.
SSDE for Head - Methods

- Similar to TG 204
- 2 groups made measurements
- 2 groups performed Monte Carlo simulations
- Compiled results of Dose in center of scan volume vs. $D_w$

Figure 2 from page 7 – different sized tissue equivalent head phantoms

Figure 5 from page 11 – CT image and voxelized patient model for simulations
SSDE for Head - Results

Figure 11 from page 16 – Conversion factors (for various kV and overall)

Figure 12 from page 18 – Comparison of conversion factors between 204 and 293
Report 293 SSDE for Head - Summary

• SSDE for Head that is consistent with SSDE for Body (but different coefficients)

\[ \text{SSDE} = (a \times e^{-bx}) \times \text{CTDI}_{\text{vol}} \]

- Scanner reported \( \text{CTDI}_{\text{vol}} \)
- \( a \) and \( b \) are known (for head, limited to 16 cm phantom)
- Patient size (x) uses \( D_w \)

• Even for the same \( D_w \), the spatial distribution of absorbed dose deposition to the brain is considerably different than the absorbed dose deposition to the body

• Primarily due to the fact that the head is encased in a shell of relatively dense bone.

• Comparing the \( f_{16} \) conversion factors between the body (AAPM Report 204, \( f_{B16} \)) and those of the head (this report, \( f_{H16} \)), it is seen
  • the shapes of the curves are quite similar
  • SSDE conversion factors for head CT are consistently lower
  • likely due to the attenuation of the skull and the more aggressive beam shaping (i.e., bow tie) filters used in head CT scans
Where is SSDE today?

• Calculated on ACR Phantom Submissions (Just Abdomen for now)
  • Automatically from CTDIvol values
  • Assumes a patient size for adult and pediatrics (5 y/o)
• Some Dose Management software systems report this
  • Though not always clear how this is done
• There is an IEC Standard (PT 62985 Ed.1.0) that has been approved ("published")
  • Hope is that manufacturers will include reporting SSDE in future software releases (DICOM RDSR?)
• ACR DIR also calculates SSDE but only for body
Clinical Use of SSDE

- SSDE overcomes some of the limitations of CTDI$_{vol}$ by accounting for patient size
- Provides an estimate of patient dose (not organ dose and not risk)
- Eventually may be able to replace (supplement?) metrics of scanner output.
- Soon captured by scanner; May eventually be displayed on scanner (not a current requirement), but at least available in RDSR
- ACR DIR already includes an estimate of SSDE
- Future investigations – can SSDE be used as an estimate of radiation dose to organs? If so, where? (and where not?) Will this be a better input to risk models than CTDI$_{vol}$ and DLP?
• AAPM Report 204 introduced the concept of SSDE
  • For body scanning
  • Used “Effective Diameter”

• AAPM report 220 introduced the concept of Water Equivalent Diameter ($D_w$)
  • Patient size metric that accounts for attenuation and not just morphology
  • Could be used in calculations developed in Report 204

• AAPM Report 293 extended these concepts to Head CT scans
  • Used $D_w$ as size metric
  • Coefficients are slightly different from those in 204
  • Combination of attenuation environment (bony skull) and bowtie filters tailored towards head

• Together, these provide a comprehensive methodology to estimate SSDE
  • For Head, Chest and Body
  • Using a standardized methodology that can be implemented automatically and widely

• IEC Standard for manufacturers to implement

• Inclusion in ACR DIR; other uses in future?
Thank you!