CT: Size Specific Dose Estimate (SSDE): Why We Need Another CT Dose Index

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Acknowledgements

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INTRODUCTION

A. Image Gently Campaign
B. Pediatric CT Public Health Concerns
C. Affect of Patient Size on Dose Indices
D. Shortcomings of Dose Indices for CT
E. Clinical Dilemma
F. Interim Solution: AAPM TG204
G. Managing Pediatric CT Patient Doses
H. Applications of SSDE

MISSION STATEMENT

Alliance for Radiation Safety in Pediatric Imaging is a coalition of health care organizations creating an education, awareness and advocacy campaign dedicated to providing safe, high quality pediatric imaging worldwide.

- 75 health care organizations/agencies
- 800,000 radiologists,
- radiology technologists,
- medical physicists
- worldwide

Adapted from Goske
Methods

Positive message
resulting dose to population will lead to higher cancer rates, accounting for as many as 2% of all cancers in the U.S.

Enroll key organizations
Increase awareness
educate
advocate
change practice

Adapted from Goske

Founding Organizations

The Society for Pediatric Radiology
American Society of Radiologic Technologists
American Association of Physicists in Medicine
American College of Radiology

Alliance
For Radiation Safety In Pediatric Imaging

Adapted from Goske
PEDIATRIC CONSIDERATIONS

A. Radiation Induced Cancer Lifetime Risk From 1 Sv Dose

1. Average
   a. 5% Males
   b. 6% Females

2. First Decade
   13 - 15%

3. Middle Age
   2 - 3%

4. Children 3 – 5 times more sensitive

AFFECT of PATIENT SIZE on DISPLAYED CTDI\textsubscript{VOL} & DLP

Adapted from Hall
Real World ....

Radiation distribution *crosses* the imaged volume

- Peak dose
- “Tails” of dose distribution

CTDI = Integral under the radiation dose profile along the z-axis from a single axial scan of width nT.
CT SCANNER DOSE INDICES

C. Measure CTDI\textsubscript{vol}

1. Measure CTDI\textsubscript{vol} with identical scan parameters
   a. kV
   b. mA
   c. Rotation time
   d. Bow Tie Filter

2. Use phantom 10, 16, and 32 cm diameter

<table>
<thead>
<tr>
<th>Phantom Diameter</th>
<th>Measured CTDI\textsubscript{vol}</th>
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<tbody>
<tr>
<td>10 cm</td>
<td>47 mGy</td>
</tr>
<tr>
<td>16 cm</td>
<td>38 mGy</td>
</tr>
<tr>
<td>32 cm</td>
<td>21.6 mGy</td>
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</table>

Measured CTDI\textsubscript{vol} increases 2.6 times as phantom size decreases!
CT SCANNER DOSE INDICES

D. Displayed CTDI$_{vol}$

1. Dose that represents distribution of dose given to cross-sectional area of a slab of the CTDI phantom (16 or 32 cm diameter)

2. Reflects changes in:
   a. Voltage to x-ray tube (kV)
   b. X-ray tube current (mA)
   c. Rotation time (sec)
   d. Pitch
   e. Bow tie filter shape, thickness, material
   f. Source to detector distance

CT SCANNER DOSE INDICES

D. Displayed CTDI$_{vol}$

3. Standardized method to estimate and compare the radiation output of two different CT scanners to same phantom.
CTDI\textsubscript{vol}

1. Is measured with a point ionization chamber such as a Farmer Chamber.
2. Displayed by the CT scanner represents the radiation dose delivered to the patient.
3. Is a standardized method to estimate and compare the radiation output of two different CT scanners to the same phantom.
4. Can be measured with a single measurement in the correct CTDI phantom.

**CLINICAL DILEMMA**

**A.** Displayed CTDI$_{vol}$ is independent of the patient size; displayed CTDI$_{vol}$ assumes either 16 or 32 cm CTDI phantom.

**B.** 16 cm CTDI phantom: adult dose over while pediatric dose under estimated.

**C.** 32 cm CTDI phantom: adult and pediatric dose under estimated ~ 2.5 times!

**D.** Propagated by DICOM Structured Reports and CT scanner dose reports.
CT SCANNER DOSE INDICES

D. Displayed CTDI\textsubscript{vol}

5. does not represent . . .

Patient dose!!

PEDIATRIC CONSIDERATIONS
CLINICAL EDUCATIONAL MATERIALS

<table>
<thead>
<tr>
<th>Abdomen Baseline:</th>
<th>kVp</th>
<th>mA</th>
<th>Time (sec)</th>
<th>Pitch Abdomen</th>
<th>Pitch Thorax</th>
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IMAGE
gently
BODY
PEDIATRIC CONSIDERATIONS
CLINICAL EDUCATIONAL MATERIALS

1. \( \text{CTD}_{\text{vol}} \) for Adults
   a. < 25 mGy Body (CTDI\(_{32}\))
   b. < 75 mGy Head (CTDI\(_{16}\))
   c. < 20 mGy Pediatric Body (CTDI\(_{16}\))
   d. < ?? mGy Pediatric Head (CTDI\(_{16}\))

2. Pediatric Patient Dose < Adult Dose
   a. Up to 2.6 times greater if do nothing

3. Developed for adult department that images children occasionally
TG 204

E. Report does not:

1. Address correction factors for heads
2. Correct small (< 1%) doses from scanned projection images
3. Correct for variation (~ 5%) in attenuation of thorax vs abdomen
4. Correct small variation in pre and post contrast scans

TG 204

E. Report does not address:

5. Changes in dose as a function of fan beam
   a. 20 cm: relative dose ~ 2
   b. 30 cm: relative dose ~ 2.3
   c. Dose Profiles vs Fan Beam Width

Adapted from J. Boone
TG 204

F. So what is SSDE?:

1. Estimate of the average patient dose within the entire scan volume of patient.
   a. Adjusts for patient size and varying attenuation from overlying tissue thickness.
   b. Uses average scanner radiation output during CT scan: $\text{CTDI}_{\text{vol}}$
      i. Output varies along z axis
      ii. Output varies as beam rotates
      iii. Output varies based on bow tie filter

SSDE:

1. Calculations account for the differences in pre and post contrast scans.
2. Conversion factors for the head are smaller than those for the trunk.
3. Calculations include corrections for the dose of the projection scan
4. Reference values published by the ACR < 20 mGy for a pediatric 5 year old body.
5. Does not correct for the failure to capture complete scatter tails when using short phantoms as addressed in AAPM Task Group Report 111.
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TG 204

F. Data from four independent investigators studying patient size correction factors.

1. Physical measurements on phantoms
   - A. Anthropomorphic Phantoms (McCollough Laboratory “Mc”)
   - B. Cylindrical PMMA phantoms (Toth / Strauss Collaboration “T-S”)

2. Monte Carlo computer modeling
   - C. Monte Carlo Voxelized Phantoms (McNitt-Gray Laboratory “MG”)
   - D. Monte Carlo Mathematical Cylinders (Boone Laboratory “Z-B”)

Adapted from TG 204
TG 204

32 cm 120 kV
Adapted from TG 204

16 cm 120 kV
Adapted from TG 204
G. What about scans performed at 80, 100, or 140 kV?

1. 5% difference overall
2. 3% difference between 1 yr old (15 cm) & adult (32 cm)

Combined TS / ZB: 80-140 kV

from 120 kV only

\[ y = 4.37809e^{-0.04331x} \]
\[ R^2 = 0.97327 \]

I. What is an effective diameter?

1. Circle with area of patient’s cross section
2. Effective diameter can be estimated if the patient’s AP or lateral dimension is known.
AGE vs PATENT SIZE

A. Same age patients vary dramatically in size.
   Abdomens of:
   1. Largest 3 year olds and
   2. Smallest adults
   are the same size.

Patient cross section size, not age, should be used.

TG 204

L. Determining patient size
   1. Measure Lateral dimension with mechanical calipers.
   2. Measure Lateral or AP dimension from
      AP or Lateral projection scan.
      a. Magnification Error
   3. Measure AP or LAT dimension from axial scan view.
M. Determining size of CTDI phantom your CT scanner used to estimate CTDIvol

1. Failure to identify correct phantom, 16 or 32 cm leads to a systematic error of 100%.

2. No standard exists. Choice may depend on:
   a. Selected protocol: adult or pediatric
   b. Selected scan field of view
   c. Year of manufacture
   d. Software level

3. Make no assumptions: contact manufacturer of your unit through its service organization.

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**Correction Factor based on 32 cm CTDI Phantom**

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<th>AP Dim (cm)</th>
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Adapted from TG 204
Q. SSDE Accuracy

1. 20%

2. Product is an *estimate* of patient dose

3. Report dose estimates with proper number of significant digits

   a. SSDE > 5 mGy: integers only, e.g. 7 or 23 mGy

   b. SSDE < 5 mGy: one decimal point, e.g. 2.7 or 4.5 mGy

---

SAMPLE CALCULATION: PRESCAN

A. Determine size of patient

1. AP Projection Scan: 16.8 cm

B. 16 cm CTDI phantom used by scanner to calculate CTDI_{vol}

C. Displayed CTDI_{vol} = 9.29 mGy

D. 9.29 mGy x 1.08 = 10 mGy SSDE
R. Dose Reporting by Radiologists

The CTDI$_{vol}$ value reported on the scanner for the [32 or 16] PMMA phantom was used with correction factors obtained from AAPM Report 204. The correction factor for this patient was based on the patient's [AP, LAT, AP + LAT, or effective dimension] This method is thought to produce dose estimates with accuracy to within 20%. For this patient, the size corrected (SSDE) estimate for this CT scan is ____ mGy.

Adapted from TG 204

SSDE:

1. Calculation has an estimated error of 10%.
2. Accounts for both the radiation output of the scanner and patient size.
3. Cannot be estimated until after the CT examination of the patient is completed.
4. Is more accurate if patient size is estimated based on the patient's age.
5. Should not be used for CT examinations of the thorax.
SSDE:
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Effective Dose Issues

T. Caution:
SSDE can NOT be substituted in place of $CTD_{vol}$ when using k-factors to estimate Effective Doses from CT exam
Effective Dose Issues

G. Effective Dose was originally defined to address radiation protection concerns of occupationally exposed workers.

H. Effective dose can be used to facilitate a comparison of biological effects between diagnostic exams of different types.

Effective Dose Issues

I. Effective Dose is NOT:

1. A patient dose
2. To be used for an individual
3. Defined for children
4. For estimating cancer risk; it assesses more than just cancer risk.

Effective Dose Issues

J. Effective Dose Recommended Reading

1. ICRP 103 Executive Summary

Effective Dose:

1. Can be used to compare biological effects diagnostic exams of different types.
2. Accuracy is improved when SSDE is multiplied times the appropriate k-factor instead of CTDIvol.
3. Can be used to estimate an individual patient’s radiation dose.
4. Can be used to estimate organ doses.
5. Was originally defined to address radiation protection concerns of medically exposed patients.
Effective Dose:

1. Can be used to facilitate a comparison of biological effects between diagnostic exams of different types.
2. Accuracy is improved when SSDE is multiplied times the appropriate k-factor instead of CTDI\textsubscript{vol}.
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Clinical Applications of SSDE

I. Ideally, unique scan parameters should be established for each individual patient accounting for:
   1. Patient size
   2. Type of CT examination
   3. Design of actual CT scanner

J. This can be done in academic centers with diligent effort.
Clinical Applications of SSDE

K. What are the odds this will happen for the occasional pediatric CT scan completed at a good community hospital? SLIM & NONE!

Yet, majority of pediatric CT imaging in US DOES NOT occur in dedicated pediatric hospitals?

Clinical Applications of SSDE

L. What is a solution?

1. Review the CTDI\textsubscript{vol} measurements completed by the facility’s medical physicist.
   a. Site CTDI\textsubscript{vol} < ACR Reference Values
   b. Verification that adult patient doses of site is reasonable.
Clinical Applications of SSDE

**L. What is a solution?**

2. Calculate SSDE after scan projection image of pediatric patient is complete.
   - Measured patient width
   - Size of CTDI phantom used by imager
   - $\text{CTDI}_{\text{vol}}$

3. Compare calculated SSDE to reference SSDE

4. Adjust scan parameters as necessary.

Managing Pediatric CT Patient Doses

**M. Starting Reference Doses (SSDE) in an adult department might be:**

1. 10 cm (Newborn)  ~  adult SSDE
2. 11 cm (1 yr old)  ~  adult SSDE
3. 14 cm (5 yr old)  ~  adult SSDE
4. 17 cm (15 yr old) ~  adult SSDE
5. 23 cm (Adult)     ~  adult SSDE
Managing Pediatric CT Patient Doses

N. Reduce the radiation output of scanner if calculated SSDE > reference SSDE
   1. Use original high Voltage
   2. Reduce the mAs:
      \[ \text{mAs} \times \frac{\text{reference SSDE}}{\text{calculated SSDE}} \]
      3. Reasonable dose with less image quality which may not be acceptable.

Managing Pediatric CT Patient Doses

O. Should voltages < 120 kV be used for Children?
   1. Reduced high voltage; same dose
      a. Set appropriate reduced mAs
      b. Note displayed CTDI\text{vol 120}
      c. Reduce kV to desired value
      d. mAs up until CTDI\text{vol kVr} = CTDO\text{vol 120}
      e. Increased Contrast at ~ same dose
Managing Pediatric CT Patient Doses

2. Reduced high voltage; reduced dose
   a. Dial up reduced mAs technique
   b. Note displayed \( \text{CTDI}_{\text{vol}}^{120} \)
   c. Measure increased contrast at \( \text{kVr} \) compared to 120 kV.
      i. ACR accreditation phantom or
      ii. CTDI phantom with Iodine Pin(s)
      iii. Clinical FoV / Bow tie Filter
   d. Estimate increase in noise by comparing \( \text{CTDI}_{\text{vol}}^{120} \) & \( \text{CTDI}_{\text{vol}}^{\text{kVr}} \)
   e. Contrast Up 40% / Noise Up 60%
   f. Increase mAs at \( \text{kVr} \) until Noise increases only 40%
   g. \( \text{CNR}_{\text{kVr}} = \text{CNR}^{120 \text{kV}} \)
   h. Same Image Quality; Reduced Dose
Managing Pediatric CT Patient Doses

3. Additional Considerations
   a. How much can the high Voltage be lowered for
      i. Each diagnostic task?
      ii. Patient size?
   b. How does this choice affect:
      i. Contrast
      ii. Noise
      iii. Artifacts
      iv. Scanning speed: Motion Unsharpness
Managing Pediatric CT Patient Doses

4. Contrast
   a. Improved
   b. Higher Noise levels
   c. Typically mAs must be increased

Managing Pediatric CT Patient Doses

5. Scanning Speed may suffer
   a. Radiation output of scanner is limited
   b. Pitch may need to be reduced
   c. Rotation time may need to be reduced
   d. b & c increase scan time and motion unsharpness
Managing Pediatric CT Patient Doses

6. Artifacts increase with lower Voltage
   a. Beam hardening
   b. Streak artifacts
   c. Problematic for images with
      i. High contrast objects
      ii. Dense materials

7. Pediatric Considerations
   a. Higher CNR needed for infants and small children.
      i. Less adipose tissue between organs and tissue interfaces
      ii. Thinner slices typically used
   b. Higher noise levels tolerated for adult images.
When reducing the high voltage of the CT scanner in an effort to improve image quality and reduce the radiation dose to pediatric patients one can ignore the effect on:

1. Contrast.
2. Noise.
3. Sharpness
4. Artifacts
5. Scanning speed

When reducing the high voltage of the CT scanner in an effort to improve image quality and reduce the radiation dose to pediatric patients, for each type of clinical examination one can ignore the effect on:

1. Contrast.
2. Noise.
3. Sharpness.
4. Artifacts.
5. Scanning Speed

CT Automatic Exposure Control: Pediatric Challenges and Solutions

2003: Dose Reduction Principle
1. Reduce radiographic techniques such that CNR remains constant as path length of x-rays changes!
2. Technique (mAs) reduction 35x from 28 – 12 cm effective diameter!
3. Why does it not work?

CT Automatic Exposure Control: Pediatric Challenges and Solutions

Infants compared to adults
1. Natural Subject Contrast significantly less in infants
2. Size of body parts:
   Different: Req Resolution
   a. Head: 1.4 : 1
   b. Abdomen: 2 : 1
3. Require more image quality
CT Automatic Exposure Control: Pediatric Challenges and Solutions

Manufacturers control AEC differently

1. Manufacturer A: Reference mAs
   a. 80 mAs < specified age
   b. 200 mAs > specified age
   c. Not logical but works!
   d. From newborn to adult
      i. CNR decreases ~ 3x
      ii. mAs increases ~ 3x
      iii. Images acceptable

2. Manufacturer B: Noise Index: NI
   a. NI $\propto$ Std Dev of noise
   b. Min & Max mA; Scan time
   c. Adopted Boone Model:
      i. Constant NI as a function of size!
      ii. Constant CNR if kV is unchanged
   b. Failure
      i. NI restrained by max & min mA
      ii. Imaging requirements not constant
CT Automatic Exposure Control: Pediatric Challenges and Solutions

Manufacturers control AEC differently

2. Manufacturer B: Noise Index: NI
e. From newborn to adult
   i. CNR decreases ~ 3x
   ii. mAs increases ~ 3x
   iii. NI increases ~ 3x
   iv. Must select
      • Min & max mA
         to allow selected NI to be expressed!

Example Clinical Case
Courtesy J Seibert, UC Davis

Pediatric patient scanned initially with a Siemens scanner in outpatient clinic
• CareDose 4D used
• Dose report recorded

Effective diameter = 25 cm
(20.5 cm x 30.4 cm)
Example Clinical Case
Courtesy J Seibert, UC Davis

Surgical intervention required placement of “Nuss Bars” to complete the treatment
Smart mA used
Dose report recorded

Dose indicator Measurements
Courtesy J Seibert, UC Davis

<table>
<thead>
<tr>
<th>Series</th>
<th>Type</th>
<th>Scan Range (cm³)</th>
<th>CTDIvol (mGy)</th>
<th>DLP (mGy·cm)</th>
<th>Phantom</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Scout</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Helical</td>
<td>14,000-134,000</td>
<td>17.73</td>
<td>536.32</td>
<td>Head 16</td>
</tr>
<tr>
<td>2</td>
<td>Helical</td>
<td>127,000-330,000</td>
<td>11.07</td>
<td>63.95</td>
<td>Head 16</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>17.73</td>
<td>600.67</td>
<td></td>
</tr>
</tbody>
</table>

CTDIvol (mGy) | DLP (mGy cm)
Siemens: 4.8 | 181
GE: (chest) 17.7 | 537
(abdomen) 11.1 | 64
(total) 28.8 | 601

First impression:
From CTDIvol: 28.8 / 4.8 = 6X higher dose
From DLP: 601 / 181 = 3.8X higher integral dose
WHY??
Example Clinical Case
Courtesy J Seibert, UC Davis

- Pediatric patient scanned initially with a Siemens scanner in outpatient clinic
  - CareDose 4D used
  - \(\text{CTDI}_{\text{vol}} = 4.78 \text{ mGy}\)
  - Effective diameter = 25 cm

Example Clinical Case
Courtesy J Seibert, UC Davis

- Smart mA used
- Post-surgery, patient scanned in-patient GE scanner
  - \(\text{CTDI}_{\text{vol}} = 17.7 \text{ mGy}\)
Conversion for Size Discrepancy
Courtesy J Seibert, UC Davis

Differences in phantoms used for CTDI calibration:
- Siemens – 32 cm will result in underestimate
- GE – 16 cm, will result in overestimate

What is the conversion factor? …… AAPM TG 204

204 Size conversion factors for CTDI$_{vol}$

<table>
<thead>
<tr>
<th>Lat + AP</th>
<th>Dim (cm)</th>
<th>Effective Dim (cm)</th>
<th>Correction Factor</th>
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</thead>
<tbody>
<tr>
<td>14</td>
<td>14.7</td>
<td>18.2</td>
<td>2.16</td>
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<tr>
<td>15</td>
<td>15.7</td>
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</tr>
<tr>
<td>27</td>
<td>27.6</td>
<td>31.7</td>
<td>1.94</td>
</tr>
</tbody>
</table>

Conversion factor: 0.71
Uncorrected Data From Scanners

Courtesy J Seibert, UC Davis

17.7 mGy / 4.78 mGy ≈ 3.7 × difference in CTDI_{vol}

TG-204 SSDE Corrections:

17.7 mGy (16 cm PMMA reference) × 0.71 ≈ 12.5 mGy

4.8 mGy (32 cm PMMA reference) × 1.47 ≈ 7.1 mGy

12.5 / 7.1 ≈ 1.7 × difference in SSDE

Even with correction, why was there a difference between scanners?

CT Digital Radiograph Localizer

Courtesy J Seibert, UC Davis

Pre-surgery

Post-surgery
Example Clinical Case
Courtesy J Seibert, UC Davis

*Comparison after SSDE conversion:*
thorax: 12.5 / 7.1 = 1.7X higher dose
(with Nuss bar attenuators)

abdomen: 7.9 / 7.1 = 1.1X higher dose
(without attenuators)

Should dose modulation be used in situations with highly attenuating materials? Maybe yes, maybe no!

Clinical Applications of SSDE

D. SSDE

1. Is useful as a first approximation of some organ doses
   a. Soft tissues only
   b. Organ completely in scan volume in z direction.
Clinical Applications of SSDE

D. SSDE

1. Useful first approximation of some organ doses
   c. Radial dose profiles
   d. Range dependent on patient diameter
      i. Pediatric vs Adult?
   e. Single estimated CTDI$_{vol}$ (83)

Clinical Applications of SSDE

D. SSDE

1. Useful first approximation: organ dose
   f. Increased error for small organs depending on location.

Less effect pediatrics

Adapted from McCollough
Conclusions

A. Due to variations in:
   1. Patient size,
   2. Type of CT examinations, and
   3. Design of actual CT scanners,
   Patient’s CT dose should be appropriately
   1. Estimated,
   2. Managed during the examination, and
   3. Recorded,
   regardless of patient size!
   SSDE can help with all three tasks!

B. Adult hospitals performing 80% of all
apediatric CT Examinations should manage their pediatric radiation doses.
   1. Use adult protocols and calculate adult SSDE.
   2. SSDE of pediatric patient prior to scan < Established reference SSDE by Dept.
Conclusions

B. Adult hospitals performing 80% of all pediatric CT Examinations *should* manage their pediatric radiation doses.

3. Manage patient dose and image quality
   a. Reducing mAs alone reduces:
      i. Patient dose
      ii. Image quality
   b. Reducing kV and increasing mAs
      i. Properly manages patient dose
      ii. Improves image quality

Conclusions

3. Manage patient dose and image quality
   c. Minor to moderate reductions in patient dose with minor loss of image quality (mAs reduction only)

      IS PREFERRED OVER

   d. Doing nothing because reduced voltage and increased mAs, is too TIME CONSUMING & IMPRACTICAL