Multi-Detector CT (MDCT) Dosimetry – Current Issues and Challenges

NC HPS SPRING MEETING
MARCH 7, 2008
CAROLINA BEACH, NC

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ACKNOWLEDGEMENT

• James Colsher, PhD, GE Healthcare
• Osama Saba, PhD, Siemens Medical Solutions
• Fred Mettler Jr. MD, University of New Mexico
• Mahadevappa Mahesh, PhD, Johns Hopkins Hospital
TODAY’S TOPICS

1. CT patient dosimetry - why so important?
2. Recent changes that affect CT dosimetry
3. Factors affecting dose
4. Dose indices – yesterday, today and tomorrow
5. Review of dose estimation methods
6. Emerging issues and opportunities
CT PATIENT DOSIMETRY - WHY SO IMPORTANT?

• Controversy generated by David Brenner and Eric Hall’s paper in 2007
  – Cancer risk from CT
• CT dose - New findings coming out of NCRP Scientific Committee 6-2 (since 2005)
• Potential danger of modern CT scanners
• Rapid advancement of CT technology
• Rapid expansion of CT applications
CT PATIENT DOSIMETRY - WHY SO IMPORTANT?

• David Brenner and Eric Hall’s controversial paper in 2007
  – Computed Tomography – An increasing source of radiation exposure
  – Suggested the radiation dose from CT scans is a cause for concern, and may be responsible for a small percentage of cancer deaths in the U.S.
  – Strong responses from professional societies such as HPS, AAPM, and ACR.
Computerized Tomography — An Increasing Source of Radiation Exposure


The American Association of Physicists in Medicine
Honoring the past
Celebrating the present
Preparing for the future
Houston, Texas • July 27-31, 2008

Announcements


A recent article by Drs. David Brenner and Eric Hall in the New England Journal of Medicine¹ has suggested that the radiation dose from CT scans is a cause for concern, and may be responsible for a small percentage of cancer deaths in the United States. While the conclusions of the Brenner article have been portrayed by some as conclusive, in reality the scientific community remains divided regarding the radiation dose effects of CT. The AAPM is an organization of 6700 Medical Physicists, and radiation dosimetry in CT and other sources of x-ray exposure is the core expertise of the vast majority of our members. Dr. Brenner’s article correctly points out that the use of CT is increasing at an exponential rate, and that CT should not be used for medical indications that are not warranted or serious. The AAPM adamantly concurs with these observations, and has long advocated that CT should be used judiciously and only when medically indicated. For example, the AAPM policy paper on CT screening has recommended against “CT screening” for many years.
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CT PATIENT DOSIMETRY - WHY SO IMPORTANT?

• CT dose - New findings coming out of NCRP Scientific Committee 6-2 (since 2005)
  – One of the subcommittees was Medical Patient Exposure
  – Previous NCRP report was published in 1987 as NCRP Report 93 (20 yrs ago)
  – What changed in the last 20 yrs?
    • Medical imaging technology
    • Clinical practice
    • Patient dosimetry
Radiation dose from CT: Then (1980) and Now (2006)

- According to NCRP report 100 (1980)
  - Collective dose for CT: 3,700 person Sv
- According to current estimations (2006)
  - Collective dose for CT: 438,000 person Sv
  - Effective dose per capita: ~1.5 mSv
CT scans by year in US (millions)

Annual growth > 10%/yr
U.S. population < 1%/yr

No. of procedures (millions)


18.3 19.5 21.0 22.6 25.1 26.3 30.6 34.9 39.6 45.4 50.1 53.9 57.6 62.0

CT procedures by year (millions)

Courtesy of Dr. Fred Mettler
CT scans of Abdomen and Pelvis
Exam distribution vs US Population*
## Preliminary Results for CT (2006)

<table>
<thead>
<tr>
<th></th>
<th>Number (millions)</th>
<th>%</th>
<th>Collective dose Person Sv</th>
<th>%</th>
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<tr>
<td>Head</td>
<td>19.0</td>
<td>28</td>
<td>38,000</td>
<td>8.7</td>
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<tr>
<td>Chest</td>
<td>10.6</td>
<td>16</td>
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<td>Abd/Pelvis</td>
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<td>38</td>
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<td>58.0</td>
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<tr>
<td>Extremity</td>
<td>3.5</td>
<td>5</td>
<td>500</td>
<td>0.1</td>
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<tr>
<td>CT Angiogram</td>
<td>4.3</td>
<td>6</td>
<td>56,000</td>
<td>12.8</td>
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<tr>
<td>Miscellaneous</td>
<td>4.2</td>
<td>6</td>
<td>15,000</td>
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<tr>
<td><strong>TOTAL</strong></td>
<td><strong>67</strong></td>
<td></td>
<td><strong>438,000</strong></td>
<td></td>
</tr>
</tbody>
</table>

* Accounting for multiple scans within a procedure

Preliminary results not yet reviewed and approved by NCRP Council

From AAPM 2007 Presentation: Dr. Mahesh, NCRP Committee
Preliminary estimate of changes in U. S. medical radiation exposure

U.S. 1980

- Natural: 2.8 mSv
- Medical: 0.54 mSv
- All other: ?? mSv

Total: 3.6 mSv per capita

U.S. 2006

- Interventional: 0.4 mSv
- Radiography: 0.3 mSv
- Nuclear medicine: 0.8 mSv
- CT scanning: 1.5 mSv
- All other: ?? mSv
- Natural: 2.4 UNSCEAR
- Medical: ~3.0 mSv

Total: ~ 5.4
Computed Tomography (CT)

In Summary

• Annual growth over 1993-2006:
  – CT Procedures > 10% vs US population < 1%

• Nearly 62 million CT procedures in US in 2006

• Data correlated to nearly 7649 hospitals in US

• Pediatric CT ~ 8-10% of total procedures
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CT PATIENT DOSIMETRY - WHY SO IMPORTANT?

• Potential danger of modern CT scanners
  – Danger of not knowing the capability of CT scanner—case report
  – Capability of modern CT scanner—extreme case study
Danger of not understanding CT dose

Radiation-induced temporary hair loss as a radiation damage only occurring in patients who had the combination of MDCT and DSA

- 3 cases reported
- MDCT perfusion + DSA (CT fluoroscopy)
- Temporary hair loss (3-5 Gy)
CT PATIENT DOSIMETRY - WHY SO IMPORTANT?

• Potential danger of modern CT scanners
  – Danger of not knowing the capability of CT scanner – case report
  – Capability of modern CT scanner – extreme case study
CAPABILITY OF MODERN CT SCANNER
Pediatric Phantom 5-year Old
Siemens 64-slice
### Summary: Siemens 64-slice

*Care= automatic tube current modulation

<table>
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<tr>
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<th>ED (mSv)</th>
<th>+/-SD (mSv)</th>
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<tbody>
<tr>
<td>Chest W Care*</td>
<td>3.05</td>
<td>0.14</td>
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<tr>
<td>Chest W/O Care</td>
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<tr>
<td>Chest Extreme</td>
<td>42.95</td>
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<td>6.83</td>
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<td>Abdomen Extreme</td>
<td>118.9</td>
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EXTREME CASES: Siemens 64-slice

### Chest W/O Care - Extreme Case

<table>
<thead>
<tr>
<th>Slice</th>
<th>Organ</th>
<th>Dose (cGy)</th>
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<tbody>
<tr>
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<td>2</td>
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<td>4</td>
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<tr>
<td>5</td>
<td>10.73</td>
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<td>6</td>
<td>3.97</td>
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<td>0.14</td>
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<td>11</td>
<td>0.04</td>
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### Abdomen W/O Care - Extreme Case

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<th>Slice</th>
<th>Organ</th>
<th>Dose (cGy)</th>
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<td>0.19</td>
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<td>2</td>
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<tr>
<td>16</td>
<td>14.68</td>
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TOPICS

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6. Research opportunities
THE BIG PICTURE

CT: Historical Milestones (II)

- Slip ring scanning, 1 s scan
- Dual-slice scanning
- Half second scanning
- Eight slice scanning
- 64 slices
- Helical scanning
- Sub second scanning
- Four-slice scanning
- Sixteen slice scanning
- 256 slices
CHANGES THAT AFFECT CT DOSIMETRY
Transition Period after 1998

- From SDCT to MDCT – transition period 1998 (confusion period)
  - Detector width increased
  - Shorter focal spot to center of rotation distance
  - Dose profile due to detector width

- Duke data between SDCT and MDCT (Snap shot)
DETECTOR WIDTH INCREASED (>1998)

GE CT/i 10 mm

GE QX/i 4-slice 20 mm
Shorter focal spot-to-center of rotation distance

- Focal spot-to isocenter shorter for MDCT
  - 630 mm vs. 540 mm
  - \((630/540)^2 = 1.36:1\)
- MDCT < SDCT
- ↓ mAs 74% with the same noise
  - \((1/1.36 = 0.74)\)
MDCT QXi dose profile (dotted line)

Qxi 4 x 5.0 mm 4i mode body (GE manual)

CTI dose profile (dotted line)

CTi, 5 mm body (GE manual)
CONFUSION PERIOD IN DOSIMETRY
1998-1999

• Many facilities continued to adopt old SDCT scan protocols in new MDCT environment without considering design changes that might affect patient dose

• Also many hospitals did not differentiate scan protocols between adults and pediatric patients; this further complicated the dosimetry issues

Relative Dose Comparison between CT/i and QX/i

![](chart.png)

Duke Body CT Protocol (2001)

(Using a 32cm acrylic phantom with TLD chips inside the center hole)
Snapshot in 2007
HEAD SCAN COMPARISON (Duke Data)
Variation in patient dose in various CT scanners

Comparison of ED (mSv)

Scanner Type

GE VCT 64 (South)  GE VCT 64 (ED)  Siemens 64  GE LP 16 (North)  GE LP 16 (North)  GE LP 16 (North)  GE LP 16 (South)  GE OX/14-slice  GE CT/1 single slice

ED (mSv)

0.00  0.20  0.40  0.60  0.80  1.00  1.20  1.40  1.60  1.80  2.00

1.52  1.58  1.86  1.62  1.62  1.62  1.62  1.69  1.22
DOSE COMPARISON UNDER SAME IMAGE QUALITY

SDCT

MDCT
Comparison of Dose Profile
4-slice QX/i and 1-slice CT/i

<table>
<thead>
<tr>
<th>scanned region</th>
<th>outside scanned region</th>
<th>TLD chips</th>
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<td>30 mm</td>
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</table>
DOSE COMPARISON
BETWEEN 20 mm QX/i AND 10 mm CT/i
(Scanned to produce the same image noise)

Dose Comparison (QXi and CTi)

scanned
outside scanned plane

QXi (151 mA)
CTi (265 mA)
% Diff.

QXi Fitted
CTi Fitted

% Difference

mm

mrad

0 10 20 30 40 50 60
0 10 20 30 40 50 60 70 80 90 100

400 600 800 1000
RECENT ADVANCES IN CT TECHNOLOGY

- Faster tube rotation times
  - <0.4 s for a full rotation
  - shorter exposure time -> tube current must increase to get same photon statistics -> higher Heat Unit

- Greater Anode Heat Capacity (HU=mA * kVp * seconds)
  - 10 MHU (64-slice MDCT)
  - MDCT (e.g., GE QX/i 6.3 MHU)
  - SDCT 2-3 MHU (e.g., GE CT/i)
  - Axial scanner (old days) 1 MHU
Toshiba 256 slice CT scanner
AAPM 2007

From 4-16-64-slice systems, the breath-hold time for helical scanning of the heart has been significantly reduced. However, it is only with the 256-slice system that the entire heart can be covered in a single rotation.
Toshiba Aquilion One (2008)

- 12.8 cm detector (2007) to 16 cm detector coverage (320 x 0.5 mm), 0.35 SEC ROTATION

Figure 3: The cone angle describes the spread of the x-ray beam in the z-direction. The cone angle on the Aquilion ONE is 5 times greater than the Aquilion multi-slice.
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FACTORS AFFECTING DOSE

1. Pitch effect
2. Focal spot wobble and tracking
3. Choice of kVp on dose
4. Patient thickness
5. Tube current (auto mA modulation)
6. Tube rotation time
7. Slice thickness
8. Beam filter
Pitch = \frac{\text{Table travel per rotation}}{\text{slice thickness}}

Pitch = \frac{10 \text{ mm}}{10 \text{ mm}} = 1

Pitch = \frac{20 \text{ mm}}{10 \text{ mm}} = 2

This definition only applies to single-detector helical CT.
1. Axial CT vs. Helical SDCT
   - For pitch=1, doses are the same (axial=helical)
   - Dose for pitch 2 in SDCT is approx. $\frac{1}{2}$ that of pitch 1
FACTORS AFFECTING DOSE

2. Coronary CTA
   - Pitch < 0.3 overlapping beams contribute higher dose (0.22 GE)
FACTORS AFFECTING DOSE

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6. Tube rotation time
7. Slice thickness
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FOCAL SPOT WOBBLE AND TRACKING

- Purpose: to follow the focal spot so that one can maintain a uniform x-ray beam that is as narrow as possible on the detector, thereby reducing dose and avoiding artifacts.
- Toth reported a dose reduction of up to 40% on GE LightSpeed QX/i.
FOCAL SPOT WOBBLE AND TRACKING

- focal spot moves in the direction of z-axis due to thermal changes in the tube and mechanical forces associated with gantry rotation and tilt angle.
Basic approach: use some detectors beyond those capturing the clinically useful signal to track the wandering of the penumbra regions.

What does tracking do?

Closed loop repositions collimator to hold the beam steady:
1. Measure position of X-ray beam
2. Compute new collimator position
3. Move collimator to follow the focal spot

Data channels that make the image stay in flat X-ray

Z axis module operates partly in the X-ray shadow

Position of X-ray shadow on Z cells determines the signal ratio

wFast response to keep beam centered on the detector
FACTORS AFFECTING DOSE

1. Pitch effect
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FACTORS AFFECTING DOSE

3. Choice of kVp on dose
   – The dose varies approximately to the power of 2; increasing kVp results in an increase in dose
   – Example: 120 kVp to 140 kVp results in the 36% dose increase, i.e., \((\frac{140}{120})^2 = 1.36\)
   – Image quality issue
   – New issue- Dual Energy CT (New Area)
FACTORS AFFECTING DOSE

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2. Focal spot wobble and tracking
3. Choice of kVp on dose
4. Patient thickness
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6. Tube rotation time
7. Slice thickness
8. Beam filter
ABDOMINAL CT FOR OBESE PATIENTS

• Schindera et al. (Duke Univ) Acad. Radiol 2007; 14:486-494.
• Studied the effect of a modified MDCT protocol for obese patients on image quality and radiation dose.
• Showed that using a modified abdominal MDCT protocol with 8 cm or more of subcutaneous fat, image quality can be substantially improved without a significant increase in radiation dose to the abdominal organs.
Figure 5. Radiation dose to different abdominal organs in three different phantom setups. Gray bar: phantom setup without any fat rings scanned with protocol A; spotted bar: phantom setup with one 4 cm thick fat ring scanned with protocol B; bar with diagonal lines: phantom setup with two 4 cm thick fat rings scanned with protocol B. Error bars represent ± standard deviation. Abdominal organ doses did not increase significantly for the phantom setup with two 4 cm thick fat rings compared with the phantom setup without any fat rings (P > 0.05).

Figure 6. Image noise using protocols A and B in the three different phantom setups, 0 cm fat, 4 cm fat, and 8 cm fat. There was a significant decrease in image noise comparing the CT protocols B with protocol A for all three phantom setups (P < .05).
FACTORS AFFECTING DOSE

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3. Choice of kVp on dose
4. Patient thickness
5. Tube current (auto mA modulation)
6. Tube rotation time
7. Slice thickness
8. Beam filter
5. TUBE CURRENT MODULATION

Basic Concept:

- Adjust the tube current to accommodate the patient contour and composition

Technical Approach:

- Modulation along z-axis
- Modulation around the cross-section
- Modulation – axial and helical
5. TUBE CURRENT MODULATION

modulation around the z-axis

modulation around the cross-section

modulation – axial and helical
How smartma works

- Projection data from a scout scan measures the patient and determines how to modulate the mA for improving dose efficiency and consistent IQ.
An AutomA Example (Noise Index = 24)
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DOSE INDICES – YESTERDAY, TODAY AND TOMORROW
3. REVIEW OF VARIOUS CT DOSE INDICES

A. CTDI\textsubscript{FDA}
B. CTDI\textsubscript{100}
C. CTDI\textsubscript{w} & CTDI\textsubscript{vol}
D. DLP
E. ED

F. ORGAN DOSES
   (Often neglected
   In the past)
A. \( \text{CTDI}_{\text{FDA}} \) (CT Dose Index)

CTDI – Mathematical Definition (FDA)

\[ CTDI_{\text{FDA}} = \frac{1}{nT} \int_{-7T}^{7T} D(z) \, dz \]

- \( z = \) position along a line perpendicular to the tomographic plane
- \( D(z) = \) dose at position \( z \)
- \( T = \) nominal slice thickness
- \( n = \) number of tomograms produced in a single scan

This definition assumes that the dose profile is centered around \( z=0 \).
CTDI – Concept (FDA)

Key points:
1. CTDI is designed to represent the dose received by a patient per slice of a multi-slice study.
2. It is the dose to a slice of the patient from the primary x-ray beam and the scatter from fourteen neighboring slices, seven on either side.
A. \( \text{CTDI}_{\text{FDA}} \) (CT Dose Index)

**Limitations:**

- Originally defined for axial CT scanners in 1984.
- \( \text{CTDI}_{\text{FDA}} \) is not applicable to either single-detector or multi-detector helical CT scanners.
Meaning of CTDI

- The equivalent of the dose value inside the irradiated slice that would result if the absorbed radiation dose profile were entirely concentrated to a rectangular profile of width equal to the nominal thickness.
- All dose contributions from outside the nominal slice width are added to the area inside the slice.
Dose descriptors - CTDI

CTDI = \frac{\text{Area} \ (\text{mGy})}{T}

Area: \text{mGy.cm}

Slice width(T): \text{cm}
CTDI – Mathematical Definition

\[ CTDI = \frac{1}{n \cdot T} \int_{-z}^{+z} D(z) \, dz \]

- CTDI is by definition only indicator of the level of local dose in the irradiated slice.

- When the number of slices is increased, the irradiated mass grows by the same amount as the energy absorbed. Therefore the dose doesn’t change.
CTDI_{100} = 

\[ \frac{1}{nT} \int_{-50mm}^{+50mm} Da(z)dz \]

- \( n \) = number image slices per scan
- \( T \) = slice width per image
- \( Da(z) \) = dose profile in z-axis (absorbed in air)
## CTDI definitions

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<th>CTDI&lt;sub&gt;100&lt;/sub&gt;</th>
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<td>FDA</td>
<td>IEC</td>
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<tr>
<td>Integration distance</td>
<td>14 slices</td>
<td>100 mm</td>
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<td>Measurement medium</td>
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<tr>
<td>Dose quoted to</td>
<td>Perspex</td>
<td>Air</td>
</tr>
</tbody>
</table>

*Both require:*
- Same standard phantoms
- Measurements at centre and periphery
1. \( \text{CTDI}_W \) consists of \( \frac{2}{3} \) of the \( \text{CTDI}_{100} \) peripheral dose plus \( \frac{1}{3} \) of the \( \text{CTDI}_{100} \) central dose.

\[
\text{CTDI}_W = \frac{2}{3} \times \text{CTDI}_{100\:\text{peripheral}} + \frac{1}{3} \times \text{CTDI}_{100\:\text{central}}
\]
\[ CTDI_{vol} = \frac{CTDI_w}{P} \]

where \( P = \text{pitch} \)
**DOSE LENGTH PRODUCT (DLP)**

<table>
<thead>
<tr>
<th>DLP (mGy*cm) = CTDI\textsubscript{vol} (mGy) * L(cm)</th>
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</thead>
<tbody>
<tr>
<td>L = scan length in cm</td>
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Descriptor of the total amount of radiation absorbed by taking into account also the extent of the body region being irradiated.
ESTIMATING ED FROM DLP

- ED from DLP
  - Adult
  - Pediatric

<table>
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<th>Region</th>
<th>$E_{DLP}$</th>
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</tr>
<tr>
<td>abdomen</td>
<td>0.019</td>
</tr>
</tbody>
</table>

$$ED (mSv) = E_{DLP} \left( \frac{mSv}{mGy \cdot cm} \right) \times DLP (mGy \cdot cm)$$

$E_{DLP}$ = anatomy-specific conversion factor
BASIS FROM DLP TO ED

CTDI data : phantom factor

Phantom Factor = $\frac{\text{CTDI}_{w}}{\text{CTDI}_{\text{air}}}$

Gelijns, K.
ImF vs Effective Dose

\[ y = 0.977x + 0.0203 \]

\[ R^2 = 0.977 \]
ED paper

• Hurwitz, Yoshizumi et al. Effective dose determination using an anthropomorphic phantom and MOSFET technology for clinical adult body multidetector array CT protocols, JCAT 31, 544-549, 2007
DUKE EXPERIENCE
16-slice GE scanner

- Comparison of Effective Dose Determined by the Dose Length Product (DLP) Method vs Direct Measurement with Metal Oxide Semiconductor Field Effect Transistor (MOSFET) Technology and an Anthropomorphic Phantom

Black columns = DLP method determination
White columns = MOSFET method determination
error bars = one SD

<table>
<thead>
<tr>
<th>CT Protocol</th>
<th>Effective Dose (mSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Chest</td>
<td>4.6 ± 0.81</td>
</tr>
<tr>
<td>PE Chest</td>
<td>11 ± 2.0</td>
</tr>
<tr>
<td>Coronary CTA</td>
<td>16 ± 4.0</td>
</tr>
<tr>
<td>Renal Stone</td>
<td>3.9 ± 0.51</td>
</tr>
<tr>
<td>Abdomen-Pelvis</td>
<td>11 ± 2.0</td>
</tr>
</tbody>
</table>

4.6 6.81 16.4 20.6 3.9 4.51 13.3
DUKE EXPERIENCE

• While the DLP method has been clinically used to estimate ED due to easy of calculations, this method may not be accurate in modern 16-slice and 64-slice scanners.

• The accuracy of absorbed organ dose and ED determination is important in radiation risk stratification for stochastic effects of radiation such as cancer induction.
TISSUE WEIGHTING FACTORS AND EFFECTIVE DOSE

- ED: \( E = \sum w_T \cdot H_T \)
  - \( w_T = \text{tissue weighting factor} \)
  - \( H_T = \text{equivalent dose} \)
- ED represents equivalent whole-body dose that would produce an equivalent detriment to the health of the individual
CONCEPT OF EFFECTIVE DOSE EQUIVALENT OR EFFECTIVE DOSE

- ICRP Report 26 (1977)
  - Dose Equivalent
  - Quality Factor
  - Weighting Factors
  - Effective Dose Equivalent

- ICRP Report 60 (1990)
  - Equivalent Dose
  - Radiation Weighting Factor
  - Tissue Weighting Factors
  - Effective Dose
**HISTORY OF TISSUE WEIGHTING FACTOR**

<table>
<thead>
<tr>
<th>Year</th>
<th>ICRP 26</th>
<th>ICRP 60</th>
<th>ICRP draft</th>
</tr>
</thead>
<tbody>
<tr>
<td>1977</td>
<td>Gonads 0.25</td>
<td>Gonads 0.20</td>
<td>BM, Colon, Breast, Lung, Stomach 0.12</td>
</tr>
<tr>
<td></td>
<td>Breast 0.15</td>
<td>Breast 0.05</td>
<td>Bladder Gonads Liver 0.05</td>
</tr>
<tr>
<td></td>
<td>RBM 0.12</td>
<td>RBM 0.12</td>
<td>Oesoph Thyroid 0.05</td>
</tr>
<tr>
<td></td>
<td>Lung 0.12</td>
<td>Lung 0.12</td>
<td>Skin, BS, Brain, Kidneys, Salivary glands 0.01</td>
</tr>
<tr>
<td></td>
<td>Thyroid 0.03</td>
<td>Thyroid 0.05</td>
<td>Remainder 0.10</td>
</tr>
<tr>
<td></td>
<td>BS 0.03</td>
<td>BS 0.01</td>
<td>Remainder 0.05</td>
</tr>
<tr>
<td></td>
<td>Remainder 0.30</td>
<td>Remainder 0.05</td>
<td></td>
</tr>
</tbody>
</table>
CTDI – How to measure?
The Measurement, Reporting, and Management of Radiation Dose in CT

Report of AAPM Task Group 23
of the Diagnostic Imaging Council CT Committee

January 2008
CTDI – How to measure?

- AAPM Report 1 (1977)
A. CHANGING TECHNOLOGIES

- # SLICES & DETECTOR WIDTH
  - 64 slices – 40 mm width (05-06)
  - 256 slices – 128 mm width (2007)
  - 320 slices – 160 mm width (2008)

Note:
- CTDI phantom length – 150 mm
- CT pencil ion chamber – 100 mm
Also addressed is the concern that as radiation beam widths for multi-slice scanners get wider, the current methodology based on the measurement of the integral of the single slice profile using a 10 cm long ion chamber (CTDI$_{100}$) may no longer be adequate. It is shown that this measurement would underestimate the equilibrium dose and dose line integral by about 20% in the center of the body phantom, and by about 10% in the center of the head phantom for a 20 mm nominal beam width in a multi-slice scanner.
Toshiba Aquilion One (2008)

- 12.8 cm detector (2007) to 16 cm detector coverage (320 x 0.5 mm), 0.35 SEC ROTATION
CTDI MEASUREMENT

Active chamber length 100 mm

20 mm (4-, 8-, 16-slice) 1998-2002
40 mm (64-slice) 2006
128 mm (256-slice) 2007
Recall the meaning of CTDI

• The equivalent of the dose value inside the irradiated slice that would result if the absorbed radiation dose profile were entirely concentrated to a rectangular profile of width equal to the nominal thickness.

• All dose contributions from outside the nominal slice width are added to the area inside the slice.
Toshiba 160 mm (320-slice)

New 40 mm (64-slice)

Toshiba detector width 16 cm > 10 cm ion chamber

• Ion chamber no longer covers the entire tail portion of the single profile
• Toshiba detector width 16 cm > 10 cm ion chamber

100 mm

10 cm active length of ion chamber
FURTHER COMPLICATIONS

- as radiation beam widths for multi-slice scanners get wider, the current methodology based on the measurement of the integral of the single slice profile using a 10 cm long ion chamber \( (\text{CTDI}_{100}) \) may no longer be adequate
- UK NRPB Monte Carlo look-up table no longer valid because \( \text{CTDI}_{100} \) values are underestimated
- 64-slice beam width (4 cm)
- Conventional CTDI no longer applicable in 256-slice (~13 cm) and 320-slice (16 cm)
REVIEW OF CT DOSE ESTIMATION METHODS

A. Manual Look-up tables (Outdated)
B. Organ dose from CTDI (limited value)
C. Monte Carlo based dose calculator (limited)
D. Effective Dose from DLP (Limited)
E. Anthropomorphic phantom with TLDs (time consuming)
F. Anthropomorphic phantom with MOSFET (metal oxide semiconductor field effect transistor) detectors (current value)
### History of dosimetry program at Duke

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997</td>
<td>TLD program for organ dose Measurements In radiology</td>
</tr>
<tr>
<td>2000</td>
<td>First generation of MOSFET Technology purchased</td>
</tr>
<tr>
<td>2002</td>
<td>Adult, ped Phantoms Purchased, 2nd generation of MOSFET</td>
</tr>
<tr>
<td>2003</td>
<td>3rd generation of MODFET technology Mobile MOSFET</td>
</tr>
<tr>
<td>2005</td>
<td>Fluoro dose monitor software</td>
</tr>
<tr>
<td>2007</td>
<td>Dual Energy</td>
</tr>
</tbody>
</table>

- **1997**: TLD program for organ dose Measurements In radiology
- **2000**: First generation of MOSFET Technology purchased
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- **2003**: 3rd generation of MODFET technology Mobile MOSFET
- **2005**: Fluoro dose monitor software
- **2007**: Dual Energy
Interventional vascular radiology

GE CT scan
VALIDATION OF MOSFET TECHNOLOGY IN CT DOSIMETRY

- Physics paper

MOSFET detectors (Best Medical Canada Ltd. Ottawa, Canada)

Standard MOSFET dosimeter: silicon chip 1mm$^2$
active area 0.2mm x 0.2mm
WHAT IS MOSFET? (metal oxide semiconductor field effect transistor)

- Components
  - Metal gate electrode
  - SiO2 layer
  - Si substrate

- Current passes from source to drain if a negative voltage (threshold voltage) exists on gate (ON position)

- When irradiated causes a permanent shift in the threshold voltage of the transistor; this shift is proportional to the absorbed dose.

\[ V_t = V_{t1} - V_{t0} \propto \text{Dose} \]
CIRS ANTHROPOMORPHIC PHANTOMS AT DUKE

ADULT FEMALE (55 Kg)

ADULT MALE (70 Kg)

10-YR OLD

NEWBORN

5-YR OLD
TODAY’S TOPICS

1. CT patient dosimetry - why so important?
2. Recent changes that affect CT dosimetry
3. Factors affecting dose
4. Dose indices – yesterday, today and tomorrow
5. Review of dose estimation methods
6. Emerging issues and opportunities
EMERGING ISSUES AND OPPORTUNITIES

1. Dual Energy CT Scanner:
   Two Designs
   – Siemens’ Definition – Two x-ray tubes
   – GE VCT – One x-ray tube

2. Coronary CTA Dosimetry
Siemens - Dual Energy
Two x-ray tubes
GE Design- Single Tube

Pulsed Dual kV Scan on LightSpeed VCT

1. 80kV
2. Switch kV
   80kV → 140kV
3. 140kV

X-Ray Spectrum

80 kVp
140 kVp

FOV 50 cm

Time chart of Dual kV Scan

80kV 660mA
0.23 sec 0.12 sec 0.23 sec
0.58 sec

140kV 200mA

Cradle Move 40mm
1.7 sec 0.58 sec

Figure: 1
Siemens - Dual Energy

How it works
Single energy CT
What do we measure?

Material differentiation works because tissues have characteristic densities.
Dual Energy
How it works

- Two dominant absorption processes determine the total attenuation, Compton and Photoelectric effect, $\mu = \sigma + \tau$

- Two independent measurements are required to solve this
Dual Energy: How it works

- Total attenuation decreases with increasing energy.
- Attenuation is characteristic for each material, depends on photon energy and material density.
- X-ray absorption depends on the inner electron shells.
- DECT is sensitive to atomic number and density.
- DECT is not sensitive to chemical binding.
Dual Energy
How it works

Therefore:

- The previous formula can be written as a material decomposition:

\[ \mu = \alpha_1 \times \mu_1 + \alpha_2 \times \mu_2 \]

- It is not possible to distinguish between more than two materials of arbitrary density – but we can utilize the fact that body materials occur with specific densities and perform a three material decomposition.
Three material decomposition – the basis for clinical applications

Dual Energy CT
Functional Information
Dual Energy CT
Functional Information

... to obtain an individual material map for each material *)

*) not available in the DualEnergy application, at least not before VA20...
Separation of Iodine and Calcium: Automatic Bone-Removal

Courtesy of Klinikum Großhadern, Munich
Dual Energy Liver Protocol
Effective Dose
Siemens 64-slice Definition

Duke University 2008
<table>
<thead>
<tr>
<th>Liver</th>
<th>Scan protocol</th>
<th>DLP (mGy*cm)</th>
<th>ED (mSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Helical auto mA 140 kVp</td>
<td>167.78</td>
<td>2.52</td>
</tr>
<tr>
<td></td>
<td>DE</td>
<td>1250.25</td>
<td>18.75 (ED=DLP*0.015)</td>
</tr>
<tr>
<td></td>
<td>Beam tracking 21% reduction applied</td>
<td></td>
<td>14.82</td>
</tr>
<tr>
<td></td>
<td>140+80 cine combined</td>
<td>1033.29</td>
<td>15.50</td>
</tr>
<tr>
<td></td>
<td>140 cine only (0.8 s)</td>
<td>712.21</td>
<td>10.68 (phantom)</td>
</tr>
<tr>
<td></td>
<td>80 cine only (0.8 s)</td>
<td>321.09</td>
<td>4.82 (phantom)</td>
</tr>
</tbody>
</table>
CORONARY CTA

• Current issues
  ▪ High ED and organ dose

• New development
  ▪ retrospectively gated helical (RGH) vs. prospectively gated axial (PGA)
HIGH DOSE IN Coronary CT Angiography (CTA)

PAPERS:


• GE 64-slice VCT scanner
  - retrospectively gated helical (RGH)
    – ED 18-32 mSv
    – Breast 5-9 cGy
RETROSPECTIVELY GATED HELICAL (RGH) VS. PROSPECTIVELY GATED AXIAL (PGA)

- Tube current on continuously vs. tube current turned only during prescribed cardiac phase
- Table moves at constant velocity vs. table steps (moves) and shoots

Diagram:
- Retrospectively gated helical acquisition
- Prospectively gated axial acquisition - SnapShot Pulse
- Table moves
- X-ray exposure time
PROSPECTIVELY GATED AXIAL (PGA)

Reduced dose achieved (Duke Data):
RGH vs. PGA: 19 mSv vs. 6 mSv at 65 BPM
GE 64-slice VCT scanner

Adult vs. pediatric:
• Higher HR in ped (~100 bpm) may prevent to use PGA; must use RGH
NEW OPPORTUNITIES

• Radiochromic film dosimetry in diagnostic radiology
FROM 2-D TO 3-D DOSE VISUALIZATION

INSERT FILM AT EACH SECTION

3-D VISUALIZATION OF DOSE
Sections 11, 13, 16

Darker color change after exposure

unexposed

After exposure
Phantom

Slice 11 Results

Lung definition

CT Image

Vertebral body/spinal cord

Gafchromic Dose distribution
Slice 11 Results-Line Profiles

- Horizontal line profile at $y = 120$
  - raw data
  - N-tap MAF

- Horizontal line profile at $y = 295$
  - raw data
  - N-tap MAF

- Horizontal line profile at $x = 295$
  - raw data
  - N-tap MAF

Slice 11-Exposure Map
CONCLUSIONS

• Witnessing continued advancement of MDCT technology since the introduction in 1998;
• Collective dose to pts from CT continues to climb
• MDCT radiation dosimetry issues still lag behind the technology due to lack of new CTDI concept
• Many new exciting opportunities exist:
  – MOSFET, radiochromic film dosimetry, glass dosimetry, Monte Carlo code development.
• New CTDI still needs to be developed
  – CBCT geometry
CT DOSIMETRY REVIEW PAPERS IN PRINT

