Optimizing CT Dose and Image Quality for Different Patient Sizes

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Financial Disclosures

$ Dianna Cody, Ph.D.
   – Paid speaker for Medical Technology Management, Inc.

$ Michael McNitt-Gray, Ph.D.
   – UCLA Department of Radiology has a Master Research Agreement with Siemens Medical Solutions
Learning Objectives

• Understand how radiation dose for CT studies is currently estimated
• Understand the trade-offs of dose and image quality, especially for large (obese) patients and in pediatric patients
• Review of the manufacturers’ dose modulation methods and how these affect dose in different patients
Talk Outline

1. Radiation Dose Basics
2. Image Quality Basics
3. Patient Size and Its Relationship to Radiation Dose
4. The Effect of Patient Size on Radiation Dose and Image Quality
5. Tube Current Modulation Methods
6. Monte Carlo Simulation Methods for Radiation Dose
7. Summary and Practical Issues on how to balance image quality and radiation dose as a function of patient size
Radiation Dose Basics: Why Care About CT Dose?

There have been significant improvements in CT technology over the past decade
- Multidetector CT (4 -> 320 rows)
- Improved temporal resolution (1 sec -> .3 sec per rotation)
- Cardiac CT
- Dual source CT
- Dual energy CT

This has led to increase in clinical utilization
- Approx 10% per year

Increased utilization has led to concerns over radiation dose
Radiation Dose Basics: Why Care About CT Dose?

- CT has recently been identified as one of the leading contributors to medical radiation exposure (Mettler et al 2008)
  - 15% of diagnostic radiology procedures
  - 50% of medical exposure
  - 25% of total exposure
Radiation Dose Basics: How do we currently measure dose in CT?

Conventional Computed Tomography Dose Index (CTDI)

- Measure exposure in phantom (16 or 32 cm diameter) in 100 mm long pencil ionization chamber
- Using an axial scan (even if protocol is helical scan)
- Calculate

\[
CTDI_{100} = \frac{fCEL}{NT}
\]

\[
CTDI_w = \left[ \left( \frac{1}{3} CTDI_{\text{center}} \right) + \left( \frac{2}{3} CTDI_{\text{periphery}} \right) \right]
\]

\[
CTDI_{vol} = \frac{CTDI_w}{p}
\]
AAPM TG 111 is proposed a revised methodology

- Use small (Farmer) ionization chamber
- Scan helically if protocol is helical (scan axially if protocol is axial)
- In this way, the small chamber integrates dose received from entire scan (both primary and scatter from adjacent images)
- Attention paid to adjustment of pitch when **measuring surface dose** in helical protocol (surface dose variations)

- Zhang et al Med Phys
  March 2009

- Some important details (phantom, which measurements to make/report, etc.) to be ironed out. TG 200
Radiation Dose Basics: Organ Dose

- BEIR VII report (2005), ICRP 103 (2007) and previous ICRP reports all use dose to radiosensitive organs (in mGy; also known as equivalent dose, expressed in mSv) as a basis for estimating metrics that relate to risk.
- BEIR VII estimates risk based on organ, dose to that organ, age, gender, etc.
- ICRP 103 uses organ dose to estimate effective dose.
# Effective Dose

<table>
<thead>
<tr>
<th>Tissue</th>
<th>ICRP 60 weighting factor ( w_T )</th>
<th>ICRP 103 ( w_T )</th>
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<tr>
<td>Gonads</td>
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<td>0.08</td>
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<tr>
<td>Red Bone Marrow</td>
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<td>0.12</td>
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<td>Colon</td>
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<td>0.12</td>
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<tr>
<td>Lung</td>
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<td>Stomach</td>
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<td>Bladder</td>
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<td>Breast</td>
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<td>Liver</td>
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<td>Esophagus</td>
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<td>0.04</td>
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<td>Thyroid</td>
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<td>0.04</td>
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<tr>
<td>Skin</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Bone Surface</td>
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<td>0.01</td>
</tr>
<tr>
<td>Brain</td>
<td>(Remainder)</td>
<td>0.01</td>
</tr>
<tr>
<td>Salivary Glands</td>
<td>(Remainder)</td>
<td>0.01</td>
</tr>
<tr>
<td>Remainder (Adrenals, etc.)</td>
<td>0.05</td>
<td>0.12</td>
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</table>
Radiation Dose Basics: Summary

- CT provides tremendous diagnostic information
- Increased utilization and radiation dose are concerns
- Currently measure dose with CTDI in phantoms
- Methods proposed to revise this, but still use phantoms
- Risk is best indicated via organ dose
- ? Some way to link these two (organ dose and CTDI)?
Image Quality Basics

• Basic Descriptors
• Examples
• More detailed/complete descriptors
Image Quality Basic Descriptors

- Noise
- Spatial Resolution
- Low Contrast Resolution
Noise – Part 1

• In its *simplest* definition
  – is the measured standard deviation of voxel values in a homogenous (typically water) phantom

• Influenced by many parameters:
  – kVp
  – mA
  – Exposure time
  – Collimation/Reconstructed image Thickness
  – Reconstruction algorithm
  – Helical Pitch/Table speed
  – Helical Interpolation Algorithm
  – Others (Focal spot to isocenter distance, detector efficiency, etc.)
Reducing mAs Increases Noise

\[ \text{Noise} \propto \frac{1}{\sqrt{\text{mAs}}} \]

- If mAs is reduced by \( \frac{1}{2} \),
  - noise increases by \( \sqrt{2} = 1.414 \) \( \Rightarrow \) (40% increase)
Reducing image thickness increases noise.

- If image thickness is reduced by \( \frac{1}{2} \),
  - noise increases by \( \sqrt{2} \approx 1.414 \rightarrow (40\% \text{ increase}) \)

- Reducing image thickness (without making any other adjustments) has the same effect on noise as reducing mAs.
Reducing mAs Increases Noise
Reducing mAs Increases Noise
Reducing image Thickness Increases Noise
Reducing image Thickness Increases Noise
Increasing mAs to Offset Reduced image Thickness
Increasing mAs to Offset Reduced image Thickness
The radiologist would like to decrease the image thickness for a particular exam from 5mm to 2.5mm and maintain the same image quality. This will require what change in radiation dose?

0%  1. Radiation dose will have to be doubled (200%)
0%  2. Radiation dose will have to be tripled (300%)
0%  3. Radiation dose can stay the same
0%  4. Radiation dose will have to be decreased by 40%
0%  5. Radiation dose will not be affected if current modulation is utilized in this case.
The radiologist would like to decrease the image thickness for a particular exam from 5mm to 2.5mm and maintain the same image quality. This will require what change in radiation dose?

1. Radiation dose will have to be doubled (200%)

High Contrast (Spatial) Resolution

• High contrast or spatial resolution within the scan plane - determined using objects having a large signal to noise ratio.
• This test measures the system’s ability to resolve high contrast objects of increasingly smaller sizes (increasing spatial frequencies).
• Several quantitative methods have been described
  – E.g. MTF using a thin wire
High Contrast (Spatial) Resolution

- High contrast spatial resolution is influenced by factors including:
  - System geometric resolution limits
    - focal spot size
    - detector width
    - ray sampling,
  - Pixel size
  - Properties of the convolution kernel / mathematical reconstruction filter
Effect of Reconstruction Filter

MTFs for Filters B10f-B40f

MTF vs. spatial frequency (1/mm)
High Contrast (Spatial) Resolution

• However, increasing x-y plane resolution by via reconstruction algorithm can result in a TRADEOFF with a nominal increase (certainly a change) in noise
  – Increase in x-y plane resolution vs. Change in Noise
Noise – Part 2

• Standard deviation does not tell the whole story
120 kVp, 40mAs, Standard

120 kVp, 640 mAs, Bone

Same Standard Deviation
Spatial Frequency

Low spatial frequencies – large objects

High spatial frequencies – small objects
120 kVp, 40mAs, Standard

120 kVp, 640 mAs, Bone

Same Standard Deviation
Noise Power Spectrum

![Graph of Noise Power Spectrum](image-url)
Simulated 2 mm image of a sphere 55 HU from background. The standard deviation of noise in both images is 21.5 HU. Part (a) was reconstructed with filter B10. Part (b) was reconstructed with filter B50.

Boedeker and McNitt-Gray PMB 52 2007
Low Contrast Resolution

- Low contrast resolution is often determined using objects having a very small difference from background (typically from 4-10 HU difference).

- Because the signal (the difference between object and background) is so small, noise is a significant factor in this test.
Low Contrast Resolution

• This test measures the system’s ability to resolve low contrast objects of increasingly smaller sizes (increasing spatial frequencies).

• Influenced by many of the same parameters as noise
Low Contrast Resolution

• An example of a low contrast resolution phantom is that in used by the ACR CT Accreditation program.

• This phantom consists of:
  – A single 25mm rod for reference and measurements,
  – Sets of 4 rods, each is decreasing in diameter from:
    • 6mm,
    • 5mm,
    • 4mm
    • 3mm
    • 2mm (typically not visible unless a very, very high technique is used).
  – All approximately 6 HU from background
ACR Phantom Low Contrast Resolution

Image of Low Contrast section at 120 kVp, 1600 mAs to show all rods;
Low Contrast - Reducing mAs

120 kVp
240 mAs
5 mm
Std Algorithm
Low Contrast - Reducing mAs

120 kVp
80 mAs
5 mm
Std Algorithm
Low Contrast – Thinner images

120 kVp
240 mAs
5 mm
Std Algorithm
Low Contrast – Thinner images

120 kVp
240 mAs
2.5 mm
Std Algorithm
Impact for Clinical Images

• Some simulated lower dose exposures
Subject 1

- Adult Abdomen Pelvis
- Constant Tube Current
250 eff. mAs
Std dev = 18.3

40 eff. mAs
Std dev = 42.2

20 eff. mAs
Std dev = 60.0
Subject 2

• Adult Abdomen
• Tube Current Modulation (CareDose4D)
250 eff mAs

20 eff. mAs
250 eff mAs  
20 eff. mAs

Table Position in mm

Tube Current in mA
Summary

– Noise
  • Affected by many factors, including mAs and image thickness (influences z-axis resolution)
  • Not just standard deviation
    – It has magnitude and frequency content

– Spatial Resolution
  • In plane resolution affected by recon kernel
    – Which also impacts noise (magnitude and frequency content)
  • Z-axis resolution affected by image thickness
    – Which also impacts noise

– Low Contrast Resolution
  • Also affected by many factors, including noise
Current/Future Questions

– Dose Reduction Technologies
– Impacts of tube current modulation on noise
  • Should reduce dose but maintain noise
  • How to assess in the field? How to assess the dose reduction? How to ensure the noise is maintained?
Patient Size

Centers for Disease Control


CDC. State-Specific Prevalence of Obesity Among Adults — United States, 2005; MMWR 2006; 55(36);985–988
Obesity Trends* Among U.S. Adults
BRFSS, 1985
(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)
Obesity Trends* Among U.S. Adults
BRFSS, 1986
(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)
Obesity Trends* Among U.S. Adults
BRFSS, 1987

(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)

[Map of Obesity Trends among U.S. Adults with color-coded states indicating obesity percentage ranges: No Data, <10%, 10%-14%]
Obesity Trends* Among U.S. Adults
BRFSS, 1988
(*BMI ≥30, or ~30 lbs. overweight for 5’ 4” person)
Obesity Trends* Among U.S. Adults
BRFSS, 1989
(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)

No Data <10% 10%-14%
Obesity Trends* Among U.S. Adults
BRFSS, 1990

(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)
Obesity Trends* Among U.S. Adults
BRFSS, 1991

(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)
Obesity Trends* Among U.S. Adults
BRFSS, 1992
(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)

[Map showing obesity trends across the United States]

Legend:
- No Data
- <10%
- 10–14%
- 15–19%
Obesity Trends* Among U.S. Adults
BRFSS, 1993

(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)
Obesity Trends* Among U.S. Adults
BRFSS, 1994
(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)
Obesity Trends* Among U.S. Adults
BRFSS, 1995
(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)
Obesity Trends* Among U.S. Adults
BRFSS, 1996
(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)
Obesity Trends* Among U.S. Adults
BRFSS, 1997
(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)
Obesity Trends* Among U.S. Adults
BRFSS, 1998

(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)
Obesity Trends* Among U.S. Adults
BRFSS, 1999
(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)
Obesity Trends* Among U.S. Adults
BRFSS, 2000
(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)
Obesity Trends* Among U.S. Adults
BRFSS, 2001
(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)
Obesity Trends* Among U.S. Adults
BRFSS, 2002

(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)
Obesity Trends* Among U.S. Adults
BRFSS, 2003

(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)
Obesity Trends* Among U.S. Adults
BRFSS, 2004

(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)
Obesity Trends* Among U.S. Adults
BRFSS, 2005

(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)
Obesity Trends* Among U.S. Adults
BRFSS, 2006

(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)
Obesity Trends* Among U.S. Adults
BRFSS, 2007

(*BMI ≥30, or ~ 30 lbs. overweight for 5’ 4” person)
Obesity Trends* Among U.S. Adults
(*BMI ≥30, or about 30 lbs. overweight for 5’4” person)

1990

1998

2007

Cody BMI ~24
Add 35lbs, BMI 30

No Data <10% 10–14% 15–19% 20–24% 25–29% ≥30%
How do we design CT protocols?

• Initially for “standard” size patients
• Sooner rather than later, “large” size patients
• Maybe – “small” size patients?
How do we assess risk?

• Assumption: “standard” size patients
• May be ok for larger patients
  – Tend to use higher techniques on larger patients, who have more tissue to dissipate energy
  – Intensity of beam more gradually decreased, reduced risk to DNA?
• Underestimated for smaller adult patients
What is “standard” size?

• “Standard” man (dose models)
  • Size: 5’9” 160 pound male
  • Size: 5’4” 132 pound female
• How many roughly “standard” size folks here?
• How many larger than standard size?
• How many smaller than standard size?
Adjust protocols for large size patients?

- Tube current modulation
- Tube heat capacity may limit this approach
- Technique chart
  - Increase effective mAs by \( \sim 30\% \)*
  - Select a size criteria
  - DFOV \( \geq 42\text{cm} \)*

* MD Anderson approach
DFOV 48cm
120 kV
740 mA
0.8 sec/rotn
Pitch .984
600 eff mAs
Image quality for large patients sensitive to miscentering (truncation)
Siemens Sens-64

DFOV 50cm
140 kV
334 mA
1.0 sec/rotn
Pitch 0.5
10mm images
668 eff mAs

Mayo Clinic
James Kofler, Ph.D.
Blocked reference detector?
Patient size thresholds

- **Lateral width** the best predictor of acceptable image quality
  - $< 36 \text{ cm} \Rightarrow 80 \text{ kV}$ imaging acceptable
  - $< 41 \text{ cm} \Rightarrow 100 \text{ kV}$ imaging acceptable
  - $> 42 \text{ cm} \Rightarrow 120 \text{ kV}$

- Larger patients may not be able to undergo low kV imaging

- Patient size selection only insures good quality

JG Fletcher, MD
Mayo Clinic
Liver Protocol

- Multiple scan phases
- Prior Settings
  - 140 kVp
  - NI: 10 - 13
- Same multiple scan phases
- Trial Settings
  - kVp according to DFOV
  - NI unchanged (goal)
Patient Example

140 kVp  NI = 10

80 kVp  NI = 10
### Exam Description: CAP W CON-- LIVER

<table>
<thead>
<tr>
<th>Series</th>
<th>Type</th>
<th>Scan Range (mm)</th>
<th>CTDIvol (mGy)</th>
<th>DLP (mGy·cm)</th>
<th>Phantom cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Scout</td>
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**Total Exam DLP:** 7200.49

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### Dose Report

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<th>DLP (mGy·cm)</th>
<th>Phantom cm</th>
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**Total Exam DLP:** 1714.38

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**140 kVp effective dose 108 mSv**

**80 kVp effective dose 26 mSv**
Another example of a small patient (36cm DFOV)
No dose report available on prior exam.
When **appropriate window/levels are used**, the contrast difference is somewhat mitigated.
Preliminary Conclusions regarding lower kV for multi-phase liver CT

- May have great potential to reduce dose (and improve IQ) in SMALLER patients
- May improve IQ in larger patients but substantial dose benefit is unlikely
What about smaller patients?

• Pediatric patients become adult patients
  – On specific birthday (18 years?)
  – Big size change before and after birthday?
• Some adult patients are small
• Don’t benefit from extra radiation dose delivered from “standard” size protocols!
Adjust protocols for smaller size patients?

- Use tube current modulation
- For some TCM schemes, need to adjust noise target for smaller patients
- Technique chart
  - Decrease effective mAs by ~30%*
  - Select patient size criteria
  - DFOV ≤ 38cm*

*MD Anderson approach
VCT TCM w/reduced max mA

LS-16 manual technique
Pediatric Patients?

- Use tube current modulation
- For some TCM schemes, need to adjust noise target for smaller patients (as well as small adults)
- Technique chart
  - Select size criteria
  - Scale effective mAs for size
  - Consider using 80 & 100 kVp
# Color Coding for KIDS

<table>
<thead>
<tr>
<th>Color Selection</th>
<th>Protocol List</th>
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</thead>
<tbody>
<tr>
<td>1 Pink 6-7.4 kg (13.0-16.4 lbs) 58.5-66.5 cm</td>
<td>0.0.0 Protocol 0</td>
</tr>
<tr>
<td>2 Red 7.5-9.4 kg (16.5-20.4 lbs) 68.5-74 cm</td>
<td>0.0.1 Protocol 1</td>
</tr>
<tr>
<td>3 Purple 9.5-11.4 kg (20.5-22.4 lbs) 74-84.5 cm</td>
<td>0.0.2 Protocol 2</td>
</tr>
<tr>
<td>4 Yellow 11.5-14.4 kg (25.5-31.4 lbs) 84.5-97.5 cm</td>
<td>0.0.3 Protocol 3</td>
</tr>
<tr>
<td>5 White 14.5-18.4 kg (31.5-40.4 lbs) 97.5-110 cm</td>
<td>0.0.4 Protocol 4</td>
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<tr>
<td>6 Blue 16.5-20.4 kg (35.5-44.4 lbs) 110-122 cm</td>
<td>0.0.5 Protocol 5</td>
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<tr>
<td>7 Orange 22.5-31.4 kg (49.5-69.4 lbs) 122-137 cm</td>
<td>0.0.6 Protocol 6</td>
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<tr>
<td>8 Green 31.5-40.4 kg (69.5-88.4 lbs) 137-150 cm</td>
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<tr>
<td>9 Black 40.5-55 kg (88.5-121 lbs)</td>
<td>0.0.8 Protocol 8</td>
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![Color Coding for KIDS](image-url)
Image Gently and Protect Our Greatest Resource
<table>
<thead>
<tr>
<th>Zone</th>
<th>Wt</th>
<th>Length</th>
<th>Age</th>
<th>Chest</th>
<th>Abd Pelvis</th>
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<tbody>
<tr>
<td>PINK</td>
<td>5.5 – 7.4 kg</td>
<td>60-67 cm</td>
<td>2.5 – 5.5 mo</td>
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<tr>
<td>RED</td>
<td>7.5 – 9.4 kg</td>
<td>67-75 cm</td>
<td>5.5 – 11.5 mo</td>
<td>10.0</td>
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<td>PURPLE</td>
<td>9.5 – 11.4 kg</td>
<td>75-85 cm</td>
<td>11.5 – 22 mo</td>
<td>10.5</td>
<td>8.5</td>
</tr>
<tr>
<td>YELLOW</td>
<td>11.5 – 14.4 kg</td>
<td>85-97 cm</td>
<td>22 mo – 3yr, 2 mo</td>
<td>11</td>
<td>9.5</td>
</tr>
<tr>
<td>WHITE</td>
<td>14.5 – 18.4 kg</td>
<td>97-109 cm</td>
<td>3 ys, 2 mo – 5 yr, 2 mo</td>
<td>12</td>
<td>10.5</td>
</tr>
<tr>
<td>BLUE</td>
<td>18.5 – 23.4 kg</td>
<td>109-121 cm</td>
<td>5 yr, 2 mo – 7 yr, 4 mo</td>
<td>13</td>
<td>11.5</td>
</tr>
<tr>
<td>ORANGE</td>
<td>23.5 – 29.4 kg</td>
<td>121-133 cm</td>
<td>7 yr, 4 mo – 9 yr, 2 mo</td>
<td>14</td>
<td>12.5</td>
</tr>
<tr>
<td>GREEN</td>
<td>29.5 – 36.4 kg</td>
<td>133-147 cm</td>
<td>9 yr, 2 mo – 13 yr, 6 mo</td>
<td>15</td>
<td>13.5</td>
</tr>
<tr>
<td>BLACK</td>
<td>36.5 – 55 kg</td>
<td>&gt;147 cm</td>
<td>&gt;13 yr, 6 mo</td>
<td>16</td>
<td>14</td>
</tr>
</tbody>
</table>

Courtesy of Don Frush, M.D.

Noise Index
<table>
<thead>
<tr>
<th>Zone</th>
<th>Wt</th>
<th>Length</th>
<th>Age</th>
<th>Chest</th>
<th>Abd Pelvis</th>
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</thead>
<tbody>
<tr>
<td>PINK</td>
<td>5.5 – 7.4 kg</td>
<td>60-67 cm</td>
<td>2.5 – 5.5 mo</td>
<td>9.5</td>
<td>6.5</td>
</tr>
<tr>
<td>RED</td>
<td>7.5 – 9.4 kg</td>
<td>67-75 cm</td>
<td>5.5 – 11.5 mo</td>
<td>10.0</td>
<td>7.5</td>
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<tr>
<td>PURPLE</td>
<td>9.5 – 11.4 kg</td>
<td>75-85 cm</td>
<td>11.5 – 22 mo</td>
<td>10.5</td>
<td>8.5</td>
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<tr>
<td>YELLOW</td>
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<td>85-97 cm</td>
<td>22 mo – 3yr, 2 mo</td>
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Courtesy of Don Frush, M.D.
Effective mAs  |  CTDIvol  |  DLP
---|---|---
22.9% | 20.3% | 16.2%
29.1% | 28.4% | 22.3%
33.0% | 31.1% | 28.6%

Average reduction relative to baseline (%)

- TCM implemented
- TCM + NI increased
- TCM + NI increased + mA values lowered
Faster Acquisitions

- Multiple images per gantry rotation
- Reduce motion artifact
  - Peristalsis, cough, crying, voluntary motion …
- Enable reduction in pediatric sedations
  - Safer for children (no shields during scout!!)
  - Money and time savings
program sponsored by several professional organizations

goal is to remind staff to always use size specific radiographic techniques for kids

guidelines for designing pediatric CT protocols
  – Manual techniques – doesn’t have guidelines for tube current modulation

new materials helpful for parents

www.imagegently.com
# Pediatric Protocols for Siemens S64

Using Tube Current Mod. (CareDose4D) and changing kVp w/ size

<table>
<thead>
<tr>
<th>Weight</th>
<th>Chest</th>
<th>Abdomen</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kVp</td>
<td>Qref mAs</td>
</tr>
<tr>
<td>&lt; 5 kg</td>
<td>80</td>
<td>45</td>
</tr>
<tr>
<td>6-15 kg</td>
<td>80</td>
<td>55</td>
</tr>
<tr>
<td>16-60 kg</td>
<td>100</td>
<td>55</td>
</tr>
<tr>
<td>&gt; 60 kg</td>
<td>120</td>
<td>55</td>
</tr>
</tbody>
</table>

Based on Kim and Newman *AJR 2010; 194:1188–1193*
Dose Reduction Options

• Some Scanners offer capability to vary mA as tube rotates around patient
  – *Currently*, based on predicted values of attenuation (from 2 planning views)
  – *Future*, adjust mA to essentially perform AEC

- Shorter, less attenuating path- needs less mA
- Longer, more attenuating path- needs more mA
Dose Reduction Options

- Dose reduction based on patient anatomy
- Lower mA in AP, higher mA in lateral directions

Methods

- Patient attenuation measured during scout scan (AP & Lat) and alter mA for each gantry rotation (Smart mA\(^1\), Sure Exposure\(^2\), Z-DOM\(^3\) and/or “on-the-fly” (Care dose\(^4\))
- Use same kV in scout as in helical sequence \(^{1,2,3}\)
- Dose reduction of 20-40% has been reported

\(^1\) GE, \(^2\) Toshiba, \(^3\) Philips, and \(^4\) Siemens MDCT
Optimal mA for a.p. and lat. Views:
On-line mA modulation
AutomA and SmartmA automatically adjust tube current

- AutomA (Z) reduces noise variation allowing more predictable IQ. Dose reduction depends on User (Noise index = image noise)

- Smart mA (X,Y) reduces dose without significantly increasing image noise

Reduced mA

Prescribed mA

Incident X-ray flux decreased vs angle depending on patient asymmetry
Use of Scout Image for TCM

Att’n pattern

Patient shape & size

Att’n pattern

Patient shape & size
mA Modulation Scout Scans

Jim Kofler, Ph.D.
Tube Current Modulation

- Set noise target (or reference mAs)
- Set **minimum** & **maximum** mA limits
- Be sure the final scout is the one with the best image quality (AP vs Lateral)
## Current Modulation Schemes

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Parameter</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>GE</td>
<td>Noise Index</td>
<td>SD water phantom</td>
</tr>
<tr>
<td>Philips</td>
<td>Reference Image</td>
<td>Raw data, scout, SD in acceptable patient image</td>
</tr>
<tr>
<td>Siemens</td>
<td>Quality Ref. Eff. mAs</td>
<td>Adult - Eff. mAs for 70kg Peds – Eff. mAs for 25 kg</td>
</tr>
<tr>
<td>Toshiba</td>
<td>SD</td>
<td>SD water phantom</td>
</tr>
</tbody>
</table>
Tube Current Modulation methods may vary the tube current:

0% 1. In the x-y plane only
0% 2. Along the longitudinal direction only
0% 3. Along time such as at different patient visits
0% 4. In the x-y plane as well as longitudinal direction
0% 5. In the x-y plane, longitudinal direction and across time
Tube Current Modulation methods may vary the tube current:

0% 1.
0% 2.
0% 3.
0% 4. In the x-y plane as well as longitudinal direction
0% 5.

Tube Current Modulation methods may be able to take into account patient size:

0% 1. For pediatric and adult patients, including obese patients
0% 2. Only for morbidly obese patients
0% 3. Only for pediatric patients
0% 4. Only for Abdominal Scans
0% 5. Only for Thoracic Scans
Tube Current Modulation methods may be able to take into account patient size:

1. For pediatric and adult patients, including obese patients

Under what condition does Tube Current Modulation fail (produce images that radiologists find unacceptable for interpretation)?

0% 1. When X-ray tube has inadequate tube performance (output)
0% 2. When a minimum mA setting is used that is too low
0% 3. When a poor scout image is used for modulation planning
0% 4. When the patient table is either way too low or way too high in the gantry opening
0% 5. All of these conditions can cause tube current modulation schemes to produce images that would be considered unacceptable by an interpreting radiologist.
Under what condition does Tube Current Modulation fail (produce images that radiologists find unacceptable for interpretation)?

1. 
2. 
3. 
4. 
5. All of these conditions can cause tube current modulation schemes to produce images that would be considered unacceptable by an interpreting radiologist.

Bismuth Shields???

• Becoming ‘red’ state vs ‘blue’ state issue…
• If staff decide to use them:
  – Place on patient AFTER scouts are completed
  – If placed before scout, dose increased by ~15%
  – Shield alone decreased breast dose by 26%
  – Shield + TCM decreased breast dose by 52%
  – IMAGE QUALITY IMPACT
Advanced Image Reconstruction

• Several Approaches with Goals of:
  – Reducing Noise
  – Preserving Image Quality

• Non-linear Image Processing
  • Reduce Noise in smooth regions, preserve edges

• Iterative Reconstructions
  – Usually take longer and so have been employed on a limited basis.
  – faster computing may make these more popular.
Advanced Image Processing Algorithms

- Adaptive filtering at the projection level reduces noise as a function of attenuation.
- Non-linear image processing algorithms reduce noise in the image while maintaining sharpness.
Full dose: CTDIvol= 25.08mGy, 10mm slice thickness

Half dose: CTDIvol= 12.42mGy, 50% Volume ASIR, 10mm slice
Noise Reduction

FBP

ASIR
When compared to conventional Filtered Back Projection techniques, Iterative Reconstructions techniques can result in:

0% 1. An increase in radiation dose.
0% 2. Lower spatial resolution
0% 3. An increase in image noise
0% 4. A decrease in temporal resolution
0% 5. A decrease in low contrast resolution
When compared to conventional Filtered Back Projection techniques, Iterative Reconstructions techniques can result in:

0% 1. 
0% 2. Lower spatial resolution 
0% 3. 
0% 4. 
0% 5. 

Iterative Reconstruction Techniques result in a reduction in radiation dose by:

| 0%  |   1. Scanning the patient multiple times with reduced radiation mA and then iterating by minimizing errors in pixel values. |
| 0%  |   2. Iterating through different mA values until the ideal image quality is obtained |
| 0%  |   3. Scanning at a lower mA technique and then applying a smoothing and edge preserving function multiple times |
| 0%  |   4. Scanning at two different kVp levels until noise levels are obtained that are similar to conventional dose images. |
| 0%  |   5. Scanning at a lower mA technique and then iterating through different patient models until the ideal noise level is reached. |
Iterative Reconstruction Techniques result in a reduction in radiation dose by:

1. 

2. 

3. Scanning at a lower mA technique and then applying a smoothing and edge preserving function multiple times 

4. 

5. 

What should sites use for CT radiation dose limit guidance?

0% 1. AAPM Report 96 for head, chest, abd, pelvis exams only.
0% 2. Most recent NEXT survey for CT.
0% 3. AAPM Report 39 for head, chest, abdomen exams only.
0% 4. FDA equipment performance standard for CT
0% 5. American College of Radiology CT Accreditation dose limits for adult chest, adult abdomen, and pediatric abdomen exams only.
What should sites use for CT radiation dose limit guidance?

1. American College of Radiology CT Accreditation dose limits for adult chest, adult abdomen, and pediatric abdomen exams only.

Lessons learned (the hard way)…

• Monitor every protocol parameter, including **min mA**

• Caution techs regarding **changing patient orientation after scout/topogram**

• Scanner may revert to default manual technique (yet another set of parameters to set and monitor)

• **End of Section on Patient Size**
Monte Carlo Simulation Methods for Estimating Radiation Dose
Monte Carlo Simulation Methods for Estimating Radiation Dose

- Monte Carlo methods
  - Used in CT for some time
    - NRPB report 250 (1990)
    - GSF (Zankl)
Background

• These early reports used:
  – Detailed Models of Single Detector, Axial Scanners
  – Idealized (Nominal) collimation
  – Standard Man Phantom
    • MIRD V (geometric model) →
    • Eva, Adam
Background

• These form the basis for:
  – CT Dose computer program
  – CT Expo
  – ImPACT dose calculator
  – k factor approach (Effective dose = k* DLP), which was derived from NRPB simulated data
Current Approaches

- Model Scanner (e.g. MDCT) in detail
- Model Patient (Geometric, Voxelized)
- Simulate Scan
- Tally Organ Dose
Modeling the CT scanner

- **Spectra**
  - Function of beam energy
- **Geometry**
  - Focal spot to isocenter, fan angle
- **Beam Collimation**
  - Nominal or actual
- **Filtration**
  - Bowtie filter (typically proprietary)
  - Other add’l filtration (also proprietary)
- **Tube Current Modulation Scheme**
  - x-y only, z-only, x-y-z, etc.
Modeling the CT scanner

- **Source Path** - dependent on scan parameters:
  - Nominal collimation
  - Pitch
  - Start and Stop Locations (of the source)
Long Axis Modulation

- Shoulder Region
- Breast Tissue
- Lung Region
- Abdomen

Tube Current (mA)

Table Position (mm)

180 degrees (LAT)
90 degrees (AP)
Modeling the Patient

- Geometric
  - e.g. MIRD
  - Standard man
  - Often androgynous (male/female organs)
  - Usually single size
- Size and age variations
  - newborn, ages 1, 5, 10, and 15 years
  - adult female, and adult male
  - Including pregnant patient
Modeling the Patient

• All radiosensitive organs identified
  – Location
  – Size
  – Composition and density
Modeling the Patient

• Voxelized Models
  – Based on actual patient scans
  – Identify radiosensitive organs – usually manually
  – Non-geometric

• Different age and gender

• Different sizes
Modeling the Patient

- GSF models (Petoussi-Henss N, Zankl M et al, 2002)
  - Baby, Child, three adult females (shown), two adult males, Visible Human
  - All radiosensitive organs identified manually (ugh!)
Modeling the Patient

- Xu – pregnant patient, RPI-AM, RPI-AF
- Bolch – UF Phantoms
- Zubal – Adult male phantoms
- Several others (see http://www.virtualphantoms.org/)
Modeling (Parts of) the Patient

- Embryo/Fetus
- Breast
7 weeks (embryo not visible)
Mature Fetus:
36 weeks
Simulating the Scan

• Select Technical Parameters
  – Type of scan (helical, axial)
  – Beam energy
  – Collimation
  – Pitch
  – Tube Current/rotation time (or tube current modulation)

• Select Anatomic Region
  – Head/Chest/Abdomen/Pelvis/etc.

• Translate this to:
  – Start/stop location -> Source Path
Monte Carlo for CT Dose - Details

• Monte Carlo Packages
  – MCNP (Los Alamos)
  – EGS

• Model Transport of Photons from modified (CT) source

• Probabilistic interactions of photons with Tissues
  – Photoelectric, Compton Scatter, Coherent Scatter

• Tissues need detailed descriptions
  – Density
  – Chemical composition (e.g. from NIST web site)
Validating the CT Scanner Model

• Benchmark MC Model against physical measurements
  – CTDI Phantoms
    • Head and Body
    • Simulate a tally in a pencil chamber
    • Each kVp and beam collimation combination
    • Measured vs. Simulated
  – Aim for < 5% difference between Simulated and Measured
Monte Carlo Methods

- Used to Estimate Organ Doses
- MDCT scanner details
- Scan protocol details
- Different patient models

- Extendable to new geometries/methods
- Evaluate effectiveness of dose reduction methods on organ dose (and not just dose to phantoms)
- Detailed organ dose approach -> basis for simpler relationships (curve fits, regression equations, etc.)
Monte Carlo Methods and Patient Size
Fetal Dose (mGy/100 mAs) for Different Sized Moms and Gestational Age

<table>
<thead>
<tr>
<th>Gestational Age (weeks)</th>
<th>Maternal Perimeter (cm)</th>
<th>Fetal Depth (cm)</th>
<th>Normalized Fetal Dose (mGy/100mAs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 5</td>
<td>123</td>
<td>10.6</td>
<td>7.3*</td>
</tr>
<tr>
<td>5.0</td>
<td>89</td>
<td>4.2</td>
<td>11.8**</td>
</tr>
<tr>
<td>5.0</td>
<td>88</td>
<td>7.6</td>
<td>10.3**</td>
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<tr>
<td>6.6</td>
<td>102</td>
<td>10.9</td>
<td>8.8**</td>
</tr>
<tr>
<td>7.1</td>
<td>90</td>
<td>5.9</td>
<td>12.6**</td>
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<tr>
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<td>88</td>
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Mean: 19.7 101 6.1 10.8

Angel et al
Radiology
Oct. 2008
Fetal Dose as a Function of Patient Perimeter

$y = -0.12x + 23.11$

$R^2 = 0.68$
The Monte Carlo approach to estimating radiation dose from CT is most often used to:

1. Measure CTDI for each scanner
2. Estimate the limitations of CTDI
3. Estimate dose to radiosensitive organs
4. Determine detector efficiencies
5. Determine which MDCT scanner is the most dose-efficient
The Monte Carlo approach to estimating radiation dose from CT is most often used to:

1. Estimate dose to radiosensitive organs


Tube current versus x-axis location of the TCM schema for a patient model with a perimeter of 125cm. Background is a sagittal view of the patient.
Breast dose versus patient perimeter for all 30 patient models in the fixed tube current simulations. Breast dose decreases linearly with an increase in patient perimeter (R²=0.76).
Breast dose versus patient perimeter for all 30 patient models in the TCM simulations. Breast dose increases linearly with an increase in patient perimeter (R²=0.46).
Percent dose reduction for the TCM simulations as compared to the fixed tube current simulations. Dose reduction decreases linearly with an increase in patient perimeter ($R^2=0.81$).
When Tube Current Modulation methods are employed in thoracic scans of adult female patients and compared to fixed tube current scans:

0% 1. Radiation dose to glandular breast tissue is always reduced
0% 2. Radiation dose to glandular breast tissue is always increased
0% 3. Radiation dose to glandular breast tissue remains the same
0% 4. Radiation dose to glandular breast tissue is reduced only for large patients
0% 5. Radiation dose to glandular breast tissue is reduced only for small patients
When Tube Current Modulation methods are employed in thoracic scans of adult female patients and compared to fixed tube current scans:

1. Radiation dose to glandular breast tissue is reduced only for small patients.

CTDI$_{\text{vol}}$ and DLP

• **CTDI$_{\text{vol}}$ currently 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)
Scenario 1: No adjustment in technical factors for patient size

CTDI$_{vol}$ = 20 mGy

The CTDI$_{vol}$ (dose to phantom) for these two would be the same
Scenario 2: **Adjustment** in technical factors for patient size

50 mAs

![32 cm phantom](CTDI\textsubscript{vol} = 10 mGy)

100 mAs

![32 cm phantom](CTDI\textsubscript{vol} = 20 mGy)

The CTDI\textsubscript{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.
Organ Dose Independent of Scanner
Organ dose (in mGy/mAs) and effective dose (in mSv/mAs) for GSF model Irene resulting from a whole body scan with similar parameters for each scanner.
Organ dose and effective dose normalized by measured CTDIvol for GSF model Irene resulting from a whole body scan.
Normalized Organ Dose as function of Pt. Size
(Abdomen Scans for each Patient)

$y = 3.780e^{-0.011x}$

$R^2 = 0.970$

Mean organ dose/CTDI$_{vol}$ across scanners

Patient Perimeter (cm)

- Stomach
- Liver
- Adrenals
- Gall Bladder
- Kidney
- Pancreas
- Spleen

Expon. (Stomach)

Turner et al RSNA 2009
Future of Dosimetry?

- Patient Size info
- Size Coefficients
- CTDI$_{vol}$ (or TG 111)

Patient Organ Dose
- Accounting for patient size
- Accounting for scanner
- Accounting for anatomic region
Summary

• There are trade-offs of dose and image quality in CT
• These can be especially important for large (obese) patients and in pediatric patients
• Lots of methods being developed to help with these tradeoffs:
  – Dose Reduction methods such as TCM
  – Image Recon methods such as Iterative Methods (ASIR, etc.) to reduce noise (and allow lower dose scans)
Summary

• Not always straightforward solutions
  – Informed Physicist input can help tremendously to obtain best results across all situations (Is there really a “routine” scan?)

• Methods being developed to provide realistic estimates of patient dose

• Movement to use Quantitative Methods for Image Quality (e.g. Noise Power Spectrum)