The Latest in Radiation Dose Reduction Techniques in CT

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DISCLOSURES

Research Support:
NIH: EB 079861
     DK 083007
     DK 059933
     EB 04898
     RR 018898

Siemens Healthcare

Off Label Usage
None
CT Dose per exam

• The radiation dose required to produce images of sufficient quality to answer the clinical question

• CTDIvol for a routine abdomen exam
Routine Body CT Doses over 2 Decades

All solid state detectors

European Commission 2000 Reference Value

American College of Radiology 2007 Reference Value

CTDvol (mGy)

10 mm section width

7 - 10 mm

1 - 5 mm

Picker 1200 (3.3 mm Al)
Picker 1200 (5.2 mm Al)
Imatron EBCT (10 mm Al)
GE 9800 (7.3 mm Al)
GE HiSpeed (7.1 mm Al)
GE LightSpeed 16 (8.3 mm Al)
Siemens Sens. 64 (9.5 mm Al)

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Clinical Impact

- Dose has decreased since 1980s by a factor of 2-3
- Expect another factor of 2 (at least)
# Dose Reduction Techniques

<table>
<thead>
<tr>
<th>Technique</th>
<th>Cardiac CT</th>
<th>Non-Cardiac CT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube current (mA) modulation (i.e. Automatic Exposure Control)</td>
<td>ECG-based</td>
<td>Attenuation-based</td>
</tr>
<tr>
<td>Axial (non-spiral) cardiac modes</td>
<td>Yes</td>
<td>N/A</td>
</tr>
<tr>
<td>Increased spiral pitch</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Organ-based tube current modulation</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Active Z-axis collimation</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Optimized tube potential (kV)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Noise reduction algorithms</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>- Projection space based (i.e. require raw data)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>- Image based</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

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AEC: Automatic Exposure Control
X-ray attenuation

- Varies over body region and with projection angle
- Noise in final image is primarily determined by the smallest number of detected photons.
- The larger number of detected photons along other directions is unnecessary radiation dose
Three Levels of AEC

• For a single cross section, automatically adjust the mA along different directions
  – (x-y modulation)

• For a single patient, automatically adjust the mA for different body parts
  – (z modulation)

• For different patients, automatically adjust the mA based upon the patient size
  – “Right sizing” dose for each patient
Example: 6 year old child

Scanned with adult protocol
(but using AEC dose reduction strategy)

Reference eff. mAs = 165

Mean eff. mAs = 38
Cardiac AEC

- Varying mA with angle or z position risks having low dose data at the needed angle/position
- Instead modulation based on phase within the cardiac cycle
Spiral Mode
ECG-based mA modulation

max. mA

0 mA

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Adjustable Phase Width

Variable width

max. mA

0 mA

© Mayo Clinic 2009
Adjustable minimum mA

Variable height

max. mA

0 mA
Sequential Mode

max. mA  

0 mA

Move table

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Arrhythmia Detection

Spiral

Axial

Scan

Move

React

Move

Scan

Move

Scan

Repeat Scan
Single source CT: upper pitch limit 1.5 for gapless z-sampling

32 row detector, slice width: 0.6 mm, pitch: 1.5 Rf=595 mm, Rd=490.6 mm, p=0 mm
Single source CT: upper pitch limit 1.5 for gapless z-sampling
Faster table feed: z-sampling gaps, degradation of image quality
Single source CT: upper pitch limit 1.5 for gapless z-sampling

Dual source CT: up to pitch 3.4 possible, depending on SFOV
Spiral “Flash” Mode (dual-source CT only)
Spiral “Flash” Mode


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Image quality evaluation

Retrospectively gated spiral

- 120 kV, 240 mAs/rot
- Pulsing 60-70%, 20% strength, ~60 bpm, pitch 0.23
- CTDIvol 30.5 mGy, DLP 560 mGy-cm
- Effective dose 7.8 mSv

High Pitch Spiral

- 100 kV, 300 mAs/rot
- ~60 bpm, pitch 3.4
- CTDIvol 2.9 mGy, DLP 60 mGy-cm
- Effective dose 0.8 mSv
Reference: Bismuth (-41%) "X-Care" (-46%)

Courtesy of Jia Wang, PhD
Active z-axis collimation to reduce over-scanning
Active z-axis collimation to reduce over-scanning
Active z-axis collimation to reduce over-scanning

0.5 – 1.5 mSv reduction in effective dose for common scan types*

*Christner et al. Dose reduction in helical CT: Dynamically adjustable z-axis beam collimation

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Background

- Majority of abdominal CT scans: 120 kV
- It is possible to reduce to 80-90 kV*
- Benefits of low-kV CT:
  - Radiation dose reduction**
  - Increased contrast provides increased conspicuity to enhancing lesions and structures ***

*Funama, et al., Radiology 2005
*Nakayama, et al., Radiology 2005
**Ende, et al., Invest Radiol 1999
**Huda, et al., Med Phys 2004
***Nakayama, et al. AJR 2006
Lower-kV Benefits – Increased Iodine Contrast

120 kV, CTDI$_{vol}$=5.18 mGy

100 kV, CTDI$_{vol}$=3.98 mGy

Courtesy of J.G. Fletcher, MD
Lower-kV Risks – Increased Noise or Artifacts
100 kV vs. 120 kV

100 kV, 330 mAs  (< 85 kg body weight)  120 kV, 330 mAs

Images courtesy of Ropers et al, Univ of Erlangen
<table>
<thead>
<tr>
<th>Dose Predictor</th>
<th>Effect on Dose (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrocardiographically controlled tube current modulation</td>
<td>$-25 (-23$ to $-28) &lt; .001$</td>
</tr>
<tr>
<td>Tube voltage, 100 kV vs $\geq 120$ kV</td>
<td>$-46 (-42$ to $-51) &lt; .001$</td>
</tr>
<tr>
<td>Sequential vs spiral scanning</td>
<td>$-78 (-77$ to $-79) &lt; .001$</td>
</tr>
</tbody>
</table>

Hausleiter et al. “Estimated Radiation Dose Associated with Cardiac CT Angiography,” JAMA 2009
The appropriateness of using lower-kV is highly dependent on patient size and diagnostic task.
General Strategy for Automatic kV selection

- Incorporate both the patient size and diagnostic task into kV selection process
- Iodine CNR is not a sufficient image quality index
- Must also constrain image noise

\[ \text{CNR} \geq \text{CNR}_{\text{ref}}, \quad \text{and} \quad \sigma \leq \alpha \cdot \sigma_{\text{ref}} \]

- Relative dose factor (RD)
  - Determine relative dose at each tube potential needed to achieve the same CNR as at the reference kV
  - A function of patient size, diagnostic task, and noise constraint \( \alpha \)
Workflow for Automatic kV Selection

- Acquire a CT radiograph (e.g., topogram, scout)
- Select a scanning technique (mAs, pitch) at a reference kV
- Select the noise constraint parameter
  - CT angiogram: minimal noise constraint ($\alpha = 1.5-2.0$)
  - Routine contrast enhanced chest: moderate noise constraint ($\alpha = 1.1-1.25$)
  - Routine non-contrast enhanced chest: maximum noise constraint ($\alpha = 1.0$)
- Calculate the relative dose (RD)
- Choose the most dose-efficient kV (with the smallest RD), and adjust the mAs, rotation time, and/or pitch
A semi-anthropomorphic thoracic phantom and three additional layers of attenuation were used to represent XS to XL adults.
patient lateral width

**Input Parameters**
- Patient Size (cm): 38
- Reference kV: 120
- QRM (mAs): 240
- CTDI (mGy): Optional 16.8
- Scan Time(s): Optional 10

**Protocol**
- Chest
- CT Angiography

**Outputs**
- Voltage (kV): 80, 100, 120, 140
- QRM (mAs): 712, 281, 240, 258
- Rot. Time (s): 0.5, 0.5, 0.5, 0.5
- Pitch: 1.0, 1.0, 1.0, 1.0
- Eff. mAs: 644, 239, 233, 215
- CTDI (mGy): 12.17, 10.07, 16.80, 23.30
- RD: 0.72, 0.60, 1.00, 1.39

**Image Quality Metric**
- CNR + Noise Constraints: 1.5

**Optimized Output**
<table>
<thead>
<tr>
<th>kV</th>
<th>QRM</th>
<th>Rot. (s)</th>
<th>Pitch</th>
<th>Eff. mAs</th>
<th>CTDI</th>
<th>RD</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>281</td>
<td>0.5</td>
<td>1.0</td>
<td>239</td>
<td>10.07</td>
<td>0.60</td>
</tr>
</tbody>
</table>

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Courtesy of Hua Li, PhD
# Optimal kV Settings

Optimal kV based on RD for different phantom sizes with different noise constraints

<table>
<thead>
<tr>
<th>Noise Constraint $\alpha$</th>
<th>Extra Small</th>
<th>Small</th>
<th>Medium</th>
<th>Large</th>
<th>Extra Large</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>80</td>
<td>100</td>
<td>100</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>1.25</td>
<td>80</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>1.50</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>2.00</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

$\alpha = 1.0$: Routine non-contrast exams  
$\alpha = 1.25$: Routine contrast-enhanced exams  
$\alpha = 1.5$: CTA with minimal noise constraint  
$\alpha = 2.0$: CT exams no noise constraint

Courtesy of Hua Li, PhD
Dose Reduction vs Noise Level

Noise Constraint $\alpha$

- $\alpha = 1.0$
- $\alpha = 1.25$
- $\alpha = 1.5$
- $\alpha = 2.0$

Dose Reduction

- Extra Small
- Small
- Medium
- Large
- Extra Large

Courtesy of Hua Li, PhD
Dose Reduction vs Phantom Size

Phantom Size

Dose Reduction

Extra small  Small  Medium  Large  Extra Large

α=1.0
α=1.25
α=1.5
α=2.0

Courtesy of Hua Li, PhD
Abdominal Phantoms

25 cm

30 cm

35 cm

40 cm

45 cm

50 cm

55 cm

Courtesy of Lifeng Yu, PhD
### Optimal kV – Abdominal CT

Optimal kV based on RDF for different phantom sizes with different noise constraint parameters

<table>
<thead>
<tr>
<th>Noise Constraint $\alpha$</th>
<th>25 cm</th>
<th>30 cm</th>
<th>35 cm</th>
<th>40 cm</th>
<th>45 cm</th>
<th>50 cm</th>
<th>55 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>140</td>
</tr>
<tr>
<td>1.25</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>120</td>
<td>120</td>
<td>140</td>
</tr>
<tr>
<td>1.50</td>
<td>80</td>
<td>80</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>120</td>
<td>140</td>
</tr>
<tr>
<td>2.00</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>100</td>
<td>100</td>
<td>120</td>
<td>140</td>
</tr>
</tbody>
</table>

- $\alpha = 1.0$: Routine non-contrast exams
- $\alpha = 1.25$: Routine contrast-enhanced exams
- $\alpha = 1.5$: CTA with noise constraint
- $\alpha = 2.0$: CTA without noise constraint

Courtesy of Lifeng Yu, PhD
Dose Reduction – Abdominal CT

Dose reduction at the optimal kV relative to 120 kV for different phantom sizes with different noise constraint parameters

<table>
<thead>
<tr>
<th>Noise Constraint $\alpha$</th>
<th>25 cm</th>
<th>30 cm</th>
<th>35 cm</th>
<th>40 cm</th>
<th>45 cm</th>
<th>50 cm</th>
<th>55 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1.25</td>
<td>36%</td>
<td>27%</td>
<td>25%</td>
<td>11%</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1.50</td>
<td>42%</td>
<td>34%</td>
<td>26%</td>
<td>18%</td>
<td>9%</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2.00</td>
<td>53%</td>
<td>49%</td>
<td>42%</td>
<td>18%</td>
<td>9%</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

- $\alpha = 1.0$: Routine non-contrast exams
- $\alpha = 1.25$: Routine contrast-enhanced exams
- $\alpha = 1.5$: CTA with noise constraint
- $\alpha = 2.0$: CTA without noise constraint
Projection-Based Noise Reduction Algorithms
IR: Iterative Reconstruction

Noise reduction enables dose reduction
Standard reconstruction

Projection data → Reconstruction → Result images
Iterative reconstruction

Projection data → +/- → Reconstruction → Result images

Reprojection
Many Different Approaches

- Algebraic reconstruction technique
  - ART
- Statistical iterative reconstruction
- Compressed sensing based methods
  - Convex and non-convex
- ...

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Like solving a big sudoku puzzle
Iterative Reconstruction

Standard recon

Iterative recon

Iterative Reconstruction

Standard recon

Iterative recon

Image-Based Noise Reduction Algorithms
Adaptive Filtering (2D or 3D)

Original Image → Perform edge detection

If edges – leave alone → If no edges - smooth

Recombine preserved edges with smoothed background → Final Image
Original 61.5 HU

3D Edge Preserving Noise Reduction 36.3 HU

- 41%

Courtesy of R. Raupach
NR minus Original

3D Edge Preserving Noise Reduction (NR)

- No smoothing of contours
- Difference essentially shows noise

Courtesy of R. Raupach
HYPR-LR
Highly constrained back Projection Local Reconstruction

Noise reduction for time-resolved CT (e.g. perfusion CT)

Image Quality Comparison

Full dose

SNR = 4.18

1/10th dose

SNR = 1.29

1/10th dose
HYPR-LR processed

SNR = 2.96
Full dose

1/10th dose, HYPR-LR processed

Liu et al
Radiology
In Press
MBF: Multiple band filtration

TSFF: Targeted Spatial Frequency Filtration

Noise reduction for perfusion CT brain CT (and more)
Multi-Band Filter (MBF): Step 1

- Time series of image data

$I_{t-1}$ $I_t$ $I_{t+1}$

- Decompose each frame into multiple frequency bands
Multi-Band Filter (MBF): Step 2

- Temporal filtering

Temporal filtering

\[ I_t' = \sum_{t-2}^{t+2} I_t \]
Effect of MBF

- noise reduction by a factor 2.5
- time-density information preserved
Measured Brain Perfusion Data

original  MBF
Thank you

Mayo CT Clinic Innovation Center and Dept. of Radiology
Lifeng Yu, Shuai Leng, Jim Kofler

http://mayoresearch.mayo.edu/CTCIC