Implementation of low dose CT strategies: How low is too low

Cynthia H. McCollough, PhD, DABR, FAAPM, FACP, FAIMBE
Director, CT Clinical Innovation Center
Professor of Medical Physics and Biomedical Engineering
Mayo Clinic, Rochester, MN

DISCLOSURES

Research Support:

<table>
<thead>
<tr>
<th>NIH</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>EB 017095</td>
<td>Siemens Healthcare</td>
</tr>
<tr>
<td>EB 017185</td>
<td>Mayo Center for Individualized Medicine Award</td>
</tr>
<tr>
<td>EB 016966</td>
<td></td>
</tr>
<tr>
<td>DK 100227</td>
<td></td>
</tr>
<tr>
<td>RR 018898</td>
<td></td>
</tr>
</tbody>
</table>

Off Label Usage
None
Radiation dose reduction over 4 decades of CT

Computerized transverse axial scanning (tomography). Part I. Description of system.
G.N. Hounsfield

Computerized transverse axial scanning (tomography). Part II. Clinical application.
J. Ambrose

1973, British Journal of Radiology, 46, 1048–1051

Computerized transverse axial scanning (tomography): Part 3. Radiation dose considerations
By B. J. Perry and C. Bridges
St. Georges Hospital, London S.W.1, and St. Georges Hospital, London S.W.17
Patient Dosage in Computed Tomography

Edwin C. McCullough, Ph.D., and J. Thomas Payne, Ph.D.

The maximum surface dosage in most clinical CT scans seems to range from 2–10 rads/study but much larger dose per study values seem possible with both rotate-translate and rotary geometry designs. The CT scanner type in itself does not significantly reduce doses. Secondary radiation dose values were measured for critical organs and indicate that dosage from secondary radiations may be reduced significantly by external shielding. Dose values in the vicinity of most CT scanners are typically 1–2 mrad/scan at 1 meter at the parameters of a typical clinical scan.

INDEX TERMS: Computed tomography, dosimetry • Computed tomography, instrumentation • Computed tomography, radiation dose

Radiology 129:457–463, November 1978

<table>
<thead>
<tr>
<th>Table I: Single-scan patient doses in CT scanning (rotate-translate)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CT Unit</strong></td>
</tr>
<tr>
<td>---------------</td>
</tr>
<tr>
<td>EM Mark I</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Pfizer 0100</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Pfizer 0200</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Delta 25</td>
</tr>
<tr>
<td>Delta 30</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Siemens</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table I: Single-scan patient doses in CT scanning (rotary)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CT Unit</strong></td>
</tr>
<tr>
<td>---------------</td>
</tr>
<tr>
<td>Amer. Sci. and Eng.</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Artronix Torscanner</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Delta 2020-P</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>GE CT/T-7800</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>GE CT/T-8800-P</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Siemens Somatom</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

14 – 195 mGy

5 – 560 mGy
Radiation dosimetry survey of computed tomography systems from ten manufacturers

By T. B. Shope, Ph.D., T. J. Morgan, Ph.D., C. K. Showalter, M.S.
Bureau of Radiological Health, Food and Drug Administration, Rockville, Maryland 20857, USA
K. S. Pentlow, M.Sc. and L. N. Rothenberg, Ph.D.
Department of Medical Physics, Memorial Sloan-Kettering Cancer Center, New York, New York 10021, USA
D. R. White, Ph.D.

A method for describing the doses delivered by transmission x-ray computed tomography

Thomas B. Shope, Robert M. Gagne, and Gordon C. Johnson

Bureau of Radiological Health, Food and Drug Administration, 5600 Fishers Lane, Rockville, Maryland 20857
≈ 50% of values between 22 and 68 mGy

Mean MSAD = 38 ± 16 mGy (3rd generation)
Mean MSAD = 58 ± 22 mGy (4th generation)
252 scanners, sampled nationwide

Again used MSAD as dose descriptor

Typical head exam was 34 – 55 mGy

- Distribution of doses more narrow than in prior survey (22-68 mGy)

Doses up to 140 mGy observed

Variations in factor of 2 or more observed for identical units

Variability across models and practices

Table 2. Patient and CT Scan Characteristics for 64-Slice Coronary CT Angiography

<table>
<thead>
<tr>
<th></th>
<th>GE 64 (n = 584)</th>
<th>Philips 64 (n = 123)</th>
<th>Siemens 64 Single-Source (n = 390)</th>
<th>Siemens 64 Dual-Source (n = 521)</th>
<th>Toshiba 64 (n = 138)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body mass index</td>
<td>25.9 (23.2-29.4)</td>
<td>27.5 (25.4-29.7)</td>
<td>25.8 (23.4-28.4)</td>
<td>26.3 (24.1-28.7)</td>
<td>26.0 (24.3-29.4)</td>
</tr>
<tr>
<td>CTDIvol, mGy</td>
<td>77.3 (51.3-99.6)</td>
<td>47.0 (42.0-52.9)</td>
<td>39.6 (35.5-65.8)</td>
<td>47.8 (35.6-60.8)</td>
<td>88.0 (60.3-121.1)</td>
</tr>
</tbody>
</table>

Hausleiter et al, Estimated Radiation Dose Associated With Cardiac CT Angiography. JAMA 2009
ACR CT Accreditation Program
Diagnostic Reference Levels (CTD\textsubscript{vol})

- **Reference doses** 2002
  - Adult Head 60 mGy
  - Adult Abdomen 35 mGy
  - Pediatric (5 yr old) Abdomen 25 mGy

ACR CT Accreditation Program
Diagnostic Reference Levels (CTD\textsubscript{vol})

- **Reference doses** 2002 2005
  - Adult Head 60 → 75 mGy
  - Adult Abdomen 35 → 25 mGy
  - Pediatric (5 yr old) Abdomen 25 → 20 mGy
U.S. Diagnostic Reference Levels and Achievable Doses for 10 Adult CT Examinations


**Head CT**

![Graph showing CT Dose and Reference Levels](image)

**Abdomen/pelvis CT with contrast**

![Graph showing CT Dose and Reference Levels](image)
ACR CT Accreditation Program
Diagnostic Reference Levels (CTD_{vol})

- **Reference doses**
  - Adult Head: 60 → 75 mGy → ≈ 60 mGy
  - Adult Abdomen: 35 → 25 mGy → ≈ 15 mGy
  - Pediatric (5 yr old) Abdomen: 25 → 20 mGy

**Routine Body CT Doses over 3.7 Decades**

- All solid state detectors
- European Commission 2000 Reference Value
- American College of Radiology 2007 Reference Value
- American College of Radiology 2017 Reference Value

<table>
<thead>
<tr>
<th>Year</th>
<th>Picker 1200 (1.3 mm Al)</th>
<th>Picker 2200 (1.5 mm Al)</th>
<th>Imatron EBCT (10 mm Al)</th>
<th>GE LightSpeed 16 (8.3 mm Al)</th>
<th>Siemens Sens. 64 (8.5 mm Al)</th>
<th>ACR 2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980s</td>
<td>50</td>
<td>35</td>
<td>25</td>
<td>20</td>
<td>15</td>
<td>7 mSv</td>
</tr>
<tr>
<td>1985s</td>
<td>45</td>
<td>30</td>
<td>22</td>
<td>18</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>1988</td>
<td>40</td>
<td>25</td>
<td>18</td>
<td>15</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>35</td>
<td>20</td>
<td>15</td>
<td>12</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>2004</td>
<td>30</td>
<td>15</td>
<td>10</td>
<td>8</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>2017</td>
<td>25</td>
<td>10</td>
<td>7</td>
<td>5</td>
<td>3</td>
<td>7 mSv</td>
</tr>
</tbody>
</table>
What technology has reduced dose?

**Beam filtration**

- Added beam filtration, such as the addition of a tin filter, may improve dose efficiency.*
  - More powerful x-ray tubes allow increased beam filtration, which reduces dose
  - Low-energy photons that do not contribute to image formation are removed by the tin filter
  - Examples: 100 kV Sn and 150 kV Sn modes on Siemens Flash and Force scanners

Beam shaping

- Beam shaping
  - “Bow-tie” filters used to reduce unneeded surface dose
  - More powerful tubes allow more aggressive filters
  - Research into “adaptive” beam shaping is ongoing

Collimation

- Collimation
  - Early scanners had post-patient collimation to define slice width, reduce scatter, and improve spatial resolution
    - Current scanners rarely use post-patient collimation (very high resolution modes are an exception)
  - Multi-slice CT
    - 4 slice MSCT scanners use of narrow z collimations (e.g. 4 x 1 mm) required a larger penumbral region and “wasted” more dose
    - Adaptive z collimation addresses spiral overranging
Adaptive collimation: Off

Adaptive collimation: On
Right sizing

- Global size adaptation (e.g. child vs. adult)
  - Image Gently campaign has helped to make “right-sizing” the dose the standard of care (e.g. protocols for children)

Tube current modulation (TCM)

- Until early 2000s, one tube current used everywhere
- Overdosed thin areas, underdosed thick areas
- TCM is now standard of care
- Includes organ specific (e.g. lens of eye) TCM
Tube potential optimization

- Early scanners offered very few tube potentials
  - 120 kVp imaging was ubiquitous
  - now 70 to 150 kV options exist
- Automatically adjust to task and patient
  - More powerful tubes allow higher mA so can use lower kV

Task specific protocols

22 mGy at 120 kV (not shown) vs. 11.5 mGy at 80 kV (shown)
Detectors

- Originally used scintillators (e.g. NaI, CsI, BGO) and photomultiplier tubes
- High pressure gas (e.g. Xenon) detectors were used in early 3rd generation scanners, but were less dose efficient (about 60% vs. 98%)
- Now use more efficient scintillators and photodiodes
- Photon counting detector technology now under investigation

Lower electronic noise detectors

80 kV (CTD\text{vol} 10.5 \text{ mGy})

Conventional detector

Integrated detector

Phantom size: 36 x 16 cm

Window center/width=150/650
Lower electronic noise detectors

- Less streaking artifacts and more homogeneous noise due to lack of electronic noise

**CTD_{vol} = 2.27 mGy**
120 kV, 30 mAs
[25, 120] keV
D30 kernel
1 mm slice

Noise reduction algorithms

- Edge preserving image filtering
- Iterative reconstruction

Noise Reduction: Image-space Denoising

- Linear or non-linear filters directly applied on the reconstructed images
- Independent of CT manufacturer
- Need to carefully control strength
- Performance requires careful evaluation for each diagnostic task

Edge preserving noise reduction

![Original Image](image), 61.5 HU, - 41% to 36.3 HU

![3D Edge Preserving Noise Reduction](image)

Courtesy of R. Raupach
Iterative Reconstruction

- Models noise statistics and possibly system geometry
- May improve spatial resolution and reduce image artifacts, typically reduces noise
- High computation load
- Can be used in a misleading fashion for marketing purposes

Iterative reconstruction

[Diagram showing iterative reconstruction process]
Iterative reconstruction and low kV

Guimaraes et al. Acad Radiol 2010

80 kV (50% dose)

80 kV + IR (50% dose)

Noise reduction: Not always for dose reduction

Image Quality Improvement
Iterative reconstruction myths

- Iterative reconstruction reduces radiation dose
  - For most (but not all) systems, user has to manually decrease the dose
- Iterative reconstruction improves lesion detection
  - IR degrades edges of low contrast lesions

High contrast spatial resolution

![MTF Graph](image-url)
Noise vs. high-contrast (spatial) resolution

![Graph showing Noise vs. MTF 50% for different mAs settings and noise levels.]

1. Noise vs. high-contrast (spatial) resolution

   - Graph showing Noise vs. MTF 50%
   - Different mAs settings: 60, 120, 240 mAs
   - Noise levels: B10, B20, B30, B40
   - Noise vs. high-contrast (spatial) resolution for different noise levels and mAs settings.
Noise vs. high-contrast (spatial) resolution

![Graph showing noise vs. high-contrast resolution](image-url)

- **B 60 mAs**
- **B 120 mAs**
- **B 240 mAs**
- **SAFIRE 60 mAs**
- **SAFIRE 120 mAs**
- **SAFIRE 240 mAs**

- Noise levels are plotted against MTF 50% for different exposure settings and post-processing techniques.

---

**Legend:**
- Blue: B 60 mAs
- Red: B 120 mAs
- Green: B 240 mAs
- Blue: SAFIRE 60 mAs
- Red: SAFIRE 120 mAs
- Green: SAFIRE 240 mAs

---

**Notes:**
- The graph illustrates the relationship between noise and high-contrast spatial resolution for various imaging conditions.
- Higher MTF values indicate better spatial resolution.
- The impact of different mAs settings and post-processing methods on image quality is clearly shown.

---

**Caption:**
- Noise vs. high-contrast (spatial) resolution

---

**Image:**
- The image shows a graph with axes labeled Noise on the y-axis and MTF 50% on the x-axis.
- Data points are marked with symbols for different exposure and processing conditions.
Dose reduction potential

- Half dose with 50% ASIR or Safire +3 has similar noise as full dose + standard recon
- Quarter dose with 100% ASIR or Safire +5 has similar noise as full dose + standard
- Does this mean
  - 50% ASIR or Safire +3 can reduce dose by 50%?
  - 100% ASIR or Safire +5 can reduce dose by 75%?

All three have similar noise:
12-13 HU and CNR

50% dose reduction? Probably not
75% dose reduction? NO
Even 25% dose reduction is questionable!

- Standard: 400 mA
- 50% ASIR: 300 mA

Dose reduction must not compromise diagnostic performance
Low contrast detection phantom:
Ensemble average

Using noise level to reflect image quality leads to conclusion that 33% of original dose maintains “image quality” for IR
However, for similar image noise, detection and characterization performance has been compromised.

Our validated Channelized Hotelling observer (task-based metric) predicts degraded performance at 25% dose.
Our validated Channelized Hotelling observer (task-based metric) predicts comparable performance at 78% dose.

Visual comparison at 78% dose.
Results: AUC vs Dose

>25% dose reduction reduces LCR performance, regardless of use of IR

Favazza et al., Use of a channelized Hotelling observer to assess CT image quality and optimize dose reduction for iteratively reconstructed images. JMI (subm.), 3/2017

Clinical implications

Two low-contrast liver lesions detected that were previously missed

Favazza et al., Use of a channelized Hotelling observer to assess CT image quality and optimize dose reduction for iteratively reconstructed images. JMI (subm.), 3/2017
How much denoising or IR is too much?

CTDVol = 22 mGy

CTDVol = 11 mGy

Practical tips for implementing low dose CT

- Start by turning on IR or denoising while keeping the dose the same
  - To get radiologists used to different noise texture
  - To sort out any workflow issues
  - View both full dose FBP and full dose IR/denoised images
  - You may have to find a work around on some systems if they couple dose level and use of IR
Practical tips for implementing low dose CT

- Incrementally turn down the dose
  - Use phantom studies to compare low dose with full dose
  - Start with higher contrast tasks (angiography, stones, diverticulitis, appendicitis, chest)
  - Run at reduced dose several weeks between decrements
  - Compare to prior exams whenever possible
  - Involve multiple radiologists
  - Introduce dose reduction in low contrast tasks last
  - Don’t exceed about approx. 25% dose reduction for low contrast tasks

Implementing Noise Reduction

- Routine Abdomen Pelvis with Contrast
  - Compare back to prior exams

<table>
<thead>
<tr>
<th>CTDIvol</th>
<th>mGy</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.4</td>
<td></td>
</tr>
<tr>
<td>5.9</td>
<td></td>
</tr>
</tbody>
</table>
Implementing Noise Reduction

- Biphase Liver with Contrast
  - Compare back to prior exams

CTDvol = 24.0 mGy
CTDvol = 16.8 mGy

Overaggressive dose reduction!

You don’t know you’ve missed what you couldn’t see

IV-contrast CT
Standard Dose (SD) = 19.7 mSv
Low Dose (LD) = 2.3 mSv
88% dose reduction

LD ASIR
LD FBP
LD MBIR
LD PICCS

Courtesy Perry Pickhardt, AJR 2012
Don’t Let Low Dose CT Destroy Medical Benefit

Low dose
6 mm thick
Single phase
-----
Pancreatic
tumor missed
2 days later

Routine dose
2 mm thick
Bi-phasic
-----
Clear low
atten. mass
Ductal dilation

Courtesy of Dr. Joel Fletcher

http://mayoresearch.mayo.edu/ctcic