New Technologies for Image Quality Improvement and Dose Reduction in CT

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Radiation exposure to US population from all sources

The new pie chart!

US 1982 (NCRP 93)

Consumer products
2%

Medical
19%

Occupational
0.3%

Background
83%

Medical 0.54 mSv per capita
Total 3.6 mSv per capita

US 2006

Consumer products
2%

Medical
48%

Occupational
0.1%

Background
50%

Medical 3.0 mSv per capita
Total 6.2 mSv per capita

NCRP 160 published March 2009

NCRP 160: Medical Exposure

Procedures vs Effective dose contributions

Percent Procedures

Effective Dose Contributions

Computed Tomography
17%

Radiography and Fluoroscopy
74%

Nuclear Medicine
5%

Interventional Fluoroscopy
4%

Computed Tomography
49%

Radiography and Fluoroscopy
15%

Interventional Fluoroscopy
14%

Nuclear Medicine
26%

Effective dose per capita from medical radiation exposure is ~3.0 mSv

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Estimated number and collective doses from various medical imaging categories using ionizing radiation*

<table>
<thead>
<tr>
<th>Modalities</th>
<th>Number Procedures (millions)</th>
<th>%</th>
<th>Collective dose (Person-Sv)</th>
<th>%</th>
<th>Per capita (mSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT</td>
<td>67^a</td>
<td>17</td>
<td>440,000</td>
<td>49</td>
<td>1.50</td>
</tr>
<tr>
<td>Nuclear Medicine</td>
<td>18</td>
<td>5</td>
<td>231,000</td>
<td>26</td>
<td>0.80</td>
</tr>
<tr>
<td>Interventional</td>
<td>17</td>
<td>4</td>
<td>128,000</td>
<td>14</td>
<td>0.40</td>
</tr>
<tr>
<td>Radiography &amp; Fluoroscopy^b</td>
<td>293</td>
<td>74</td>
<td>100,000</td>
<td>11</td>
<td>0.30</td>
</tr>
<tr>
<td>Total</td>
<td>~395</td>
<td>899,000</td>
<td>~3.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

^a Number of CT scans
^b Excludes dental bitewing and full mouth procedures, but includes 2500 person –Sv for collective dose

Computed Tomography (CT)

- **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**
Number of CT procedures in US

Collective doses for CT (2006)

<table>
<thead>
<tr>
<th></th>
<th>Number (millions)</th>
<th>%</th>
<th>Effective dose per scan (mSv)</th>
<th>Collective dose Person-Sv</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>19.0</td>
<td>28</td>
<td>2</td>
<td>38,000</td>
<td>8.7</td>
</tr>
<tr>
<td>Chest</td>
<td>10.6</td>
<td>16</td>
<td>7</td>
<td>74,000</td>
<td>17.0</td>
</tr>
<tr>
<td>Abd/Pelvis</td>
<td>25.4</td>
<td>39</td>
<td>10</td>
<td>254,000</td>
<td>58.0</td>
</tr>
<tr>
<td>Extremity</td>
<td>3.5</td>
<td>5</td>
<td>0.1</td>
<td>500</td>
<td>0.1</td>
</tr>
<tr>
<td>CT Angiogram</td>
<td>4.3</td>
<td>6</td>
<td>5 (Head)</td>
<td>56,000</td>
<td>12.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20 (Cardiac)</td>
<td></td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>4.2</td>
<td>6</td>
<td></td>
<td>15,000</td>
<td>3.4</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>67</strong></td>
<td><strong>6</strong></td>
<td></td>
<td><strong>438,000</strong></td>
<td></td>
</tr>
</tbody>
</table>

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NCRP Report 160
Cancer Risks

- Average risk for radiation induced cancer in general population is 5% per Sv
- Children are 2-3 times at higher risk than adults (as high as 15% per Sv)
- For persons aged > 50 years risk is 1/5th to 1/10th of that for younger adults

1 Sv = 100 rem
10 mSv = 1 rem

Hall EJ, Ped Radiol, 2002

Deterministic Effects - Rare but possible in CT
Categories of CT procedures
(62.0 million in 2006)

HCAP: ~80% of all CT procedures
IMV Report, 2006

MDCT growth in US as percent CT scanners in clinical use

Survey Year | 2004 | 2006 | 2007
---|---|---|---
Total CT installed in US | 9,380 | 10,110 | 10,300
MDCT | 51% | 71% | 81%
SDCT | 42% | 28% | 18%
Other | 7% | 1% | 1%

Mahesh M, MDCT: The Basics …, Lippincott, 2009
Distribution of median (interquartile range) estimated effective dose by computed tomography study type

Effective dose for CT procedure varied within and across institutions with a mean 13-fold variation between highest and lowest dose for each study type


CT scans and associated Risks

Estimated number CT scans performed in the United States in 2007 according to sex and age at exposure

Projected number of future that could be related to CT scan use in the United States in 2007, according to age at exposure

Probable causes for increase in medical exposures

- Advances in medical technology
- Demand of improved patient care
- Easy to use -
  - Out of the box solution, for ex: CT
- Accessibility
  - Emergency Rooms - Outpatient - Doctor’s offices - …

- Overall Benefits outweighs Risks!
Radiation Dose Reduction Strategies

- Optimal tube current (mA) selection
  - Dose modulation strategies
- Reduce tube voltage in suitable patients
- Minimize scan range
- Heart rate reduction
- ECG gated tube current modulation
- Sequential Scanning
- Perform calcium scoring only if needed
- Iterative Reconstruction...

CT Dose Modulation
CT dose reductions with tube current modulation

• X-ray attenuation lower in AP and higher in lateral projection
• However, CT doses are uniform on the surface and decreases radially towards center
• Various dose reduction options are been considered

Dose modulation in z-direction

• Graph of tube current superimposed on a CT projection radiograph to illustrate longitudinal dose modulation concept, with variation of the tube current along the z-axis

Dose modulation in z-direction

- Tube current as function of time (hence table position) during spiral CT of 6 year child


Cardiac CT Imaging
Retrospective ECG Gating

Temporal Resolution
Radiation dose higher than prospective triggering

Continuous recording of spiral scan and ECG

ECG

Time / Pos.

Spiral Scan

N*T: 64*0.625 – 40 mm scan coverage

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Prospective ECG Triggering

Temporal resolution
Radiation dose minimized
Limited data set

Conventional Axial “Partial Scan” (Step and Shoot)

Prospective ECG Triggering

N*T: 64*0.625 – 40 mm scan coverage
Radiation Dose Report - CT Angiography Exam

Effective dose (mSv)
- 2.0 mSv
- 0.7 mSv
- 15.0 mSv

Total effective dose (mSv) 17.7 mSv

Coronary CT Angiography:
Prospective Triggered vs Helical Retrospective gated

Effective dose for CTA portion:
- 4-6 mSv

Effective dose for CTA portion:
- 12-15 mSv


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Radiation Dose and Image Quality Comparison for Helical Vs Sequential Cardiac CT Scan

![Radiation Dose](image1)  
![Image Quality](image2)


Wide detector (320 row) MDCT
Scan coverage - 320 vs 64 slice MDCT

Aquilion 64 - 32 mm beam width
Aquilion One - 320 slice MDCT - 160 mm beam width

X-ray beam profiles*: DSCT vs 320 MDCT

Siemens DSCT (w both tubes ON)

Toshiba 320 row MDCT (measured at isocenter)
320 MDCT: Cardiac CTA Protocol
Single Heart Beat Protocol (for HR ≤ 65 bpm)

- Single Heart Beat Protocol (for HR ≤ 65 bpm)
  - Exposure
  - Without ECG Dose Modulation
  - With ECG Dose Modulation
- 2-Heart Beat Protocol (for HR ≥ 65 bpm)
  - Exposure
  - Without ECG Dose Modulation*

SureCardio Prospective on 320 MDCT scanner

- Ultra low dose cardiac CTA acquired in continuous helical mode
- Extension of dose modulation technique: X-rays turned completely OFF during systole

SURECardio Prospective: 80% dose reduction
Dual Source CT

Single Source vs Dual Source CT*

64 Slice MDCT ~190 ms
180° Data Acquisition

DSCT ~ 90 ms
90° Data Acquisition per tube

Result: Comparable image quality and spatial resolution

Temporal resolution: ~ 1/3rd to 1/4th of gantry rotation time

* Siemens
DSCT*: Definition vs Definition FLASH

**Definition**
- 2nd detector set smaller than 1st
- SFOV-1: 50 cm
- SFOV-2: 26 cm
- Capable of 64 slices
- Anatomical coverage per rotation: 28.8 mm

**Definition – FLASH**
- 2nd detector set still smaller than 1st
- SFOV-1: 50 cm
- SFOV-2: 34 cm
- Capable of 128 slices
- Anatomical coverage per rotation: 38.4 mm

* Siemens

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DSCT Detector Configuration:
Definition vs Definition FLASH

**DSCT-Definition**
- 4 x 1.2 mm
- 32 x 0.6 mm
- 4 x 1.2 mm

**DSCT-Definition - FLASH**
- 64 x 0.6 mm

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**Dual Source CT: Definition FLASH**

**Definition – FLASH**
2nd Detector set still smaller than 1st but larger than Definition
SFOV: 1st detector – 50 cm, 2nd detector – 34 cm

* Siemens

Johns Hopkins – May 2009

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**Data Acquisition with DSCT-Flash**

- Table speed: 430 mm/s
- Pitch: 3.2
- Gantry rotation time: 0.28 sec
- Beam width: 38.4 mm
- Maximum slices: 128
- Scan range: 120 mm
- Scan time: 280 ms

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DSCT: Cardiac Imaging with ECG Pulsing

- Effective doses and additional fatal cancer risks associated with standard and optimal ECG pulsing versus no ECG pulsing
- Dose reduction up to 55% in patient with high heart rates
Dose Reduction Opportunities with DSCT

- **Cumulative dose reduction for coronary CT angiography obtained by using four dose-reduction mechanisms implemented with dual-source CT (DSCT) system**


Beam shaping filters specific to cardiac CT

- **Body and targeted field-of-view (cardiac) beam shaping filters**
- **Radiation dose outside the cardiac region can be lowered**

Radiology 2007;243:775-784
Iterative Reconstruction

• Conventionally filtered back-projection has been the choice of CT image reconstruction
• Iterative reconstruction method makes several passes over the raw data (obtained at low dose techniques) to produce more accurate model of image and reduce amount of noise
• Can result in 40 to 80% reduction in radiation dose
• Trade-off: need for more processing power and additional time for the process
Iterative Reconstruction – Work in Progress

Projection data Measured $P_m$

(filtered) Backprojection Calculation of image from projection data

Image $I$

Projection data Synthetic $P_s$

Artifacts / Sharpness

Correction image $I_c$

Noise reduction @ same Sharpness

Image $I_{n-1}$

Regularization

Low-pass filtering Noise reduction @ contrast depended sharpness

Sum

Replication Calculation of synthetic projection data from the image

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Iterative Reconstruction - Noise Reduction

Standard reconstruction | 2 Iterations | Standard

Comparison Full Dose / Dose Reduction 50% + iDose

120kV, 120/60 mAs
Apart from the cysts, the first CT shows thrombus in portal vein. On the follow up study, (6 weeks later) the thrombus has disappeared.

Follow up with 50% Dose Reduction

50% Dose (60 mAs) - FBP

Full Dose (120 mAs) - FBP

50% Dose (60 mAs) + iDose

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DECT approaches

- Dual x-ray tube – each tube set at different kVp
- Switching kVp on the fly to obtain dual energy CT data
- CT detector in Sandwich form – yielding dual signal for each exposure
- Photon counting detector with energy resolving capability

Further Potential for Dose Reduction
Auto kV – Basic Idea

Fig. 3. (A) Graph of the CT number of a 2% iodine solution for small, medium, and large phantoms at various x-ray tube potentials. (B) Graph of noise (standard deviation of CT numbers within the water background) in images of small, medium, and large phantoms at different tube potentials. (C) Graph of the contrast-to-noise ratio (CT number of iodine solution divided by the background noise level) in small, medium, and large phantoms at different tube potentials.

McCollough M, et al., RCNA, 2010
Variable Helical Pitch (vHP)

- ECG Gated Helical Pitch
- Table Speed Change
- Standard Helical Pitch

Toshiba

Multiphasic CT exams

- 3 phase liver study
- Chest CT with and without contrast
- Cardiac CT exam including functional studies that involves CTA + CT Perfusion
CT exam of abdomen and pelvis: Sample dose reports

Arterial and Venous scan series

<table>
<thead>
<tr>
<th>Patient Position</th>
<th>Total mAs</th>
<th>Total DLP</th>
<th>CTDIvol</th>
<th>DLP</th>
<th>TI</th>
<th>cSSL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topogram</td>
<td>123</td>
<td>123</td>
<td>32.31</td>
<td>1889</td>
<td>0.30</td>
<td>0.6</td>
</tr>
<tr>
<td>ARTERAL</td>
<td>123</td>
<td>450</td>
<td>32.24</td>
<td>1889</td>
<td>0.33</td>
<td>0.6</td>
</tr>
<tr>
<td>VENOUS</td>
<td>123</td>
<td>450</td>
<td>32.24</td>
<td>1889</td>
<td>0.30</td>
<td>0.6</td>
</tr>
</tbody>
</table>

41 mSv

Arterial, Venous and Delay scan series

<table>
<thead>
<tr>
<th>Patient Position</th>
<th>Total mAs</th>
<th>Total DLP</th>
<th>CTDIvol</th>
<th>DLP</th>
<th>TI</th>
<th>cSSL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topogram</td>
<td>123</td>
<td>534</td>
<td>36.34</td>
<td>1212</td>
<td>0.50</td>
<td>0.6</td>
</tr>
<tr>
<td>ARTERAL</td>
<td>123</td>
<td>530</td>
<td>36.02</td>
<td>1437</td>
<td>0.50</td>
<td>0.6</td>
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<tr>
<td>VENOUS</td>
<td>123</td>
<td>900</td>
<td>36.96</td>
<td>1324</td>
<td>0.50</td>
<td>0.6</td>
</tr>
</tbody>
</table>

58 mSv

k = 0.015 mSv/mGy.cm

Triple Phase CT Protocols: Virtual vs True Non-enhanced Images

• Typical triple phase CT protocols
  - True non-enhanced + arterial + delayed phase

• Virtual non-enhanced images with DECT equivalent in image quality with true non-enhanced images

• Reduces dose by nearly 35%

Graser A et al. Radiology 2009;252:433-440

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Over-ranging in CT scans

Over-ranging in MDCT

• Over-ranging is specific to reconstruction-algorithm
• Generally increases with collimation and pitch
• Over-ranging may lead to substantial but unnoticed exposure to radiosensitive organs

Over-scanning effect with 64 slice MDCT

• Over-scanning increases with pitch
• Adaptive shielding can reduce dose by nearly 7% for all scan lengths and can even reduce up to 38% for scan lengths smaller than 12 cm

Deak, P. D. et al. Radiology 2009;252:140-147

Adaptive Dose Shield

• Conventional pre-patient collimator results in over-scanning
• Adaptive dose shield minimizes radiation to target region and reduces overall dose

Siemens
Conventional and Adaptive Collimation

Dose distribution

X-CARE: Dose and Image Quality
Organ based dose modulation reduces radiation exposure of the breast by 30-40%
Noise level is maintained with dedicated reconstruction technique

New Horizons on Dose Saving
Dose reduction with X-CARE to Breast Tissue

X-ray tube current

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CT Dose – Positive Developments

• Dose modulation techniques
• American College of Radiology
  - Relative Radiation Levels
  - Appropriateness Criteria
  - CT Accreditation program
• Increased awareness
  - Such as Image Gently campaign
• Education and Radiation awareness

Image Gently®

• Increase awareness for need to decrease radiation dose to children during CT scans
• Down-size adult CT protocols to kids size
• Consider eliminating multi-phase scans

Image Wisely®

• Increase awareness for need to decrease radiation dose even in adult protocols
Impact of increase awareness about radiation risks

- 5 year follow-up study among members of Society of Pediatric Radiologists
- Significant decrease in tube current and tube voltage settings


Distribution of Patients by Estimated Radiation Dose

Percentage of Patients Achieving Target Dose of Less Than 15 mSv by Bimonthly Intervals


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NIH Radiation Dose Reporting Policy
Electronic Reporting of Radiation Exposures from Medical X-ray Imaging Procedures

Key Points

• Dose modulation – applicable for most adult CT protocols – achieve significant dose reduction
• Dose modulation for pediatric CT – need careful selection – correct positioning – selection correct reference mAs
• Over-scanning – can be lowered with attention to prescribing the scan region on topograms and also examining new dynamic collimation technologies
Conclusions

- Radiation dose from CT is of concern and has been in the limelight recently
- Optimization of CT protocols are key
- New methods – both technological and practice methods are leading the efforts to reduce CT dose
- Dose reporting is becoming front and center
- Understanding radiation issues and justifying appropriateness of medical x-ray imaging is critical

Past – Present - Future

Slice Wars!

Dose Wars!