Radiation from Medical Imaging

Marilyn J. Siegel, M.D.
Mallinckrodt Institute of Radiology
Washington University School of Medicine
St. Louis, MO
Learning Objectives

• Describe concerns about CT and radiation
• Describe CT doses and measures
• Discuss radiation risks from CT
• Review strategies to minimize radiation exposure
Why is CT under scrutiny?

• In the past 15 years, the rate of CT use has increased approximately 10% per year
• CT now accounts for
  – about 17% of all imaging exams AND
  – 50% of population radiation exposure
• The concern is the potential risk of CT radiation-induced cancer

Mettler FA. Et al. Radiologic and nuclear medicine studies in the U.S and worldwide. Radiology 2009; 253:520-531
## Population Exposure Data

<table>
<thead>
<tr>
<th>2006</th>
<th>Number of procedures (millions)</th>
<th>% of all exams</th>
<th>Per capita exposure %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiography</td>
<td>310</td>
<td>74</td>
<td>11</td>
</tr>
<tr>
<td>Interventional</td>
<td>13</td>
<td>4</td>
<td>14</td>
</tr>
<tr>
<td>Nuclear medicine</td>
<td>21</td>
<td>5</td>
<td>26</td>
</tr>
<tr>
<td>CT</td>
<td>67</td>
<td>17</td>
<td>49</td>
</tr>
</tbody>
</table>

CT largest source of **medical** radiation dose

Per Capita Exposure

U.S. 1980
- Natural: 3.0 mSv
- Medical: 0.54 mSv
Total: 3.6 mSv per capita

Medical Radiation Exposure: On the increase

U.S. 2006
- Natural: NCRP 3.0
- Interventional: 0.4 mSv
- Radiography: 0.6 mSv
- Nuclear medicine: 0.7 mSv
- CT scanning: 1.5 mSv
- Medical: 3.2 mSv
- All other: <1 mSv
Total: ~ 6.2 mSv per capita

Total = medical + background
CT under scrutiny

- On the basis of extrapolation models, it has been estimated that 1.5% to 2.0% of cancers in the U.S could be attributable to CT scanning

- Although the extent of the risk is controversial, the risk is considered real

The Increasing Use of CT: What does this mean to the radiologist?

• You will be considered an “expert” regarding radiation and its deleterious effects, because
  – You do the examination
  – You choose the equipment
  – You select the protocol
  – You can affect the radiation exposure
What else does this mean?

• You need to be aware of the amount of radiation that is given for higher-dose procedures, such as CT, AND

• You need to be able to explain to the public the value of this procedure and what protective measures you are taking

Learning Objectives

• Describe concerns about CT and radiation
• Describe CT doses and measures
• Discuss radiation risks from CT
• Review strategies to minimize radiation exposure
CT “Dose” Measurements

<table>
<thead>
<tr>
<th>Scan</th>
<th>kV</th>
<th>mAs</th>
<th>CTDI_{vol}</th>
<th>DLP</th>
<th>TI</th>
<th>cSL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topogram</td>
<td>1</td>
<td>120</td>
<td>7.25</td>
<td>251</td>
<td>5.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Chest Routine</td>
<td>2</td>
<td>120</td>
<td>93</td>
<td></td>
<td>0.42</td>
<td>0.8</td>
</tr>
</tbody>
</table>

- CTDI_{vol} = volume CT dose index
- DLP = dose length product
- THESE MEASURES ARE ON PATIENT INFORMATION SHEET
- They are available at the scanner

Huda W, Mettler FA. Volume CT Dose Index and Dose-Length Product Displayed during CT. Radiology 2011; 258: 236-258
CTDIcon

- $\text{CTDIcon}$ is NOT a patient “dose”
- Measure of scanner radiation output
- Is an estimate of average radiation dose within a volume of tissue
- Reported in mGy
- Why use it? -- allows comparison of different protocols across patients, practices and scanners

McCullough CH, et al. CT dose index and patient dose: they are not the same thing. Radiology 2011; 259:311-316
Dose Length Product (DLP)

- DLP is NOT a patient "dose"
- DLP takes into account scan length
- It is the length of the irradiated scan volume and the average CTDI$_{vol}$ over that distance
- Unit is the mGy.cm
- DLP is used to obtain effective dose or "whole-body equivalent" dose
Estimating Effective Dose

- Effective dose = DLP x $k$ (where $k$ is a weighting factor)
  - $k$ based on region of body scanned
  - Unit is sievert (mSv)

- Representative adult values for $k$ are:
  - Head/Neck: 0.0031
  - Head: 0.0021
  - Neck: 0.0059
  - Chest: 0.014
  - Abdomen: 0.015
  - Trunk: 0.015

Report of AAPM Task group 23. AAPM report No. 96. 2008; 1-34
Effective Dose Estimate
example: chest CT

- DLP = 251 mGy-cm
- Effective dose = DLP x 0.014 (k) = 3.5 mSv

**MEASURES AVAILABLE ON SCANNER**
2012-more complicated
Size Specific Dose Estimate (SSDE)

- AAPM report #204
- SSDE = $CTD_{vol} \times \text{conversion factor (f}_{\text{size}}$) for sum of AP + lateral diameters of the scanned region
- Report #204 provides look-up tables for the $f_{\text{size}}$
- SSDE reported in mGy
- Takes into account patient size
- Estimate of patient dose but sill not exact dose

Christner et al. Size-specific dose estimates for adult patients at CT of the Torso. Radiology 2012; 265:841
AAPM Working Group Report (#204) Size-specific dose estimates (SSDE) in pediatric and adult body CT. 2011
Example: Abdominal CT in a Child

SSDE = 5.4 mGy x 2.50
= 13.0 mGy
Radiation Doses

• To date, CTDIvol and effective dose are the most widely used measures of radiation in CT and they are used for accreditation

• The use of SSDE likely will increase as new automated technologies emerge to calculate imaging data
What are the effective doses in Diagnostic Imaging?

Mettler FA. Radiology 2008; 248:254-263
Effective doses in radiology and diagnostic nuclear medicine
Mean E Doses in General Radiology (mSv) for one exam

- Chest PA/Lat: 0.1-0.01
- Skull x-ray: 0.1
- Cervical spine: 0.2
- Pelvis: 0.6
- Upper GI series (fluoro): 6
- Small bowel series: 5
- Barium enema: 8

www.cancer.gov/cancertopics (NCI)
Mettler Radiology 2008; 248:254-263 Hollingsworth
AFR 2007; 189:12-18
Estimated Effective Doses For CT
(mean mSv)

- Chest PA/Lat 0.1-0.01
- Head 2
- Chest 7
- Abdomen 8
- Pelvis 6
- Coronary CTA (retrosp gating) 16
- Coronary CTA (pros trig) 3

McCollough C, et al. Diagnostic Reference Levels from the ACR CT Accreditation Program JACR 2011; 8:795–803
Typical Radiation Doses per year (mSv)

- Natural background* 3.2
- Medical population 0.3-0.6

*From natural radiation in soil & rocks, radon gas which seeps into homes & other buildings, plus radiation from space
Another Issue: Cumulative Radiation Exposure

- 31,463 patients who had diagnostic CT in 2007 & had undergone CT exams over previous 22 years
- Calculated cumulative CT dose

Stockson radiology 2009; 251:175
Cumulative Exposure

- **Number of CT scans**
  - 33%: ≥ 5
  - 5%: > 22
  - 1%: 38

- **Cumulative Dose mSv**
  - 15%: > 100
  - 4%: 250 - 375
  - 1%: > 399

*Mean diagnostic CT 2-20 mSv*

Stockson radiology 2009; 251:175
Repetitive studies

• Repetitive studies most likely to occur in ED
• Usually repeat visits for chest or abdominal pain
• 5-year ED study 2003-2008
  – 12% of patients received 100 or more mSv

Bullard, et al. Annual Meeting of the Society for Academic Emergency Medicine. Orlando Regional Medical Center
Learning Objectives

• Describe concerns about CT and radiation
• Describe CT doses and measures
• Discuss radiation risks from CT
• Review strategies to minimize radiation exposure
Background

Every good idea has disadvantages equal to or greater than its advantages.
Big Issue is Cancer

Monday, January 22, 2001

Newsline

CT scans in children linked to cancer later

David Rosen of Columbia University says, "People get x-rays for a host of reasons, and about 1000 of these will be scans of children who have no signs of any particular disease." He notes that CT scans are commonly used in children without any specific disease diagnosis, and he is concerned that the scans could lead to later cancer risks. "The scans are often used to look for tumors and other abnormalities, and the radiation from these scans can cause cancer later in life," he says.

David Rosen of Columbia University says, "We found that when children have CT scans, they get 7% of the total radiation dose over the next 5 years. This radiation has been linked to an increased risk of cancer later in life."

The findings are based on a study of children who had CT scans and were followed for up to 20 years. The researchers found that children who had CT scans were more likely to develop cancer later in life compared to those who did not have scans.

The study, published in the journal Radiology, is the first to show a clear link between CT scans and cancer risk in children. The researchers say that the findings highlight the importance of minimizing radiation exposure during childhood, particularly for routine CT scans.

The study also highlights the need for better radiation protection for children who receive CT scans. The researchers say that efforts should be made to reduce the radiation dose during CT scans, and that patients and healthcare providers should be aware of the potential risks.

The study was funded by the National Cancer Institute and the National Institute of Radiation Protection and Measurement.
The Big Issue is Cancer
Atomic Bomb Survivor Data
No extrapolation

- 35,000 survivors exposed to doses < 150 mSv
- Followed for cancer incidence over 55 years
- Direct, significant evidence for risk in the dose range from 5 to 150 mSv
- Diagnostic CT 2 - 20 mSv

Relative Risk
Putting CT in Context

• To an individual:
  – Lifetime cancer risk: 20-25% (1 in 4 to 5)
  – Added risk for 10 mSv CT exam
    » 0.05% (1 in 2000)

• Younger patients at higher risk
  – More radiosensitive
  – More years to live
The Issue is Cancer--BEIR V (1990)

Risk vs. Age

Atomic Bomb - Additional Lessons

• Radiation-induced cancers appear at the same age as spontaneous cancers of the same type
• Risks persist throughout life
• Children are 10x more sensitive to radiation induced cancers than adults (girls > boys)
• Bone marrow, thyroid, breast, and lung are at greatest risk
Controversies

• Atomic bomb exposure involved instantaneous whole body exposure to x-rays, neutrons, particulate radiation
• No consensus on whether high dose whole body exposure can be extrapolated to low dose partial body exposure
Summary: Key Points About Risk

• Ongoing controversy regarding magnitude of the risk from diagnostic doses of radiation

• No controversy regarding the fact that risk from diagnostic doses of radiation is real

• Thus, recommended to keep doses of diagnostic radiation as low as reasonably achievable (The ALARA principle)
Learning Objectives

• Describe concerns about CT and radiation
• Describe CT doses and measures
• Discuss radiation risks from CT
• Review strategies to minimize radiation exposure
"Make a habit of two things -- to help, or at least do no harm"

Hippocrates, Of The Epidemics
400 BC
Basic Dose Reduction Steps
what the radiologist can do:

1. Study justification
2. Adjust scan parameters
3. Use dose reduction technologies

Apply to children and adults
Step 1: Study Justification

- Is the study needed?
- Appropriate utilization is required to minimize radiation exposure
- “CT should be avoided when an ultrasound or MRI offers comparable or more information”
- **BENEFIT V. RISK**
Step 2: Adjust Scan Parameters

• Limit scan to region of interest
• Adjust CT parameters (when possible)
  – Increase collimation & pitch
  – Decrease kVp, mAs
  – Use short scan time
• Limit number of contrast phases
• Center the patient
Limit Z-Axis Coverage
(Image Creep)

• Easiest adjustment
• Use a low-dose “scout” scan to determine the range
• ”shrink to size”
Limit the Phases

- Patients who undergo abd/pelvis CT exams receive unnecessary multiphase exams that add excess radiation

- In one study of 500 patients, 52.8% received phases not supported by ACR appropriateness criteria, most commonly delayed imaging, constituting 33.3% of total radiation dose (i.e. = excess dose)

Patient Centering

• Centering the patient in the gantry is VITAL for most automated systems

• Studies have shown that miscentering of only 2.2 cm from isocenter can increase average $CTDI_{vol}$ by 23% and image noise by 7% due to inaccurate AEC modulation

• Errors more likely in smaller patients

Optimize mAs, kVp, Pitch Effects on Dose

- 50% decrease in mA = 50% dose decrease
- 80 kVp = 30% to 50% dose decrease
- 50% increase in pitch = 50% dose decrease
- Caveat: in some scanners, effect of pitch is negated because mAs increases in order to maintain image quality
3. Dose Reduction Technologies

How do you select best parameters?

• Manual technique charts based on weight (or other size parameters) and CT task (contrast vs. non contrast CT)
  – “best guess approach”

• Automated technology
  – mAs modulation
  – kVp selection
  – Iterative reconstruction
Tube Current (mA) Modulation

• mA is adapted to thickness of the area of interest, not patient weight, based on attenuation measurements from topogram

• Exception is skull where beam attenuation comes from bone formation and this process is age dependent so mA is age dependent

Automated Current (mA) Selection

- Parts with less thickness need less radiation
- Dose modulation done in x, y, z planes
- 25 to 50% dose reduction, no loss of image quality

Average mAs
Ex: Adult
Ref value 150 mA
Tube Current (mA) Modulation
Mean Dose Reduction

- **Stone disease** 64%
  - Mulkens AJR 2007; 188: 553

- **Cardiac CT** 60%
  - Herzog, AJR 2008; 190:1232

- **Colonography** 35%
  - Graser, AJR 2006; 187:695
A Tale of Two Technologies

Kilovoltage Adjustment
Why use low kV---Rationale

- Lowers radiation dose
- Improves contrast
- Greatest benefit in contrast CT exams

Siegel MJ Radiology 2004; 233:515
Funama, et al., Radiology 2005
Nakayama, et al., Radiology 2005
Huda, et al., Med Phys 2004
Nakayama, et al. AJR 2006
Low kVp / Contrast

- **Rationale:** K-edge of iodine 32 keV
- **Mean photon energy**
  - 80 kVp 44 keV
  - 100 kVp 52 keV
  - 120 kVp 57 keV
  - 140 kVp 62 keV

Limitation is increased noise

120kV

80kV
KEY POINT-kVp Reduction

• *The effect of lower kV is highly dependent on patient size and diagnostic task*

• Increases in contrast are seen **ONLY**
  with **IODINATED** substances
  – *NOT water, soft tissue, bone*

• **Benefit greatest in children and small sized adults**
Use of Lower kV

- In practice, it is difficult to select the best kVp that will maintain image quality
- Often have to increase mAs
- Selecting the best mAs for a lower kV has been difficult
- Problem solved with automated kV technology
Automated kV—newest technology

- A tool that selects kVp based on patient size and exam type to achieve desired image quality at a lower dose
- *Chooses one kVp for entire scan - kVp not modulated*
Automated kV selection based on the attenuation profile of the topogram is feasible, provides a diagnostic image quality for body CTA, and reduces overall radiation dose by 25% as compared with a standard protocol with 120 kV.
Auto kV vs. Image Quality

Adapts to body size

Winklehner et al. Invest Radiol 2011; 46:767
Children--Automated kV 2013

*Radiology* 2013; 268:538-547

Effects of automated kilovoltage selection technology on contrast-enhanced pediatric CT and CT angiography.
Siegel MJ¹, Hildebolt C, Bradley D.

- Automated kV selection provides **diagnostic image quality** for pediatric body CT and CTA, and **reduces overall radiation dose by 27%** as compared with a standard 120 kVp protocol
- Greatest reduction for CTA - 49%
Auto kV Chest CTA

- 3 year old girl
- REF: 120kV
- 70kV

3.57 mGy
1.6 mGy
Thoracic and Cardiac CTA
20-100 kG
ITERATIVE RECONSTRUCTION

Noise Reduction Reconstruction Algorithm
Post-processing software
(ASIR, SAFIRE, iDose)
Iterative Reconstruction

- Technology to achieve dose reduction with great image quality
- Scan at lower mAs
- Then IR “cleans up” the image noise
- Allows up to 60% dose reduction
Iterative Reconstruction

\[ \sigma = 26.8 \text{ HU} \quad \text{Low dose initial data set} \]

\[ \sigma = 7.8 \text{ HU} \quad \text{IR} \]

Shows high noise

Noise 3X less
Dose Reductions with IR

<table>
<thead>
<tr>
<th>Exam</th>
<th>% decrease in mAs</th>
<th>% decrease in CTDI$_{vol}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abdomen</td>
<td>30%</td>
<td>30%</td>
</tr>
<tr>
<td>Chest</td>
<td>40%</td>
<td>60%</td>
</tr>
<tr>
<td>CTA Body</td>
<td>35%</td>
<td>40%</td>
</tr>
</tbody>
</table>

Kaza RK, et al. CT enterography at 80kVp with ASIR versus 120 kVp. AJR 2012; 198:1084-1092
ORGAN SHIELDING
Step 4: Shield Superficial Organs

- **Thyroid** and **breast** in chest CT scans and **gonads** in pelvic CT receive high doses, although they are **not** areas of interest for the CT.
- These structures are very sensitive to radiation.
## Organ Doses (mGy)

<table>
<thead>
<tr>
<th>Examination</th>
<th>Thyroid</th>
<th>Breast</th>
<th>Uterus</th>
<th>Ovaries</th>
<th>Testes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chest</td>
<td>2.3</td>
<td>21</td>
<td>0.06</td>
<td>0.08</td>
<td>*</td>
</tr>
<tr>
<td>Abdomen</td>
<td>0.05</td>
<td>0.72</td>
<td>8.0</td>
<td>8.0</td>
<td>0.7</td>
</tr>
<tr>
<td>Pelvis</td>
<td>*</td>
<td>0.03</td>
<td>26</td>
<td>23</td>
<td>1.7</td>
</tr>
</tbody>
</table>

* dose < 0.005 mGy

ICRP 87
Shielding

- Options:
  - Bismuth latex shields
  - No shielding, use automated mA selection
  - Organ specific shielding
Automated Organ-based mAs Reduction

- Turns tube current off over radiosensitive organs, e.g. breasts or eye lenses
- However, to maintain image quality, mAs may need to be increased at other view angles, so absorbed dose to other organs may increase

Full dose to breast  Reduced dose
Breast Dose Reduction

• Bismuth shields
  – 30-50% dose reduction
  – 40-100% noise increase

• Reduced tube current or use selective shielding
  – 30-60% dose reduction,
  – 10-30% noise increase
  – “win-win” scenario

Geleijins Eur Radiol 2006; 16:2334
Vollmar, Kalendar Eur Radiol 2008
• **AAPM Position Statement on the Use of Bismuth Shielding for the Purpose of Dose Reduction in CT scanning Feb 2012**

• “For equivalent levels of image noise, the percent dose reduction to the anterior surface from bismuth shielding can be achieved by reducing the x-ray tube current”

The Bottom Line

• Beautiful pictures do not need to come at the cost of higher radiation dose

• Need to decide what level of image quality is necessary to make an accurate diagnosis

Slovis T. CT and Computed Radiography: The Pictures are Great, but is the Radiation Dose Greater than Required?, AJR 2002; 179: 31-49
We are getting closer
(weight range 2 to 120 kg)

<table>
<thead>
<tr>
<th>EXAM</th>
<th>Auto mAs</th>
<th>Auto mAs Auto kVp</th>
<th>Auto mAs Auto kVp 20% IR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abd/pelvis</td>
<td>8.4</td>
<td>6.2</td>
<td>3.2</td>
</tr>
<tr>
<td>Chest</td>
<td>8.3</td>
<td>6.1</td>
<td>2.6</td>
</tr>
<tr>
<td>CTA</td>
<td>6.4</td>
<td>3.34</td>
<td>0.9</td>
</tr>
<tr>
<td>Mean</td>
<td>8.1</td>
<td>5.8</td>
<td>2.7</td>
</tr>
</tbody>
</table>
Summary

- CT use continues to increase
- Need to review all protocols to be sure:
  - Examination is indicated
  - Protocols and CT parameters are appropriate for clinical question
    » mAs, kVp, thickness, pitch
- Need to assess benefit v. risk
- CT is one of our best exams if used properly
What can we Expect in the Future?

• More regulations
  – National CT dose registry
  – Compliance with dose reference levels
  – CT accreditation for radiologists

• That means there will be a greater need to understand CT measures, doses and risks and dose reduction technologies to ensure compliance with guidelines
Dial Down the Dose

Thank you