Ch 10: Radiation Dose and CT

Lecture Objectives

1. Why dose matters
2. Radiation doses associated with CT
3. How CT dose is measured
4. How CT dose can be reduced
5. Issues of pediatric and whole-body CT scanning and radiation exposure
6. Radiation safety practices for technologists

You’ve seen the Headlines and the Horrible Pictures...

CT scans in children can cause small but significant increases in the risk of leukemia and brain cancer, a new study finds.

The Radiation worry prompts FDA to regulate medical scanners

The Preamble Cancer Toll of CT Scans

A week ago, a boy
Cancer is the fourth
highest cause of death among children, and they are increasing the risk of future cancer, new study suggests.

The case of the boy who survived.

The case of the boy who survived.

The case of the boy who survived.
Everyone Reacts!

- Facilities
  - Investigations
  - Response to patients / community / media relations
- Society
  - Patients and community
  - Celebrities and others with “opinions”
- Professional Organizations
  - ACR, AAPM, ASRT, etc
- The Government
  - Recommendations to HCP, Pts, etc
  - FDA initiatives
  - Regulations/Legislation - Senate Bill 1237 (California)

The Joint Commission’s Requirements for Diagnostic Imaging Services

- Revised by this year!
- “…radiologic technologists who perform CT examinations participate in ongoing education that includes annual training on radiation dose reduction techniques, Image Gently, and Image Wisely.”
- Minimum competency for radiology technologists, including registration and certification by July 1, 2015
- Annual performance evaluations of equipment by a medical physicist
- Documentation of CT radiation dose in the patient’s clinical record
- Meeting needs of the pediatric population → pedi-specific protocols, considering patient size/body habitus when establishing protocols
- Management of safety risks in the MRI environment
- Collection of data on incidents where pre-identified radiation dose

Do you agree?

- “Soon medical imaging, with CT scans as the largest contributor, will approach or potentially exceed background radiation as the single largest source of radiation for humans” (NCRP, April 2007) – from ImageGently
Trends in CT Imaging

- You've seen this before → CT is EVERYWHERE!
  - In 2001 – 39.6 million
  - In 2006 – 67 million
  - In 2011 – 85.3 million
  - Expected to increase ~10% every year …

Image from NRCP Report 160 - 2009

More Statistics

- Studies conducted by Duke University and UNC at Chapel Hill on the use of CT in ERs reveal significant increase in use of CT:
  - From 2000 to 2005 in adult patients → Head: 51%, C-Spine: 463%, Chest: 226%, Abdomen: 72%
  - From 2000 to 2006 in pediatric patients → Head: 66%, C-Spine: 731%, Chest: 675%, Abdomen: 104%

Trends in CT Imaging

- Sept 2013, IMV survey:
  - 2012 → # of CT studies fell 5.5% to 80.6 million
  - 2013 → # of CT studies fell another 5.5% to 76 million
  - What is behind the decline?

Image from AuntMinnie and IMV – Sept 2013

https://www.youtube.com/watch?v=JqQs44VHsdw#t=117
As Technologists, What Can We Do?

- CT is a diagnostic tool → any tool in the wrong hands can be a weapon
- Ask yourself:
  - Why are the doses in CT so high?
  - What is the dose to the patient at my facility?
  - What can be done to reduce the high exposures in CT to protect both patients and staff?

Let’s Review…

Sources of Radiation

- Natural / Background radiation
  - Earth
  - Cosmic
  - Human body
- Man-made
  - Nuclear industry/fallout
  - Consumer products
  - Medical/dental

Sources of Radiation

- 50% of public exposure is from background sources and 48% is from medical and diagnostic treatments

NRCP Report No. 160 - 2009
1980s – what has changed?

In 2006…

Radiation Quantities & Their Units

- Collective Dose
  - Amount of radiation received by a group of people
  - Calculated by:
    - Avg effective dose x # of persons exposed
    - Expressed in person-sieverts (person-Sv)
Radiation Quantities & Their Units

- Radiation Exposure In Air
  - Kinetic energy transferred from photons to electrons during ionization and excitation
  - SI unit: Air Kerma (Gy)
  - Traditional unit: Roentgen (R) = Coulomb/kg

- Absorbed Dose
  - Amount of energy absorbed per unit mass of material (patient)
  - Biologic risks and effects are usually related to the radiation absorbed dose
  - SI unit: Gray (Gy)
    - 1 Gy = Joules/kg
  - Traditional unit: rad (r)
    - 1 r is equal to 0.01 Gy

- Effective Dose Equivalent (E)
  - Used to quantify risk from partial-body exposure to that from equivalent whole-body dose
  - Considers radiation type and tissue sensitivity
  - SI unit: Sievert (Sv)
  - Traditional unit: rem
    - 1 Sv = 100 rems

\[ E = \sum T \left( D_{TR} W_T W_R \right) \]

where \( D_{TR} \) is the absorbed dose to the tissue (T), \( W_T \) is the tissue-weighting factor, \( W_R \) is the radiation-weighting factor, and the symbol \( \sum T \) is the "sum over."
### Radiation Quantities & Their Units

- Effective dose equivalent (E) relates exposure to risk
- How much is too much?
  - Brenner (2006) - evidence of increased cancer risk
  - Children exposed to acute doses of 10 mSv
  - Adults exposed to acute doses of 50 mSv

| E with rad imaging < natural background (3 mSv/yr) |
| E from fluoro and CT exams are ~ natural background |
| E is much higher with interventional radiology procedures |

### Effective Dose - Various Procedures

- Chest x-ray = 0.02 mSv
- Abdomen x-ray = 0.7 mSv
- Upper G.I exam = 5 mSv
- CT head = 2 mSv
- CT chest = 7 mSv
- CT abdomen = 10 mSv
- Coronary Angiography (CTA) = 16 mSv

### What’s the big deal about radiation dose anyway?

- Ionizing - ability to eject or accept e- from atoms = change atomic structure
- Cause Bioeffects
- Stochastic vs Deterministic Effects
- Each exam adds directly to an individual’s risk in proportion to the dose
  - Somatic effects
  - Genetic effects
  - Fetal/embryonic effects

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**Table 1. Relative radiation level breakdown along with common exam combinations for each classification**

<table>
<thead>
<tr>
<th>Relative Radiation Level</th>
<th>Adult Dose Range (mSv)</th>
<th>Radiation Exams</th>
<th>Example Examination</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.01-0.1</td>
<td>Chest radiograph, Fluoroscopy</td>
<td>Abdominal CT, Nuclear medicine base line</td>
</tr>
<tr>
<td>2</td>
<td>0.02-0.5</td>
<td>CT, Angiography, Bone density</td>
<td>Abdominal CT without oral &amp; with contrast, Whole body PET</td>
</tr>
<tr>
<td>3</td>
<td>0.5-2.5</td>
<td>Cardiac catheterization, Mammography</td>
<td>CTA aorta abdomen and pelvis with contrast, Transesophageal echocardiogram dual planeimage</td>
</tr>
</tbody>
</table>
Radiation Bioeffects

Dependent on:

- Age
- Dose Rate (length of time of exposure)
- Tissue Sensitivity
- Area/Volume of Irradiated tissue

Radiation Bioeffects

- Stochastic Effects
  - Probability of effect increases with increasing dose
  - Considered late effects because occur years after exposure
  - Linear no threshold (LNT) dose-response model
    - Radiation risk increases as dose increases → there is no threshold
    - Even small dose has potential to cause bioeffect!
  - Examples → cancer, leukemia, and hereditary effects

Radiation Bioeffects

- Deterministic (Non-Stochastic) Effects
  - Severity of the effect increases with increasing dose
  - There is a threshold dose
    - Below threshold dose, effects are not observed
    - Threshold doses = relatively high doses that can kill cells and cause degenerative changes in tissues that are exposed to radiation
  - Ex → erythema, epilation, pericarditis, cataracts…
  - Organ absorbed doses in CT are substantially lower than threshold doses (Huda and Vance (2007))
Dose Report

- Current CT scanners display the CTDI_vol and DLP indices before and after the scan is performed
- Required since 2002

<table>
<thead>
<tr>
<th>Series</th>
<th>Type</th>
<th>Scan Design (mAs)</th>
<th>CTDI (mgGy)</th>
<th>DLP (mgGy cm)</th>
<th>Pitch</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Scan</td>
<td>515.5/760-330/250</td>
<td>5.18</td>
<td>37.00</td>
<td>Body 32</td>
</tr>
<tr>
<td>5</td>
<td>Helic</td>
<td>515.5/760-330/250</td>
<td>5.18</td>
<td>30.73</td>
<td>Body 32</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

CT Dose Descriptors

- MSAD → Multiple Scan Average Dose
  - Based on conventional CT; out of date
- CTDI → CT Dose Index
  - Measures mean absorbed dose in scanned object volume (for single slice)
  - Measured in Gray (mGy, cGy)
    - CTDI_vol calculated over 100 mm dosimeter
    - CTDI_wght weighted based on measurements at periphery and center of phantom
    - CTDI_vol relates weighted index and pitch
- DLP → Dose Length Product
  - CTDI_vol x scan length of exposure (z-axis)

CT Dosimetry

- Pencil ionization chamber
  - Used to accurately quantify radiation exposure
  - X-rays produce ionizations in air filling chamber
  - Free e- are measured as electric charge proportional to amount of radiation
  - The charge is removed and measured with an electrometer

Head phantom
CT Dose Descriptors

CTD: CT Dose Index (mGy)
Energy absorbed per unit of mass

DLP: Dose Length Product (mGy cm)
Energy absorbed per unit of mass over a scanned length

Beam Geometry and Exposure in Radiography

- X-ray tube is above/in front of patient (fixed)
- Cone shaped beam → open-beam geometry
- Entrance exposure is 100% → NOT risk!
  - Overestimation → as dose decreases as it passes through the patient (attenuation, inverse square law)

Beam Geometry and Exposure in CT

- Beam is well-collimated to fan-shaped or cone-shaped beam → rotates around pt at least 360°
- Dose distribution pattern is more uniform in CT → x-ray beam is rotating 360° around pt's body
Image Quality and Dose

- Dose and noise
  - To decrease noise by factor of 2 requires increase x 4 of dose
- Dose and slice thickness
  - Reducing slice thickness by factor of 2 requires doubling of dose (to maintain noise level)
- Dose and mA
  - Doubling mA doubles exposure and dose
- Dose and kVp
  - Dose is proportional to square of kVp

Factors Affecting Pt Dose in CT

- Patient centering
- Overranging / overscanning
- Exposure factors
  - mA / mAs; effective mAs
  - kVp
- Collimation
- Pitch
- Number of detectors

How we can help protect our patients from too much radiation!!

Patient Centering!

- Pt must be centered in the gantry isocenter for accurate imaging of the anatomy!
- Assures proper dose distribution
- Inaccurate pt centering:
  - Degrades the image quality
  - Increases the dose to the patient (especially with ATCM)
Patient Centering!

- Position patient correctly so that radiation is not applied to sensitive areas
- Pedi heads or neuro perfusions, position the head so the eyes are out of the primary beam

Improper Patient Centering and Positioning

- Improper centering of the patient in the gantry isocenter can lead to an increase in surface dose as well as the peripheral dose to the patient
- Study on effect of pt centering on CT dose and image noise, Toth et al (2007):
  - On a 32-cm CTDI body phantom:
    - Miscentering of 3 cm results in increase in doses by 18%
    - Miscentering of 6 cm results in increase in doses by 41%

Overranging/Z-Axis Overscanning

- Planned length of tissue coverage requires additional rotations before & after area of interest for image reconstruction process
- Effective dose values increase with increasing Z-axis overscanning
  - Substantial but unnoticed exposure to radiosensitive organs
Overranging

- To avoid irradiation of the eyes, brain CT is normally planned to exclude the eyes from the imaged area
- Eyes receive a significant dose, even though no images are reconstructed from data obtained in that area

Overranging / Z-Axis Overscanning

- Mar/April 2014 – University of Texas Southwestern Medical Center, Dallas, TX
  - Retrospective - 300 CT studies – R/O urolithiasis
  - 21,460 mm of extra scan length → mean length of 74 mm per pt
  - Mean DLP for extra cephalad/caudal images was 122.4 & 104.4 mGy·cm,
  - Accounted for approx 18% (226.8 of 1250 mGy·cm) of the mean total DLP

Pitch

- Ratio of the distance the table travels per rotation to the total collimated x-ray beam width
- SSCT → pitch values greater than 1 allow for the acquisition of a given scan volume in a shorter time
- MSCT → As the pitch increases, the dose per section (CTDvol) decreases
  - Increase in pitch results in a marked increase in image noise
  - Compensated for by an increase in mA → little net improvement in patient radiation dose
- DSCT (“Flash”) → high pitch (pitch > 2)
  - Rule of thumb: dose = 1/pitch
Pitch

- Why cardiac CT exams are associated with a higher radiation dose!
- Variable mAs values - require higher pitch values
- ECG gating used

  Prospective ECG-triggered "Flash spiral mode now being used to image the heart in a single heart beat"

Number of Detectors

- Detectors are much more efficient nowadays!
- More detector rows = more "slices" per revolution
- Moore et al, 2006 - study comparing dose from MSCT
  - Measured radiation dose is inversely proportional to # of detector rows
  - As the # of detector rows increases, the dose decreases

Collimation

- In CT, collimation defines beam width for the exam
- 2 collimators → shape and limit the x-ray beam
  - Pre-patient: at the x-ray tube
  - Post-patient: at the detector
  - Determines the slice thickness
  - Reducing slice thickness / 2 requires doubling of dose (to maintain noise)
Exposure Factors

- Kilovoltage peak
  - kVp = tube potential \( \rightarrow \) “penetrating power” of the photons coming from x-ray tube
  - Higher kVp \( \rightarrow \) higher energy photon \( \rightarrow \) more penetrating of thicker parts
  - High kVp techniques are used \( \rightarrow \) 120 kVp for adults

- Radiation dose is proportional to the square of kVp (Bushberg et al., 2004)
  - As the kVp increases, the dose increases
  - To decrease noise by factor of 2 requires increase dose \( \times 4 \)

Exposure Factors

- Change in kVp – what effect does it have?

Exposure Factors

- Milliamperage \( \rightarrow \) tube current + exposure time (s) \( \rightarrow \) mAs
  - mAs determines the quantity of photons incident on the patient for the duration of the exposure \( \rightarrow \) dose
  - Dose is directly proportional to mAs \( \rightarrow \) if mAs is doubled, dose is doubled

- Constant Milliamperage-Seconds
  - Selection of mAs, or mAs before scan begins, keeping all other technical factors constant

- Effective Milliamperage-Seconds
  - Denotes mAs per slice used for MSCT
  - Effective mAs = True mAs / pitch
  - To keep the effective mAs constant, as the pitch increases, the true mAs must be increased as well
Automatic Tube Current Modulation (ATCM)

- Optimizes the dose to the pt
- Maintains constant image quality regardless of:
  - Pt size in the z-axis
  - Attenuation changes (tissue differences) in the x-y axis
- As tube rotates around and along patient, mA is adjusted for body part in beam
  - May be based on scout/topogram or may be dynamic

The Scout(s)

Results:

![Results Image]
**Longitudinal Tube Current Modulation**

- Based on attenuation differences among parts in z-axis
- Thicker body parts attenuate more than thinner body parts

120kVp

Designed to change mA automatically as pt is scanned while maintaining uniform noise level for different thicknesses of body parts examined

**Angular Tube Current Modulation**

- Based on variations in attenuation from Anterior-Posterior (low attenuation) to Lateral projection (high attenuation) occurring as the tube rotates around the patient
- The x-y axis TCM algorithm ensures that a uniform noise level is maintained during the scanning process
  - Ex: Care Dose (Siemens), Smart Scan (GE Healthcare), and DOM-Dose Modulation (Philips)

**Angular – Longitudinal Tube Current Modulation**

- Both x-y axis and z-axis modulation used together to adjust patient-specific attenuation in all planes
  - Angular-longitudinal modulation can reduce dose by as much as 52%
  - Ex: CareDose 4D (Siemens), Smart mA (GE Healthcare), Z-DOM (Philips), and Sure Exposure (Toshiba)
ECG-Based Tube Current Modulation

Multiple heartbeats and table positions may be required to collect all data required to reconstruct FOV including the heart.

So What Can WE Do?

- Dose Optimization!
  - ALARA → ensure that doses delivered to pts kept as low as is reasonably achievable
  - Reduce radiation dose while maintaining required image quality needed for making a diagnosis
  - Radiation protection in CT should follow ALARA concepts!

Justification, Optimization, Limitation

**Justification**
- Must have benefit with every exposure
- Intended for referring physicians
- Reduces dose for pts

**Optimization**
- Doses delivered are kept as low as reasonably achievable (ALARA)
- Always apply radiation protection to ensure that dose is optimized and image quality is not compromised

**Dose Limitation**
- Keep doses within recommended limits
- Intended to reduce probability of stochastic effects and to prevent detrimental deterministic effects
So What Can WE Do?

- Eliminate unnecessary/duplicate exams
  - Must be a strict clinical indication
  - Are possible benefits greater than the possible risks?
  - Are there other more appropriate exams/tests?
    - Could MRI or ultrasound be used instead?
  - Has the pt had a recent CT?
    - Is ordering provider aware of this?

- Good communication
  - Between you, referring physician, and radiologist
  - Give good patient instructions (to avoid repeats)
  - YOU are the patient’s advocate now more than ever!
    - Your patient deserves the BEST scan possible regardless of size, hospital politics, misinformation, etc!
    - Never “SHAME” patient for their condition or size!

- Target exams to particular organs and patients
  - Know your scanner! Optimize scan protocols
    - Is the pre-contrast / multi-phase / multiple contrast scans etc necessary?
    - Change kV / mAs / pitch / collimation …
    - Customize – pediatrics, patients of all sizes
    - Automatic Tube Current Modulation
    - Scan lengths to clinically indicated region
    - Reference Dose Levels!

Chest-abdomen-pelvis is not a single word!
Shielding in CT?

- AAPM Recommends against bismuth in-plane
- What about out-of-plane lead shielding?
  - Most gonadal exposure from internal scatter and not primary beam (unless scanning gonadal region)
  - Wrap-around → think beam geometry!
  - Shield anyone who needs to stay in room with patient
- What about the psychological impact of shielding?

Check out “Shielding in Computed Tomography: An Update” in Radiologic Technology

Dose Notification and Alerts

- National Electrical Manufacturers Association (NEMA) XR 25 CT Dose-Check Standard
  - All new CT scanners sold in the US
  - Existing manufacturers making efforts to ensure installed units also meet this relatively new radiation safety standard
  - Notification Value vs Alert Value

Example from Siemens

Dose Notification Values

- Used to trigger a message when a single planned and confirmed scan is likely to exceed a pre-programmed value (CTD\textsubscript{vol} and/or DLP).
  - Programmed value is set for each scan sequence in an exam
  - Values were set by AAPM so that notifications would be infrequent, but can be changed by department
Dose Notification Values

<table>
<thead>
<tr>
<th>CT Scan Region (associated with one scan series or scan phase)</th>
<th>CT Dose* Notification Value (mGy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adult Head</td>
<td>80</td>
</tr>
<tr>
<td>Adult Torso</td>
<td>50</td>
</tr>
<tr>
<td>Pediatric Head</td>
<td>&lt;2 years old 50</td>
</tr>
<tr>
<td>2 – 5 years old</td>
<td>60</td>
</tr>
<tr>
<td>Pediatric Torso</td>
<td>&lt;10 years old 25</td>
</tr>
<tr>
<td>&lt;10 years old (16-cm phantom; GE, Hitachi, Toshiba)</td>
<td>10</td>
</tr>
<tr>
<td>&lt;10 years old (32-cm phantom; Siemens, Philips)</td>
<td></td>
</tr>
<tr>
<td>Brain Perfusion</td>
<td>exam series that repeatedly scans same anatomic level to measure flow of contrast media through the anatomy</td>
</tr>
<tr>
<td>Adult Head</td>
<td>25</td>
</tr>
<tr>
<td>Adult Torso</td>
<td>10</td>
</tr>
<tr>
<td>Pediatric Head</td>
<td>600</td>
</tr>
<tr>
<td>Pediatric Torso</td>
<td></td>
</tr>
<tr>
<td>Cardiac</td>
<td>Retrospectively gated (spiral)</td>
</tr>
<tr>
<td></td>
<td>Prospectively gated (sequential)</td>
</tr>
<tr>
<td></td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>50</td>
</tr>
</tbody>
</table>


Dose Alert Values

- Used to trigger a message when cumulative dose at a location, plus the dose for next planned and confirmed scan(s), is likely to exceed a pre-programmed value
  - Programmed value is set once & applies to all exams
  - Scanner parameter, not protocol or sequence specific
  - When cumulative CTDI<sub>vol</sub> for a study exceeds the dose alert level, the scan can not be performed until alert is addressed
  - FDA-recommend default value is CTDI<sub>vol</sub>=1000 mGy

So What Does This Mean for Us?

- Automated evaluation of CTDI<sub>vol</sub> and/or DLP before patient scanning can help protect patients from inadvertent use of excessively high CTDI<sub>vol</sub> and/or DLP
  - NOT designed to “optimize” dose
  - NOT radiation limit – the x-ray does not shut off
  - WAS designed to prevent egregious errors
  - Notifications draw attention to potentially “high” exposure so users can confirm that settings are appropriate
  - Operator education is essential!
- Don’t forget to monitor event logs!

* Howard, ME et al., Use of CT Dose Notification and Alert Values in Routine Clinical Practice, JACR, March 2014
Other Things You Can’t Control:

- CT system technical configuration - contain things out of your employee profile that affect patient dose:
  - Source-detector distance - As distance from tube to detectors decreases, dose increases
  - Filtration within the CT x-ray tube - 6 - 9 mm Al eq material
  - Beam-shaping / bow-tie filters are added compensation
  - Detector efficiency - inherent vs geometric
  - Scatter radiation does occur in the immediate area surrounding the CT scanner - room shielding requirements must be evaluated by a qualified radiologic health physicist

What about the protection of the CT Technologist?

- Time, Distance, Shielding
  - Remember –
    - dose is proportional to time of exposure
    - dose is inversely proportional to the square of the distance

- Patient is the main source of scatter
  - Control contrast injection from control panel or…
  - Stay in room and manually control, but….WEAR LEAD
  - Even if you have “had all your babies”
  - You still wear your personnel dosimeter right?
  - ALARA always!
Pediatric Patients
- Immobilize and communicate
- Adjust technical factors – mA, kV, pitch
- Child-size protocols
- Avoid repeat scans
- Ensure QC of scanner
- “Image Gently”

Size-based Imaging
- In designing scan for each patient, consider:
  - Patient size and shape
  - Body habitus
  - Patient age
  - Pathology or condition
  - Scanner ability

Whole-Body CT for Screening
- FDA has no scientific evidence demonstrating that benefit of full-body CT screening outweighs risk
  - High dose of radiation and associated risk, especially with repeated testing
- Value of CT screening for lung cancer in certain smokers, colon cancer (virtual colonoscopy), and heart disease (calcium scoring) is being evaluated
  - National Lung Screening Trial (NLST) sponsored by National Cancer Institute released in 2011, confirmed low-dose CT improves survival rate of lung CA pts by 20%, compared to standard CXRs
End of Ch 10!