Radiation Dosimetry and Cancer risks of Imaging

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Harvard Catalyst Imaging Consortium

- Provide expert consultation and guidance to the CTSC participants in the use of imaging as part of clinical translational research
- Educate and advise about available imaging and image processing capabilities in the Harvard environment
<table>
<thead>
<tr>
<th>Harvard Catalyst Imaging Consortium</th>
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<tbody>
<tr>
<td><strong>Bruce Rosen, Director</strong></td>
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<td><strong>Randy Gollub, Co-Director</strong></td>
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<td><strong>Gordon J. Harris, Consultant</strong></td>
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<td><strong>William Hanlon, Consultant</strong></td>
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<td><strong>Robert Lenkinski, Consultant</strong></td>
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<td><strong>Ivan Pedrosa, Consultant</strong></td>
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<td><strong>Clare Tempany, Consultant</strong></td>
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<td><strong>Ron Kikinis, Consultant</strong></td>
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<td><strong>Charles Guttmann, Consultant</strong></td>
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<td><strong>Todd Perstein, Consultant</strong></td>
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<td><strong>Gordon Williams, PI for CTSC Translational Technologies</strong></td>
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<td><strong>Stephan Voss, Consultant</strong></td>
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<td><strong>Simon Warfield, Consultant</strong></td>
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<td><strong>Annick D. Van den Abbeele, Consultant</strong></td>
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<td><strong>Jeffrey Yap, Consultant, Director of Education</strong></td>
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<td><strong>Valerie Humblet, Imaging Liaison</strong></td>
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<td><strong>Yong Gao, Imaging Informatics Architect</strong></td>
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**http://catalyst.harvard.edu/services/imagingconsult/**
Objectives

- Learn the imaging modalities that involve ionizing radiation
- Understand the potential risks of ionizing radiation used in imaging
- Learn the ALARA principle and some of the techniques used to reduce radiation exposure
- Understand the radiation safety protocol screening form and model consent risk statements

Benefits versus Risks

- We must focus on knowing/reducing the risks. Benefits should always outweigh the risks

Risks
- Claustrophobia
- Discomfort
- Noise
- Radiation Exposure
- Contrast reactions

Benefits
- Non-invasive
- Early detection
- Staging
- Response assessment
- Pharmacokinetics
- Pharmacodynamics
- Biopsy/Surgical guidance
- Safety monitoring
**Definition of Ionizing Radiation**

- High energy radiation that detach electrons from atoms or molecules resulting in an ionized particle

**Sources of ionizing radiation**

- Nuclear Reactors
- Radiation therapy (external beam, brachytherapy)
- Therapeutic nuclear medicine (e.g. $^{131}$Iodine, Bexxar, Quadramet)
- Diagnostic Imaging
- Cosmic radiation
- Radon and other naturally occurring radioisotopes
Imaging modalities that use ionizing radiation

- **Radiology**
  - X-ray
  - Dual Energy X-ray Absorptiometry (DEXA)
  - Fluoroscopy
  - Mammography
  - Computed Tomography (CT, CAT scan)
- **Nuclear medicine**
  - Gamma camera (e.g. bone scans, MUGA)
  - Single photo emission computed tomography (SPECT)
  - Positron emission tomography (PET)

Mammography

- Very low radiation dose procedure
- High spatial resolution capable of detecting small lesions
- Used for early detection in routine screening and surveillance
- Only used for detecting locoregional disease (not a whole-body technique)
X-ray Computed Tomography (CT)

- 3-dimensional whole-body imaging
- Higher radiation dose than planar x-ray
- To provide information about the size and location of the tumor and whether it has spread;
- Ideal for image guidance (biopsy/surgery/radiation)
- Standard for response assessment in clinical oncology trials

Bone Scintigraphy (Bone scan)

- Nuclear medicine technique using $^{99m}$Tc-MDP to measure bone function
- Can detect arthritis, infection (cellulitis or osteomyelitis), tumors, fractures
- Used in protocol screening for bone metastasis (e.g. breast, prostate cancer)
RVG/MUGA scan

- Can detect wall motion abnormalities
- Estimate cardiac ejection fraction
- Used in screening for trial eligibility
- Performed during or after treatment for safety monitoring (cardiotoxicity)
- Uses $^{99m}$Tc-labelled red blood cells

Positron Emission Tomography

- Functional and molecular imaging modality
- Can detect early disease and response to therapy
Imaging Modalities that involve *non-ionizing* radiation

- Photography
- Optical imaging
- Bioluminescence
- Ultrasound (e.g. sonogram, echocardiogram)
- Magnetic Resonance Imaging (MRI)
  - Nuclear Magnetic Resonance (NMR)
  - Functional MRI (fMRI)
  - MR Spectroscopy (MRS)

Increase in radiation exposure

*NCRP Report No. 160, Ionizing Radiation Exposure of the Population of the United States*

<table>
<thead>
<tr>
<th>Year</th>
<th>Background (50%)</th>
<th>Occupational/Industrial (0.3%)</th>
<th>Consumer (2%)</th>
<th>Medical (10%)</th>
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</thead>
<tbody>
<tr>
<td>Early 1980s</td>
<td>835,000</td>
<td>835,000</td>
<td>3.6</td>
<td>3.6</td>
</tr>
<tr>
<td>2006</td>
<td>1,870,000</td>
<td>1,870,000</td>
<td>6.2</td>
<td>6.2</td>
</tr>
</tbody>
</table>

Collective effective dose (person-Sv):

- Early 1980s: 3.6
- 2006: 6.2
Radiation risks

- Very high dose radiation can have immediate tissue damage and risk of future cancer (deterministic effect)
  - Examples: radiation therapy, radiation burns from overdose, workers in nuclear disaster
- Low dose radiation may have increased long term risk of cancer (stochastic effect)
- Most stochastic risk models are based on survivors of catastrophic radiation incidents (atom bomb, Chernobyl)

Why increase in dose?

Dose is related to image quality
Why increase in dose?

High dose scan

Low dose scan

How do we estimate radiation dose from imaging procedures?

Conventional radiography

Dose Gradient

x-ray skin dose
2 mGy/0.2 rad
How do we estimate radiation dose from imaging procedures?

Head CT scan

Body CT scan

How do we estimate radiation dose from imaging procedures?

Radiation Concentration

Total Radiation

Exposure Dose

Total Photons
Total Energy
In CT, CTDI (dose index) is "radiation concentration"
Effective dose is the "total radiation"

How do we estimate radiation dose from imaging procedures?

Dose distributions in CT measured in phantoms (center & periphery)
How do we estimate radiation dose from imaging procedures?

- CTDI parameters quantify CT scanner dose characteristics, not patient doses
- Dose (risk) in CT is best measured by effective dose (E)

Effective Dose

- Proposed by International Commission on Radiological Protection (ICRP Report 60, 1990)
- Risk based metric, relating partial body irradiations (individual organ or tissue, limited x-ray field) to uniform whole body irradiation
- The effective dose (E) is the sum of the weighted equivalent doses in all the tissues and organs of the body.
- \( E = \sum W_T H_T \)
  - \( W_T \) is the weighting factor for tissue T
  - \( H_T \) is the individual tissue or organ dose for tissue T
Organ doses can be measured in phantoms

- Sensitive organs ($w_i = 0.12$)
  - Red bone marrow
  - Colon
  - Lung
  - Stomach
- Moderately sensitive organs ($w_i = 0.05$)
  - Bladder
  - Breast
  - Liver
  - Esophagus
  - Thyroid
Dosimetry of individual organs can be measured with low dose scans.

Radiation exposure is proportional to the quantity of injected radiopharmaceutical.

For a given amount of radiation, damage and risk is higher for pediatric populations.
Image Gently℠

- Initiative of the Alliance for Radiation Safety in Pediatric Imaging
- Goal: change practice by increasing awareness of opportunities to lower radiation dose in the imaging of children
- Pause and child-size the technique, use the lowest Pulse rate possible. Consider ultrasound or MRI when possible.

Image Wisely™

- Awareness program of the American College of Radiology, the Radiological Society of North America, the American Association of Physicists in Medicine, and the American Society of Radiologic Technologists.
- Image Wisely's objective is to encourage practitioners to avoid unnecessary ionizing radiation scans and to use the lowest optimal radiation dose for necessary studies.
Radiation Dose Calculator

- The American College of Radiology (ACR) and the International Atomic Energy Agency (IAEA) both recommend hospitals monitor radiation exposure.
- Calculator allows to track imaging history and estimate risk.

DFCI Radiation Safety Committee dose spreadsheet
<table>
<thead>
<tr>
<th>Procedure</th>
<th>Effective Dose (mSv)</th>
<th>Effective Dose (rem)</th>
<th>Effective Dose per Unit Activity (mSv/mBq)</th>
<th>Effective Dose per Unit Activity (rem/mBq)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head CT</td>
<td>0.05</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>ACR 82</td>
</tr>
<tr>
<td>mammography</td>
<td>0.04</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>ACR 83</td>
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<tr>
<td>Bone Scintigraphy</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>ACR 82</td>
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<tr>
<td>Special Exam</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>ACR 82</td>
</tr>
<tr>
<td>Head CT</td>
<td>120</td>
<td>130</td>
<td>5.05</td>
<td>5.05</td>
<td>Kaszkin 98</td>
</tr>
<tr>
<td>Chest CT</td>
<td>120</td>
<td>130</td>
<td>5.05</td>
<td>5.05</td>
<td>Kaszkin 99</td>
</tr>
<tr>
<td>abdomen CT</td>
<td>120</td>
<td>130</td>
<td>5.05</td>
<td>5.05</td>
<td>Kaszkin 98</td>
</tr>
<tr>
<td>Brain CT</td>
<td>120</td>
<td>130</td>
<td>5.05</td>
<td>5.05</td>
<td>Kaszkin 98</td>
</tr>
<tr>
<td>DPA CT</td>
<td>120</td>
<td>130</td>
<td>5.05</td>
<td>5.05</td>
<td>Kaszkin 98</td>
</tr>
<tr>
<td>Gastroscopy</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>ACR 82</td>
</tr>
</tbody>
</table>

Total Effective Dose (rem) for all Radiology Procedures: 6.0
Equivalent to Number of Years of Maximum Annual Occupational Exposure: 10.0
Linear No Threshold Model

- Assume linear relationship between radiation exposure and the risk of cancer
- Assumes that any exposure, regardless of how low, increases risk of cancer
- Greater lifetime risk for exposure at younger age due to greater sensitivity and longer lifespan to potentially develop cancer

**BEIR VII**

Table 1: Lifetime Attributable Risk of Cancer from Exposure to Radiation

<table>
<thead>
<tr>
<th>Age at Exposure</th>
<th>Male</th>
<th>Percent</th>
<th>Female</th>
<th>Percent</th>
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<tbody>
<tr>
<td>0</td>
<td>2583</td>
<td>2.56%</td>
<td>4777</td>
<td>4.78%</td>
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<tr>
<td>5</td>
<td>1816</td>
<td>1.82%</td>
<td>3377</td>
<td>3.36%</td>
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<tr>
<td>10</td>
<td>1445</td>
<td>1.45%</td>
<td>2611</td>
<td>2.61%</td>
</tr>
<tr>
<td>15</td>
<td>1182</td>
<td>1.18%</td>
<td>2064</td>
<td>2.06%</td>
</tr>
<tr>
<td>20</td>
<td>977</td>
<td>0.98%</td>
<td>1648</td>
<td>1.65%</td>
</tr>
<tr>
<td>30</td>
<td>686</td>
<td>0.69%</td>
<td>1065</td>
<td>1.07%</td>
</tr>
<tr>
<td>40</td>
<td>646</td>
<td>0.65%</td>
<td>886</td>
<td>0.89%</td>
</tr>
<tr>
<td>50</td>
<td>591</td>
<td>0.59%</td>
<td>740</td>
<td>0.74%</td>
</tr>
<tr>
<td>60</td>
<td>499</td>
<td>0.49%</td>
<td>595</td>
<td>0.59%</td>
</tr>
<tr>
<td>70</td>
<td>343</td>
<td>0.34%</td>
<td>409</td>
<td>0.41%</td>
</tr>
<tr>
<td>80</td>
<td>174</td>
<td>0.17%</td>
<td>214</td>
<td>0.21%</td>
</tr>
</tbody>
</table>

Estimated Organ Doses and Lifetime Cancer Risks from Typical Single CT Scans of the Head and the Abdomen

N Engl J Med 2007;357:2277-84

Incidents of overexposure

Doctors ‘Shocked’ by Radiation Overexposure at Cedars-Sinai

BY EMMA COTTLER

Oct 13, 2009

Doctors have expressed outrage and concern for the unsuspecting patients who received eight times the normal dose of radiation during a specific type of brain scan at Cedars-Sinai Medical Center in Los Angeles.

The overexposure was discovered when a patient reported bad patches of hair following a CT scan.

The error, which Cedars-Sinai attributed to a "misunderstanding" about an incorrectly programmed CT machine, in a statement released Oct. 12, remained unchecked for 16 months, involved 206 people, and sparked existing concerns that patients nationwide are being exposed to excess radiation during medical testing.

"To me, even as a professional, this is a fairly shocking story," said Dr. James Stoler, associate professor of cardiology at the NYU Langone Medical Center. "The fact this error occurred and went undetected for 16 months is a well regarded medical institution is rather unbelievable.”
Incidents of overexposure

**NY times**

West Virginia Hospital Overradiated Brain Scan Patients, Records Show

A large West Virginia hospital seriously overradiated patients suspected of having cancer with CT scans for more than a year, a similar episode prompted federal officials to instruct hospitals nationwide to be especially careful when using these and other scans, the Times reports.

The patients, at Cabell Huntington Hospital in Huntington, W.Va., were overexposed with radiation until late November, records show, even after the Food and Drug Administration told the hospital for federal certification that it must stop using such scans on its patients and that it had conducted an audit in February.

Federal records indicate that Cabell knew of some of the overexposures three months before it did not know how many patients were exposed, an official said.

Dr. Charles L. Siegel, a hospital spokesman, declined to say how many patients were exposed or to estimate the number. But he said the hospital had determined that there had been no harm and that the patients were still being treated.

The hospital’s release also acknowledged that it had been “aware of the problem” and had been working to correct it.

Who is at risk?

- **Patient / research subject**
- **General public**
- **Workers**
  - Imaging and radiation oncology physicians
  - Technologists and imaging staff
  - Flight staff
How to reduce exposure?

• Time
• Distance
• Shielding (room and/or personal)

How do we protect them?

• Patient / research subject
  – Departmental safety policies and screening procedures
  – IRB
  – Radiation Safety Committee
  – Radioactive Drug Research Committee
  – Regulatory oversight (Joint Commission, DPH, FDA)

• General public
  – Shielding of exam rooms from magnetic fields and radiation
  – Regulated transport/release of radioactive materials

• Workers
  – Training and monitoring requirements
  – Annual radiation exposure limits
  – ALARA policies
ALARA

• It is the guiding principle in radiation protection
• Radiation exposure should always be …

As
Low
As
Reasonably
Achievable

How to eliminate unnecessary radiation?

• Tracking of exams (electronic medical records)
• Appropriateness criteria
• Alternative methods of assessment (ultrasound, MRI)
Radiation Safety Protocol Screening Form

- All research use of radiation must be approved by institutional Radiation Safety Committee
- Screening form allows the RSC to
  - Determine whether there is research use of radiation
  - Estimate the radiation dose to patient
  - Determine if use of radiation is appropriate and safe
  - Provide risk statement for consent form

DF/HCC Radiation Risk Statement

“This research study involves exposure to radiation from two additional PET/CT scans. Please note that this radiation exposure is not necessary for your medical care but is required to obtain the desired research information. From participating in this study, the maximum amount of additional radiation your body will be exposed to in one year is less than what a person performing your imaging scans is allowed to receive in one year. There is thought to be an increased long term risk of cancer associated with radiation.”
Additional Resources

- Institution Radiation Safety Office
- Institution Departments of Radiology/Nuclear Medicine
- Havard Catalyst Imaging Consortium (http://catalyst.harvard.edu/services/imagingconsulting.html)
- jeffrey_yap@dfci.harvard.edu

References

- http://www.xrayrisk.com/
- http://www.pedrad.org/associations/5364/ig/
- http://www.imagewisely.org/
- Brenner and Hall:  
Acknowledgements

Walter Huda, PhD, SUNY Upstate Medical University