Radiation Dose and Risk in Pediatric Nuclear Medicine
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NB: This material was gleaned from the following reference: Fahey FH, Treves ST, Adelstein SJ, Minimizing and Communicating Radiation Risk in Pediatric Nuclear Medicine. J Nucl Med. 2011;52:1240-1251. All figures and tables are used with permission.

Primary Objective: To review radiation dosimetry and risk to aid nuclear medicine practitioners in their dealing of the pediatric patient and their families

Additional Objectives: After reviewing this material, the participant will be able to understand and describe:

1. The growing use of nuclear medicine
2. Factors that affect the radiation dosimetry regarding the use of radiopharmaceuticals
3. Issues associated with CT dose in the context of PET/CT and SPECT/CT
4. The scientific basis for radiation risk estimation in the context of pediatric nuclear medicine
5. Approaches for effective communication of risk to patients’ and their families
6. Methods for radiation dose reduction in pediatric nuclear medicine

Growing Use of Nuclear Medicine

1. Many applications of Pediatrics Nuclear Medicine including oncology, cardiology, neurology, endocrinology, urology, gastroenterology and orthopedics.
2. Numbers of Examinations
   a. 18 million nuclear medicine procedures in 2006 (up from 6.3 million in 1984, 1% in children)
3. Estimated Annual Dose to US Population
   a. Per capita annual dose to US population from medical imaging is 3.0 mSv in 2006 (up from 0.5 mSv in 1982) according to NCRP 160
   b. Per capita annual dose to US population from nuclear medicine is 0.8 mSv in 2006 (up from 0.14 mSv in 1982) a large fraction of which is from nuclear cardiology, a procedure not as commonly performed in children

Dosimetry of Pediatric Nuclear Medicine

1. Dosimetry of Radiopharmaceuticals
   a. Factors affecting radiopharmaceutical dose
      i. Radiopharmaceutical administered including radionuclide
ii. Amount of radioactivity administered  
iii. Organ distribution of administered radiopharmaceutical  
iv. Clearance of the radiopharmaceutical  

b. How radiopharmaceutical dose may differ in children relative to adults  
   i. Patient size  
   ii. Organ size and orientation  
   iii. Organ distribution of administered radiopharmaceutical  

c. Critical organ is the organ that receives the highest radiation dose  

d. Effective dose is weighted sum of individual organ doses based on the biological radiosensitivity of each organ  

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>Estimates of Critical Organ and Effective Dose for Common Pediatric Nuclear Medicine Procedures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (kg)</td>
<td>Max admin act (MBq)</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>$^{99m}$Tc-MODP</td>
<td>740</td>
</tr>
<tr>
<td>Bone surface (mGy)</td>
<td>54.5</td>
</tr>
<tr>
<td>Effective dose (mSv)</td>
<td>2.8</td>
</tr>
<tr>
<td>$^{99m}$Tc-ECD</td>
<td>740</td>
</tr>
<tr>
<td>Bladder wall (mGy)</td>
<td>4.1</td>
</tr>
<tr>
<td>$^{99m}$Tc octaemb</td>
<td>740</td>
</tr>
<tr>
<td>Gallbladder (mGy)</td>
<td>5.4</td>
</tr>
<tr>
<td>$^{99m}$Tc-MAG3</td>
<td>370</td>
</tr>
<tr>
<td>Effective dose (mSv)</td>
<td>1.2</td>
</tr>
<tr>
<td>$^{111}$In-MIBG</td>
<td>370</td>
</tr>
<tr>
<td>Liver (mGy)</td>
<td>3.4</td>
</tr>
<tr>
<td>Effective dose (mSv)</td>
<td>1.0</td>
</tr>
<tr>
<td>$^{153}$Tc-FDG</td>
<td>370</td>
</tr>
<tr>
<td>Bladder wall (mGy)</td>
<td>5.2</td>
</tr>
<tr>
<td>Effective dose (mSv)</td>
<td>---</td>
</tr>
</tbody>
</table>

| Note | Based on ICRP 80 (25). |
| Note | Based on ICRP 108 (26). |
| Note | Max admin act = maximum administered activity is that administered to adult or large child (70 kg) (administered activities for smaller children are scaled by body weight); ECD = ethyloctanato dimer; MIBG = metaodobenzylguanidine. |

2. Dosimetry of CT (refer to Image Gently CT resources)  
   a. Factors affecting CT dose include tube voltage (in kVp), tube current time product (in mAs), table speed (pitch), extent of patient scanned, Use of automated exposure control, use of shields  
   b. Parameters to measure CT dose  
      i. CT Dose Index (CTDI$\text{vol}$)  
      ii. Dose Length Product (DLP)  
      iii. Effective Dose  
   c. CT Dose in context of PET/CT and SPECT/CT
i. Whole body PET/CT typically acquired over large portion of patient (from base of skull to mid-thigh)

ii. Use of CT in PET/CT and SPECT/CT
   1. Diagnostic CT
   2. Attenuation correction (dose can be VERY low)
   3. Anatomical correlation (dose lower than diagnostic CT)

3. Dose from nuclear medicine compared to other radiologic procedures

<table>
<thead>
<tr>
<th>TABLE 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adult Effective Doses (mSv) for Radiographic and Nuclear Medicine Procedures</td>
</tr>
<tr>
<td>Procedure</td>
</tr>
<tr>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>Posterior/anterior and lateral chest radiography</td>
</tr>
<tr>
<td>$^{99m}$Tc-radioluidic cystography</td>
</tr>
<tr>
<td>Mammography</td>
</tr>
<tr>
<td>Lumbar spine radiography</td>
</tr>
<tr>
<td>Head CT</td>
</tr>
<tr>
<td>$^{99m}$Tc-MAG3 renal scanning</td>
</tr>
<tr>
<td>Intravenous urography</td>
</tr>
<tr>
<td>$^{99m}$Tc-MDP bone scanning</td>
</tr>
<tr>
<td>$^{123I}$-metadobenzylguanidine scanning</td>
</tr>
<tr>
<td>$^{99m}$Tc-ethylcytastine dimer brain scanning</td>
</tr>
<tr>
<td>Pelvic CT</td>
</tr>
<tr>
<td>$^{99m}$Tc-sestamibi for stress/rest cardiac scanning</td>
</tr>
<tr>
<td>Chest CT</td>
</tr>
<tr>
<td>Coronary angiography</td>
</tr>
<tr>
<td>$^{18F}$FDG PET scanning</td>
</tr>
<tr>
<td>Abdominal CT</td>
</tr>
<tr>
<td>Coronary angioplasty with stent placement</td>
</tr>
</tbody>
</table>

Radiopharmaceutical doses are from Table 1 except $^{99m}$Tc-radioluidic cystogram dose (24-27). Radiographic doses are from Mettler et al. (23).

Radiation Risk in Children

1. Epidemiologic Evidence
   a. Life Span Study of survivors of Hiroshima and Nagasaki
      i. As of last report, 87,000 individuals followed from 1950 and 1997
      ii. 440 excess cases estimated
iii. 80% of subjects received a whole body dose of less than 0.1 Gy, and 10% (44) of the estimated excess cancers occurred in this population

b. Epidemiology is limited in its ability to show small health effects since a very large population would be required making it difficult to control its heterogeneity

2. Biological evidence
   a. DNA within the cellular nucleus is the target of most interest
   b. Cellular radiation damage can be direct
   c. More commonly indirect from free radicals caused by the radiolysis of water
   d. Biological damage can be affected by genetic instability and secondary effects such as the bystander effect

Evaluation of Radiation Risk for Pediatric Nuclear Medicine

1. BEIR VII Phase 2 Report (2007) of Biological Effects of Ionizing Radiation Committee of the US National Academy of Sciences
   a. Recommends
      i. Linear no threshold model (LNT) for solid tumors
      ii. Linear quadratic model for leukemia
   b. Choice of models may be controversial but LNT is prudent for radiation protection purposes
   c. Estimates of lifetime excess attributable risk as a function of age and gender can be estimated using models from BEIR VII Phase 2

<table>
<thead>
<tr>
<th>Tumor type</th>
<th>Sex</th>
<th>Newborn</th>
<th>10-y-old</th>
<th>40-y-old</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breast</td>
<td>F</td>
<td>27.4</td>
<td>16.7</td>
<td>3.5</td>
</tr>
<tr>
<td>Lung</td>
<td>F</td>
<td>64.3</td>
<td>44.2</td>
<td>21.2</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>31.8</td>
<td>21.9</td>
<td>10.7</td>
</tr>
<tr>
<td>Colon</td>
<td>F</td>
<td>10.2</td>
<td>7.3</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>16.3</td>
<td>11.7</td>
<td>6.0</td>
</tr>
<tr>
<td>All solid</td>
<td>F</td>
<td>172</td>
<td>105</td>
<td>45.5</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>103</td>
<td>64.1</td>
<td>31.0</td>
</tr>
<tr>
<td>Leukemia</td>
<td>F</td>
<td>5.3</td>
<td>5.3</td>
<td>5.2</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>7.1</td>
<td>7.1</td>
<td>6.7</td>
</tr>
</tbody>
</table>
d. Younger patients and particularly younger females at higher risk. Approximately, a 1, 10 and 40 year old have a 1 in 700, 1000 and 2000 risk (red dashed lines above) of dying of cancer from a 10 mSv whole body dose

**Communication of Risk to Parents and Children**

1. Perceptions of radiation risk
   a. Varies for the public and scientists alike
   b. Media reports lead to more public awareness
   c. Pediatricians often have little understanding of radiation risk
   d. When parents ask about dose, what they are really asking about is risk!

2. How best to communicate radiation risk
   a. Our patients and their families have heard a bit more about radiation in the media and possibly in school and require a more sophisticated explanation
   b. Not adequate to just state that our studies are safe
   c. Being informed about radiation dose and risk does not adversely affect willing to receive an imaging procedure
   d. A reasonable approach may include the following:
      i. The nuclear medicine procedure will involve the patient receiving a small amount of radioactivity
ii. This radioactivity will emit radiation similar to that given off by x-ray machines

iii. The radiation dose received is similar to that received from other radiologic exams

iv. This exposure lead to a slight increase in the risk of contracting cancer sometime in the patient's life

v. Lastly, the risk should be discussed in the context of the benefits the patient will receive from the procedure

e. In the cases where the patient needs more specific information regarding risk, a graphical approach is preferred (example below)

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**FIGURE 7.** Demonstration of 1 in 2,500 risk in comparison to 550 in 2,500. For example of 10-y-old receiving $^{99m}$Tc-MDP bone scan, excess attributable risk for cancer death is 1 in 2,500. In this figure, there are 2,500 small circles. Lone red star at lower right represents 1 case in 2,500 in which bone scan patient may contract fatal cancer. In addition, there are 550 dark blue circles that represent number of the original 2,500 that will naturally die of cancer (22%).
f. In some cases, it may be helpful to compare the risk of receiving a radiological exam to other risks associated with daily living

<table>
<thead>
<tr>
<th>Activity</th>
<th>Lifetime risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assault</td>
<td>214</td>
</tr>
<tr>
<td>Accident while riding in car</td>
<td>304</td>
</tr>
<tr>
<td>Accident as pedestrian</td>
<td>652</td>
</tr>
<tr>
<td>Choking</td>
<td>804</td>
</tr>
<tr>
<td>Accidental poisoning</td>
<td>1,030</td>
</tr>
<tr>
<td>Drowning</td>
<td>1,127</td>
</tr>
<tr>
<td>Exposure to fire or smoke</td>
<td>1,161</td>
</tr>
<tr>
<td>Cancer from $^{18}$F-FDG PET scan (10-y-old)</td>
<td>1,515</td>
</tr>
<tr>
<td>Falling down stairs</td>
<td>2,024</td>
</tr>
<tr>
<td>Cancer from $^{99m}$Tc-MDP bone scan (10-y-old)</td>
<td>2,560</td>
</tr>
<tr>
<td>Cancer from $^{18}$F-FDG PET scan (40-y-old)</td>
<td>2,700</td>
</tr>
<tr>
<td>All forces of nature</td>
<td>3,100</td>
</tr>
<tr>
<td>Accident while riding bike</td>
<td>4,734</td>
</tr>
<tr>
<td>Cancer from $^{99m}$Tc-MDP bone scan (40-y-old)</td>
<td>4,760</td>
</tr>
<tr>
<td>Accidental firearms discharge</td>
<td>5,333</td>
</tr>
<tr>
<td>Accident while riding in plane</td>
<td>7,058</td>
</tr>
<tr>
<td>Falling off ladder or scaffolding</td>
<td>10,606</td>
</tr>
<tr>
<td>Hit by lightning</td>
<td>84,388</td>
</tr>
</tbody>
</table>

*Lifetime risk of 304 for accident while riding in car indicates that 1 of every 304 Americans will die as result of accident while riding in car during his or her lifetime.*

**Dose Reduction in Pediatric Nuclear Medicine**

1. **Standardization**
   a. A pediatric nuclear medicine study should only be performed if necessary
   b. Use of dose guidelines such as the recently published North American consensus guidelines for pediatric nuclear medicine can assure administered dose is reasonable
   c. PET/CT and SPECT/CT procedures also need to be standardized

2. **Research is Dose Reduction**
   a. Further research may be needed for some applications to determine the most appropriate administered dose
   b. Use of new imaging equipment or image processing capability may make it feasible to perform high-quality nuclear medicine studies with even lower administered dose