Dose Reduction and Radiation Safety Practices in Nuclear Medicine

63rd Annual Meeting
Southwestern Chapter
Society of Nuclear Medicine and Molecular Imaging

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Disclosures

• None!
Educational Objectives

1. Discuss tools and techniques for reducing radiation exposure to staff and patients in nuclear medicine settings
2. Evaluate radiation considerations for specific patient populations such as pregnant and pediatric patients
3. Use effective and appropriate techniques to ensure radiation safety in the nuclear medicine lab.
GENERAL RADIATION SAFETY
Radiation Workers

• Radiation Worker
  – Defined by level of occupational exposure
  – Worker classification
    • Adult > 18 years old
    • Pregnant worker
      – Must declare pregnancy
      – Exposure limits only valid during declared pregnancy
    • Minor < 18 years old

• Annual Exposure Limits

<table>
<thead>
<tr>
<th>Worker Class</th>
<th>Total Dose</th>
<th>Extremity Dose</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adult</td>
<td>50 mSv (5 rem)</td>
<td>500 mSv (50 rem)</td>
<td></td>
</tr>
<tr>
<td>Pregnant Worker</td>
<td>5 mSv (0.5 rem)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minor</td>
<td>5 mSv (0.5 rem)</td>
<td>50 mSv (5 rem)</td>
<td></td>
</tr>
<tr>
<td>General Public</td>
<td>1 mSv (0.1 rem)</td>
<td>0.02 mSv/hr (0.002 rem/hr)</td>
<td></td>
</tr>
</tbody>
</table>
Radiation Sources

• Short-lived radiation
  – Radiopharmaceuticals
    • Hot lab
      – $^{18}$F, $^{99m}$Tc, etc.
  – Injected Patients
    • Uptake rooms
    • Scanner bays
    • Patient restrooms
  – X-ray sources
    • Hybrid scanners

• Long-lived radiation
  – Sealed sources
    • $^{57}$Co, $^{68}$Ge, $^{137}$Cs, etc.
  – Radioactive waste
    • Long-lived
    • Short-lived
Radiation Protection

• ALARA- As Low As Reasonably Achievable
  – Make every reasonable effort to maintain radiation exposures as far below the dose limits as is practical
    • Takes into account technology and financial considerations
  – Written policies, procedures and instructions are in place to foster ALARA philosophy
Radiation Protection

• Time
  – Half-life of most radiopharmaceuticals is relatively short

• Distance
  – Exposure proportional to $1/r^2$

• Shielding
  • Half-value layer lead
    – $^{99m}$Tc 0.011 in
    – $^{18}$F 0.256 in
Radiation Protection Practice

- Do not eat or drink in restricted areas
- Wear laboratory coats and gloves when working with RAM
- Cover work areas with absorbent material
- Use remote handling whenever possible
- Wear badges when in restricted areas
- Assess spills promptly and clean up or isolate as appropriate
NUCLEAR MEDICINE IMAGING IN PREGNANT FEMALES
Imaging Pregnant Females

• Fetal exposure ‘frightening and complicated’ issue
  – Understandably concerned about possible detrimental effects of radiation exposure to developing embryo/fetus

• No known threshold for stochastic effects
  – “No safe level?”
Imaging Pregnant Females

• Pregnant females have many of the same conditions/diseases where diagnostic imaging would be useful
  – Cancer in pregnant females is 1 in 1000\textsuperscript{1}

• Imaging is a vital component for the management/treatment of many diseases
  – Pregnant females are no different
Imaging Pregnant Females

• “No Safe Level” only applies when there is no benefit
  – Clearly not the case in certain situations
• Safety is taking appropriate actions to limit the risk to a level justified by the benefit
• Imaging radiation must be as low as reasonably achievable and medical benefit must counterbalance risk
Determining Fetal Dose

- Can’t perform experiments for ethical reasons
- Use data from
  - Bomb survivors
  - Accidental exposure survivals
  - Animal data
- Extrapolate from high exposure to levels common in nuclear medicine
  - Error? Appropriateness?
- Need large numbers to obtain statistically significant data
- Manuscripts and case studies are being reported with experiences and techniques
Radiation Effects on Embryo/Fetus

• According to BIER V Report\(^2\)
  – Early gestation/First trimester
    • Most sensitive stage
    • “All or nothing injury”
  – 2\(^{nd}\) Trimester
    • Gross congenital malformation
    • Mental retardation
  – 3\(^{rd}\) Trimester
    • Growth retardation
    • Induced childhood cancer

From Bushburg\(^3\)

**FIGURE 25-20.** Relative incidence of various adverse health effects associated with radiation exposure in utero at various stages of gestation. (Adapted from Mettler FA, Upton AC. Medical effects of ionizing radiation, 2nd ed. Philadelphia: WB Saunders, Co., 1995.)
Risks from Fetal Exposure

- **Mental Retardation**
  - Appears to be a linear function of dose
    - Risk ~40% per Gy above 100 mGy at 8-15 weeks post-conception \(^4,5\)
    - Loss of IQ is ~13-21 points per Gy at doses above 700 mGy \(^4,5\)

- **Leukemia**
  - Most common of radiation-induced childhood cancers
  - Absolute risk of inducing childhood cancers is ~6% per Gy
    - Fetal dose of ~10 mGy increases absolute risk by ~0.06%
    - But relative risk is ~40%
      - Because childhood cancers are rare
Risks from Fetal Exposure

• Fetal dose of < 50 mGy represents non-measurable cancer risk at any stage of gestation \(^6\)
  – Fetal dose < 100 mGy “should not be considered a reason for terminating a pregnancy” \(^7\)
• Fetal dose of 100 mGy has < 1% chance of inducing childhood cancer
• Fetal dose > 500 mGy can lead to significant fetal damage
• Dose > 1,000 mGy increases risk for miscarriage and neonatal death
• Potential risks to fetus are not increased from most standard medical tests with radiation dose < 50 mSv \(^8\)
## Fetal radiation doses for select nuclear medicine procedures

<table>
<thead>
<tr>
<th>Tracer</th>
<th>Dose (mCi)</th>
<th>≤ 3 Mo (mGy)</th>
<th>3 Mo (mGy)</th>
<th>6 Mo (mGy)</th>
<th>9 Mo (mGy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>¹⁸F FDG</td>
<td>10</td>
<td>9.99</td>
<td>6.29</td>
<td>3.48</td>
<td>3.00</td>
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<tr>
<td>¹¹¹In WBC</td>
<td>0.5</td>
<td>2.60</td>
<td>1.92</td>
<td>1.92</td>
<td>1.88</td>
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<tr>
<td>⁹⁹mTc DMSA</td>
<td>6</td>
<td>1.12</td>
<td>1.03</td>
<td>0.88</td>
<td>0.75</td>
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<tr>
<td>⁹⁹mTc DTPA</td>
<td>20</td>
<td>9.00</td>
<td>6.53</td>
<td>3.08</td>
<td>0.35</td>
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<td>⁹⁹mTc DTPA Aerosol</td>
<td>1.1</td>
<td>0.23</td>
<td>0.17</td>
<td>0.09</td>
<td>0.12</td>
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<tr>
<td>⁹⁹mTc MAA</td>
<td>6</td>
<td>0.62</td>
<td>0.88</td>
<td>1.10</td>
<td>0.88</td>
</tr>
<tr>
<td>⁹⁹mTc Disofenin</td>
<td>10</td>
<td>5.95</td>
<td>5.25</td>
<td>4.20</td>
<td>2.35</td>
</tr>
<tr>
<td>⁹⁹mTc MAG3</td>
<td>20</td>
<td>13.50</td>
<td>10.50</td>
<td>4.13</td>
<td>3.90</td>
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<tr>
<td>⁹⁹mTc MDP</td>
<td>20</td>
<td>4.58</td>
<td>4.05</td>
<td>2.03</td>
<td>1.80</td>
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<tr>
<td>⁹⁹mTc RBC in vitro</td>
<td>25</td>
<td>6.32</td>
<td>4.37</td>
<td>3.16</td>
<td>2.60</td>
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<tr>
<td>⁹⁹mTc RBC in vivo</td>
<td>15</td>
<td>5.95</td>
<td>4.00</td>
<td>3.07</td>
<td>2.51</td>
</tr>
</tbody>
</table>
Steps to Reduce Fetal Radiation Exposure

• Reduction in administered dose (typically at most 50%)
• Increase in imaging time (related to dose – usually double)
• Reduction of exposure from maternal bladder
  – Catherization
  – Hydration (Oral, IV)
• Awareness of radiopharmaceutical’s ability to cross the placenta
  – $^{131}$I is prime example
• Use lowest dose CT possible

From Image Wisely PET-CT in the Pregnant Patient 10
30 year old woman with history of juvenile laryngeal papillomatosis and lung cancer

34 year old woman, 28 weeks pregnant. Recently diagnosed with squamous cell carcinoma of cervix
Summary

• Nuclear medicine studies in pregnant females should be considered when appropriate.

• For most studies, fetal exposure, while non-zero, is well-within an acceptable risk-benefit ratio.

• Counseling of patient and referring physician is likely needed.

• Extra caution/consideration should be taken when developing protocols for pregnant females.
PEDIATRIC NUCLEAR MEDICINE
Pediatric Nuclear Medicine

• Value of pediatric diagnostic imaging is well established
  – Provides valuable diagnostic information \(^{12,13}\)
  – ~200,000 pediatric cases in 2006 \(^{14}\)
  – The average child will have 7 radiologic examinations by age 18 \(^{15}\)
    • 85% radiograph
    • 12% CT
    • 1% nuclear medicine
Radiation Dosimetry in Children

- Dosimetry based on adult experiments
  - Patient size vastly different
  - Organs are small and closer together
  - S-values used are simple shapes 16, 17
- Children vary greatly in body size and habitus
  - No ability to account for individual variations
- Models based on adult physiology
  - Metabolism, etc. potentially very different in children
- Radiation dose to individual may vary by 100%-200%
Radiation Risk in Children

- Risk of ionizing radiation varies with age and sex
  - Younger subjects have significantly more risk
    - Actively growing tissue is more radiosensitive
    - Children have a longer lifespan than adults
      - Longer time for that risk to be realized
  - Girls have a 50% higher cancer induction risk than boys
    - Primarily due to excess breast cancer risk
Evaluation of Pediatric Risk

- Risk depends on dose delivered to each radiosensitive organ and the risk of cancer for that organ
  - 10 mSv exposure
    - 1 in 700 for 1 year old
    - 1 in 1000 for 10 year old
    - 1 in 2000 for 40 year old
- Administered dose is scaled by weight
- Radiation risk per unit dose increases in younger patients

Lifetime attributable risk of cancer death as function of age at time of exposure and sex resulting from 10-mSv exposure. 18
# Pediatric Radiation Dose Estimates

<table>
<thead>
<tr>
<th>Procedure</th>
<th>1 yr old</th>
<th>5 yr old</th>
<th>10 yr old</th>
<th>15 yr old</th>
<th>Adult</th>
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</thead>
<tbody>
<tr>
<td><strong>99mTc-MDP</strong></td>
<td>54.5</td>
<td>46.0</td>
<td>45.6</td>
<td>49.2</td>
<td>46.6</td>
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<tr>
<td>Bone surface</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>99mTc-ECD</strong></td>
<td>13.4</td>
<td>23.0</td>
<td>30.5</td>
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<td>37.0</td>
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<tr>
<td>Bladder wall</td>
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<td></td>
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<td></td>
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<tr>
<td><strong>99mTc-Sestamibi</strong></td>
<td>32.9</td>
<td>20.9</td>
<td>20.4</td>
<td>27.0</td>
<td>28.9</td>
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<tr>
<td>Gallbladder</td>
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<tr>
<td><strong>99mTc-MAG3</strong></td>
<td>17.2</td>
<td>19.8</td>
<td>31.3</td>
<td>44.1</td>
<td>42.7</td>
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<td>Bladder wall</td>
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<td></td>
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<tr>
<td><strong>123I-MIBG</strong></td>
<td>16.6</td>
<td>18.5</td>
<td>22.4</td>
<td>25.6</td>
<td>24.8</td>
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<tr>
<td>Liver</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>18F-FDG</strong></td>
<td>25.6</td>
<td>35.9</td>
<td>44.4</td>
<td>48.8</td>
<td>50.5</td>
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<tr>
<td>Bladder wall</td>
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</table>

Estimates of critical organ doses for common pediatric nuclear medicine procedures \(^{19,20}\)

<table>
<thead>
<tr>
<th>Procedure</th>
<th>1 yr old</th>
<th>5 yr old</th>
<th>10 yr old</th>
<th>15 yr old</th>
<th>Adult</th>
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<tbody>
<tr>
<td><strong>99mTc-MDP</strong></td>
<td>2.8</td>
<td>2.9</td>
<td>3.9</td>
<td>4.2</td>
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<td>(mSv)</td>
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</tr>
<tr>
<td><strong>99mTc-ECD</strong></td>
<td>4.1</td>
<td>4.6</td>
<td>5.3</td>
<td>5.9</td>
<td>5.7</td>
</tr>
<tr>
<td>(mSv)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>99mTc-Sestamibi</strong></td>
<td>5.4</td>
<td>5.9</td>
<td>6.3</td>
<td>7.2</td>
<td>6.7</td>
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<tr>
<td>(mSv)</td>
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<td></td>
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<tr>
<td><strong>99mTc-MAG3</strong></td>
<td>1.2</td>
<td>1.3</td>
<td>2.2</td>
<td>2.8</td>
<td>2.7</td>
</tr>
<tr>
<td>(mSv)</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td><strong>123I-MIBG</strong></td>
<td>3.4</td>
<td>3.8</td>
<td>4.5</td>
<td>5.0</td>
<td>4.8</td>
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<tr>
<td>(mSv)</td>
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<td></td>
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<tr>
<td><strong>18F-FDG</strong></td>
<td>5.2</td>
<td>5.9</td>
<td>6.6</td>
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<td>7.4</td>
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<td>(mSv)</td>
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</tbody>
</table>

Estimates of effective dose organ doses for common pediatric nuclear medicine procedures \(^{19,20}\)
Communication of Risk to Parents and Children

• Perceptions about radiation vary widely
  – Parents
  – Scientists
  – Pediatricians

• Resources for communication
  – Image Gently 21, 22
  – SNMMI, ACR, SPR 23

<table>
<thead>
<tr>
<th>Activity</th>
<th>Lifetime Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accident while riding in car</td>
<td>1 in 304</td>
</tr>
<tr>
<td>Choking</td>
<td>1 in 894</td>
</tr>
<tr>
<td>Drowning</td>
<td>1 in 1,127</td>
</tr>
<tr>
<td>Cancer from $^{18}$F-FDG PET (10 yr old)</td>
<td>1 in 1,515</td>
</tr>
<tr>
<td>Cancer from $^{99m}$Tc-MDP bone scan (10 yr old)</td>
<td>1 in 2,560</td>
</tr>
<tr>
<td>Cancer from $^{18}$F-FDG PET (40 yr old)</td>
<td>1 in 2,700</td>
</tr>
<tr>
<td>All forces of nature</td>
<td>1 in 3,190</td>
</tr>
<tr>
<td>Accident while riding bike</td>
<td>1 in 4,734</td>
</tr>
<tr>
<td>Cancer from $^{99m}$Tc-MDP bone scan (40 yr old)</td>
<td>1 in 4,760</td>
</tr>
<tr>
<td>Accident while riding in plane</td>
<td>1 in 7,058</td>
</tr>
<tr>
<td>Hit by lightning</td>
<td>1 in 84,388</td>
</tr>
</tbody>
</table>

Compressed mortality: 1999-2007 24
Dose Reduction in Pediatric Nuclear Medicine

• Administered dose is easiest controlled parameter
  – Most centers use weight based protocol
    • With minimum and maximum allowed doses

• Changes in protocol
  – Ex. No longer evaluating perfusion phase of $^{99m}$-Tc-MAG3 renogram allows reduction of dose without compromising analysis and interpretation
  – Anesthesia?

• Changes in technology
  – Dual-detector SPECT
  – Focused collimators in SPECT
  – 3D PET
  – PET/MR
  – Improved reconstruction algorithms
Pediatric Dose Management
11-year-old female with stage IVA Hodgkin lymphoma (patient 1) demonstrating increased uptake in a right subcarinal lymph node. Biopsy revealed atypical lymphoid hyperplasia. 25
Summary

• Study should only be performed if appropriate for answering clinical question
• Protocol should be optimized to minimize radiation risk to patient
• Technology should be utilized where appropriate to minimize radiation risk
• Care should be taken to communicate risk to patient and parents
RADIATION THERAPY IN RADIONUCLIDE THERAPIES
Radionuclide Therapy

- Targeted radionuclide therapies are becoming common
  - Targeted therapy by attaching radionuclide to biologically active molecule
    - Delivers radiation to targeted cells versus normal cells

**FDA Approved**

- Zevalin - $^{90}\text{Y}$
  - Non-Hodgkin’s lymphoma (NHL)
- Metastron - $^{89}\text{Sr}$
  - Metastatic prostate to bone
- Quadramet - $^{153}\text{Sm}$
  - Osteoblastic metastatic bone lesions
- Xofigo - $^{223}\text{Ra}$
  - Castration resistant prostate cancer
- LUTATHERA - $^{177}\text{Lu}$
  - Gastroenteropancreatic neuroendocrine tumors

**In the Near? Future**

- DOTATOC - $^{177}\text{Lu, }^{90}\text{Y}$
  - Neuroendocrine
- DOTATATE - $^{177}\text{Lu, }^{90}\text{Y}$
  - Neuroendocrine
- PSMA - $^{177}\text{Lu}$
  - Prostate

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From Advancing Nuclear Medicine Through Innovation
Radiation Safety Issues

• Patient radiation dose
  – Isolation?
  – Release criteria?

• Medical staff and caregiver exposure
  – Long lived isotopes
  – Alpha and beta emitters (vs x-ray and gamma)

• General public exposure
Written Directive

- An authorized user’s written order for the administration of byproduct material or radiation from byproduct material to a specific patient or human research subject as specified in 10 CFR 35.40.

- Clinical procedures affected
  - $^{131}$I -NaI administration $> 30$ μCi
  - Any therapeutic dosage of unsealed byproduct material
  - Any therapeutic dose of radiation from byproduct material

- Authorized User - Any physician whose credentials have been reviewed and approved by the NRC and is currently listed on your facilities Material’s License by name

- Must include:
  - Patient name
  - Total dose
  - Radionuclide
  - Route of administration
  - Prescribed dose
  - Authorized User’s Signature and Date
Dosing

• Based on models
  – One size fits all
    • Xofigo – 50 kBq per kg body weight

• Based on imaging
  – Pre therapy imaging
    • Using $^{68}$Ga-PSMA PET to measure PSMA expression
      – Low expression is contraindication for radiotherapy
  – Post-therapy imaging
    • Therapy effectiveness
    • Salvage therapy

This set of “before and after” PET/CT images demonstrates the use of these nuclear imaging modalities to evaluate the clinical effects of radioimmunotherapy using radiopharmaceutical compounds such as yttrium-90 ibritumomab tiuxetan (Zevalin®) in the treatment of malignant lymphoma. 26
Release Criteria

- Regulatory guide from NRC published in 1997\textsuperscript{27}
  - Update expected 4\textsuperscript{th} quarter 2018
  - Agreement states may have further restrictions
- Provides following release criteria
  - Administered activity
  - Retained activity
  - Measured dose rate
  - Patient-specific calculations
- May require instructions to patients
  - Minimize dose to caregivers
  - Special requirements for breast-feeding women
- Requires release records if not based on administered activity

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-life (d)</th>
<th>Activity at or below for release (mCi)</th>
<th>Dose rate at 1 meter at or below for release (mrem/hr)</th>
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</thead>
<tbody>
<tr>
<td>$^{131}$I</td>
<td>8.04</td>
<td>33</td>
<td>7</td>
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<tr>
<td>$^{153}$Sm</td>
<td>1.93</td>
<td>700</td>
<td>30</td>
</tr>
<tr>
<td>$^{89}$Sr</td>
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<td>N/A</td>
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<tr>
<td>$^{223}$Ra</td>
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<td>N/A</td>
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<tr>
<td>$^{90}$Y</td>
<td>2.67</td>
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<td>N/A</td>
</tr>
<tr>
<td>$^{177}$Lu</td>
<td>6.7</td>
<td>Not published</td>
<td>Not published</td>
</tr>
</tbody>
</table>
Practical Considerations

• Patient identification
• Confirm written directive
• Confirm dose (per regulations if required) within tolerances
  – Dose Calibrator calibration?
• Administer dose
  – Minimizing staff exposure
• Confirm release criteria if required
• Provide patient instructions if required
Staff Radiation Safety

- Exposure routes
  - Inhalation
  - Needle stick
  - Ingestion
  - Topical Exposure

- Radiopharmaceutical preparation
  - Can range from drawing dose to commercial kits to full radiolabeling
  - Need to consider
    - Waste streams
    - Storage of raw materials
    - Safe handling/manipulation
    - Quality assurance
Emergency Care Considerations

• During administration
  – Only essential staff for resuscitation should be near patient
  – Do not provide mouth to mouth resuscitation
    • Mask-bag system

• After administration
  – Surgery should be postponed if possible
    • Use of double gloves will provide some protection vs beta/alphas
    • All instruments/staff must be checked for contamination
  – ICU/hospitalization
    • Precautions against external radiation
    • Body fluid contamination possible
Summary

• Radionuclide therapies are increasing in frequency and variety
• Radionuclide therapies are now being performed at diagnostic imaging centers
• Need to be aware of radionuclides with longer half-lives and different emission radiation
• Ensure the safety of staff, caregivers, and patients
References (in order of appearance)

1. Blum D. Pregnancy and cancer. Cancer.net. Available at: