Radiation protection for PET/CT

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Acknowledgement

• Dr P. L. Khong, PET/CT center, HKU
• Dr Martin Law, MPU/COD/QMH
• Dr Mark Madsen, Radiology, University of Iowa.
• Dr Jon Anderson, Radiology, University of Texas Medical Center at Dallas.
• Radiation Health Unit/ Department of Health / HKSAR
Motivation for Task Group 108

• Explosion of PET and PET/CT facilities since 2000.
• Conflicting advice from physicists and manufacturers.
• AAPM Leadership Role


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Courtesy of Dr Mark Madsen
Comparison of x-rays and Annihilation Radiation

• X-rays
  • Limited duration
    – CT Scan Time (minutes per patient)
  • Low energy
    – 60 – 100 keV
  • Easily shielded
    – 1.5 mm of Pb yields 1000 x dose reduction

• Annihilation Radiation
  • Always “on”
    – Patient is main source
    – Clinic time > 1 hour/patient
  • High energy
    – 511 keV
  • Substantial shielding
    – 10 mm of Pb provides x 4 reduction

Courtesy of Dr Mark Madsen
Who (or what) needs protection?

- **PET Technologists and Nurses**
  - Radiation workers in the PET center
- **Facility employees**
  - Radiation workers (Non-PET)
  - Non-radiation workers
- **General public**
  - Relatives and associates of patients
- **Radiation detection equipment**
  - Probes, well counters, gamma cameras
What specific areas should be considered?

- Radionuclide storage & disposal
- Radiopharmaceutical administration
- Uptake room
- Tomograph room
  - Control room
- Patient bathroom
- Surrounding areas (especially uncontrolled areas with high occupancy factor).

Courtesy of Dr Mark Madsen
FACTORS AFFECTING RADIATION PROTECTION

• Radionuclide
  – Half life, emissions

• Procedure protocol
  – Administered activity, uptake time, scan time

• Dose rate from the patient
  – Dose constants, patient attenuation, decay, number of patients per week.

• Facility layout
  – Controlled vs uncontrolled areas, occupancy factors, detection instrumentation

• Regulatory Limits

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Courtesy of Dr Mark Madsen
Positron (β+) Decay

1.02 MeV Energy Threshold

Energy

Parent

Daughter

Z →

Daughter

Parent

A

Z X

511 keV

511 keV

Courtesy of Dr Mark Madsen
## PET Radionuclides

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>T&lt;sub&gt;1/2&lt;/sub&gt;</th>
<th>Decay Mode</th>
<th>Eβ&lt;sub&gt;max&lt;/sub&gt; (MeV)</th>
<th>Energy (keV)</th>
<th>photons/decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>¹¹C</td>
<td>20.4 m</td>
<td>β⁺</td>
<td>0.96</td>
<td>511</td>
<td>2.00</td>
</tr>
<tr>
<td>¹³N</td>
<td>10.0 m</td>
<td>β⁺</td>
<td>1.19</td>
<td>511</td>
<td>2.00</td>
</tr>
<tr>
<td>¹⁵O</td>
<td>2.0 m</td>
<td>β⁺</td>
<td>1.72</td>
<td>511</td>
<td>2.00</td>
</tr>
<tr>
<td>¹⁸F</td>
<td>109.8 m</td>
<td>β⁺, EC</td>
<td>0.63</td>
<td>511</td>
<td>1.93</td>
</tr>
<tr>
<td>⁸²Rb</td>
<td>76 s</td>
<td>β⁺, EC</td>
<td>3.35</td>
<td>511</td>
<td>1.90, 776</td>
</tr>
<tr>
<td>⁶⁸Ga</td>
<td>68.3 m</td>
<td>β⁺, EC</td>
<td>1.9</td>
<td>511</td>
<td>1.84</td>
</tr>
<tr>
<td>⁶⁴Cu</td>
<td>12.7 h</td>
<td>β⁻, β⁺, EC</td>
<td>0.65</td>
<td>511</td>
<td>0.38</td>
</tr>
<tr>
<td>¹²⁴I</td>
<td>4.2 d</td>
<td>β⁺, EC</td>
<td>1.54, 2.17</td>
<td>511</td>
<td>0.5, 603, 1693</td>
</tr>
</tbody>
</table>
What types of studies should be considered?

- **Myocardial Perfusion**
  - $^{82}\text{Rb}$, $^{13}\text{N}$-Amonia

- **Neurological Studies**
  - $^{15}\text{O}$-Water Cognitive Activation
  - Receptor imaging ($^{18}\text{F}$-Fluorodopa)

- **Oncologic Research**
  - $^{11}\text{C}$-Methionine, $^{11}\text{C}$-Choline

- **Clinical Oncology**
  - $^{18}\text{F}$-Fluorodeoxyglucose (FDG)
Oncologic Imaging with F-18 FDG

Lung Cancer
Colon Cancer
Esophogeal Cancer
Hodgkins Lymphoma Pre-Treatment
Hodgkins Lymphoma Post-Treatment

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Courtesy of Dr Mark Madsen
**Mechanism of Action**

- **FDG** is a glucose analog that competes with glucose for hexokinase phosphorylation to FDG-6-phosphate (FDG-6-P).
- Because FDG-6-P is not a substrate for further glycolytic pathways and has a low membrane permeability, the tracer becomes entrapped within the tissues in proportion to the rate of glucose utilization of that tissue.  

![Fludeoxyglucose F18 (18F-FDG)](image)

<table>
<thead>
<tr>
<th>Production</th>
<th>Half-life</th>
<th>Decay constant</th>
<th>Decay mode</th>
<th>Principle emissions (MeV)</th>
<th>γ ray constant (R-cm²/mCi-hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{18}$F</td>
<td>$^{18}$O(p,n)$^{18}$F</td>
<td>109.8 min</td>
<td>0.0063 min⁻¹</td>
<td>$\beta^+$, EC</td>
<td>0.65 $\beta^+$ (97%) 0.511 $\gamma$ (194%)</td>
</tr>
</tbody>
</table>

Courtesy of Dr Mark Madsen
- Patient is positioned on imaging system.
- CT transmission acquired 1st, then PET emission.
- Patient is released.

\[^{18}\text{F FDG Oncologic Studies}\]

- Patient is administered \( \sim 555 \text{ Mbq of F-18 FDG} \) in a quiet, low light room.
- Patient remains at rest for 30-90 minutes prior to PET study.
  - No walking or other muscular activity
- Patient voids prior to imaging

Courtesy of Dr Mark Madsen
Patient Dose Constant

- Unshielded $^{18}$F source constant is 0.143 $\mu$Sv m$^2$/MBq h
- Self absorption when distributed in patient.
- Wide variation in measured values reported in published reports.
- Task Group 108 recommends using 0.092 $\mu$Sv m$^2$/MBq h

Courtesy of Dr Mark Madsen
Patient as a source of radioactivity

- The patient associated dose rate depends on:
  - Number of patients
    - 50 patients/week
  - Administered activity
    - 370 - 740 MBq
  - Procedure time
    - Uptake time: 1 hour
    - Scanning time: 0.5 hour
Distances to be used in shielding calculations

Distances:
- 0.3 m (floor to ceiling)
- 1 m
- 0.5 m
- 1.7 m (typically 4.3 m)

Above and below rooms:

Courtesy of Dr. Mark Madsen
P values based on NRC 10CFR20.1201 & 10CFR20.1301

Occupational: 1000 μSv/week
ALARA (typical): 100 μSv/week
Public: 20 μSv/week

Courtesy of Dr Mark Madsen
Patient Voiding

• Patients typically eliminate at least 15% of the remaining activity from their bladder when they void after the uptake period.

• Note: A bathroom should be available within the immediate PET facility. Problems are often encountered when a radioactive PET patient walks through a nuclear medicine clinic.
Shielding Transmission Factors

• Shielding information is available in the scientific literature, but …
  – Variability among authors
  – Insufficient methodological information

• Task Group 108 relied on the Monte Carlo calculations of Doug Simpkin.
  – Mathematical model is known
  – All calculations were performed consistently
Lead Transmission Factors

Monte Carlo Simulation (Broad Parallel Beam)
Constant TVL 16.6 mm

Courtesy of Dr Mark Madsen
What is different when you have PET/CT in your facility

- 511 keV energy
  - Increases exposure rate from doses and patients.
  - Greatly increases thickness of required shielding.
- Requirements for patient handling during injection and uptake phase.
- Combined modality scanners (PET/CT) require consideration of both gamma-ray and x-ray hazard.
The $^{18}\text{F}$-Injected Patient as a Source
(average of different investigators, 2003)

<table>
<thead>
<tr>
<th>Superior</th>
<th>0.075 ($\mu$Sv/hr)/MBq</th>
<th>0.279 (mrem/hr)/mCi</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Lateral</th>
<th>0.104 ($\mu$Sv/hr)/MBq</th>
<th>0.383 (mrem/hr)/mCi</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Inferior</th>
<th>0.018 ($\mu$Sv/hr)/MBq</th>
<th>0.065 (mrem/hr)/mCi</th>
</tr>
</thead>
</table>

all at 1 m from surface of body, average value from all applicable reports

not as anisotropic as it might seem

<table>
<thead>
<tr>
<th>Anterior</th>
<th>0.103 ($\mu$Sv/hr)/MBq</th>
<th>0.383 (mrem/hr)/mCi</th>
</tr>
</thead>
</table>

compare this to
0.014 ($\mu$Sv/hr)/MBq or 0.05 (mrem/hr)/mCi for $^{99}\text{mTc}$: factor of 8!
A Revealing Comparison of Lead Requirements: X-Ray vs PET

<table>
<thead>
<tr>
<th>#HVL's</th>
<th>Lead Thickness Required mm (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X-ray (^1) (average primary for rad room)</td>
</tr>
<tr>
<td>1</td>
<td>0.044 (&lt; 1/16)</td>
</tr>
<tr>
<td>2</td>
<td>0.103 (&lt; 1/16)</td>
</tr>
<tr>
<td>4</td>
<td>0.278 (&lt; 1/16)</td>
</tr>
<tr>
<td>8</td>
<td>0.718 (&lt; 1/16)</td>
</tr>
<tr>
<td>10</td>
<td>1.366 (&lt; 1/16)</td>
</tr>
</tbody>
</table>

Even a single half-value layer for PET is an expensive proposition!

1. NCRP 147: Structural Shielding Design for Medical X-Ray Imaging Facilities
2. Simpkin, 2004, developed for AAPM Task Group on PET Facility Shielding

AAPM Annual Meeting, 2006  jon.anderson@utsouthwestern.edu
Workflow at the PET Center (FDG Whole Body Scans)

1. Arrival of patient
2. Pt instruction and prep
3. Injection of Pt
4. Uptake of pharmaceutical
5. Have Pt empty bladder
6. Transport Pt to scanner
7. Position Pt
8. Scan
9. QA Check of Scan
10. Read study
11. Release Pt
12. Print for file and referring; distribute to PACS

* steps with highest technologist exposure
N: Maximum Workload Estimation

PET Facility Throughput Example:
1 Hour Uptake, 30 Minute Scan

This facility needs two uptake areas

#pts/day = (T_{work} - T_{uptake})/T_{scan\_rm}
# uptake areas = T_{uptake}/T_{scan\_rm}

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Examples of Shadow Shields

from JA Anderson, RJ Massoth, and LL Windedahl, 2003 AAPM

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Magnitude of Technologist Exposure

Consistent with conventional nuclear medicine practice, most of technologist dose comes from positioning, transport, and injection.

Technologist Doses

average dose/procedure < 10 μSv (1 mrem)

<table>
<thead>
<tr>
<th>Reference</th>
<th>μSv/MBq (mrem/mCi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benetar</td>
<td>0.018</td>
</tr>
<tr>
<td>Chisea</td>
<td>0.012</td>
</tr>
<tr>
<td>Chisea</td>
<td>0.023</td>
</tr>
<tr>
<td>McElroy</td>
<td>0.019</td>
</tr>
<tr>
<td>UTSW</td>
<td>0.019</td>
</tr>
<tr>
<td>Roberts</td>
<td>0.011</td>
</tr>
<tr>
<td>Guillet</td>
<td>0.009</td>
</tr>
<tr>
<td>Biran</td>
<td>0.029</td>
</tr>
<tr>
<td>Yester</td>
<td>0.021</td>
</tr>
<tr>
<td>Average</td>
<td>0.018</td>
</tr>
</tbody>
</table>

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More on Technologist Exposure

1) It is often seen that the technologist dose per mBq handled drops as a function of experience in the PET clinic.

A 2004 update to the previous UTSW data for the same two technologists as shown on preceding slide showed a normalized WB dose of 0.011 µSv/MBq (0.041 mrem/mCi), down by 40% since 2002.

2) Assuming an average dose of 0.018 µSv/MBq injected, 8 pt/day and 370 MBq (10 mCi) injected/pt, this would yield a yearly dose of 13.3 mSv (1330 mrem), within regulation but above usual ALARA investigational limits. Over nine months, it would be 10.4 mSv (1040 mrem), well above the declared pregnancy limit.

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Method of radiation protection in PET/CT HKU

- Primary barrier design
- Lead sheet, lead apron, lead glass and lead door
- Radiation controlled area
- Source delivery route
- L-block for source preparation
- Syringe shield and lead box for injection.
Method of radiation protection in PET/CT HKU

- Remote controlled radiation monitoring
- Personal monitoring
- Radiation warning sign
- Decontamination kit.
- Decontamination shower
Method of radiation protection in PET/CT HKU

• Minimizing radiation risk in working procedure
• Minimizing time with radioactive patient (Pre-injection briefing, intercom, CCTV etc)
• Minimizing positioning time.
• Follow local radiation protection rules
Delivery route and Patient flow
Lead glass

Concrete barrier 300 mm

Lead door 20 mm Pb

Warning sign

Radiation monitor
Control access in Radiation controlled area
Radiation monitoring

- Geiger counters installed in preparation room, corridor, waiting area and patient toilet.
Radiation monitoring

Corridor

Reception
Computer display of Geiger counter measurement
New radiopharmaceutical temporary storage

Lead-lined drawer for temporary storage
Temporary storage of FDG

2 cm Pb equivalent

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Storage for radioactive waste
Storage for decayed radioactive waste
Hot lab: Dose assay and preparation area

Lead block with lead glass
Tungsten syringe shield
Radiation monitor for contamination check
Shower room for decontamination
Lead door for PET/CT

Lead equivalence = 20 mm
Patient monitoring through CCTV

- Preparation rooms
- Waiting area
Patient monitoring through CCTV
Inter-com at control room
Inter com at uptake room
Lead apron in PET/CT

- Useful for some paediatric patients under CT but not PET
Patient setup and positioning
Patient setup and positioning
Patient setup and positioning
Patient setup and positioning
To minimize the risk of spill by using SAFSITE® Needle-free system
Local licensing requirement

Design criteria
• < 1 μSv/h at public area (uncontrolled area)
• < 3 μSv/h at radiation controlled area

Remark: Workload, Use factor and Occupancy factor would also be considered.
PET/CT center at HKU

- 10 mm Pb lead glass
- 350 mm concrete
- 200 mm concrete
The site of PET/CT center at HKU
Opening for cable trunking
Opening at the source preparation room to the MRI unit at the upper floor
Corridor of PET/CT center
Lead lining for air duct and trunking
Confirm the transmission factor of concrete wall and ceiling by using radioactive source
Lead-lined walls PET/CT room
Radiation measurement for concrete wall at reception
Dose comparison with other radiation workers


The Distribution of Whole Body Dosimeter Users by Job Categories, 2006

- medical, 53.42%
- dental, 12.74%
- industrial, 11.74%
- others, 22.10%

Courtesy of Radiation Health Unit/DH/HKSAR
The Average Annual Occupational Whole Body Dose by Job Categories, 2006

- Dental: 0.05 mSv
- Industrial: 0.08 mSv
- Medical: 0.11 mSv
- Others: 0.05 mSv
# The Distribution of Whole Body Dose by Gender, 2006

<table>
<thead>
<tr>
<th></th>
<th>x&lt;=0.17mSv</th>
<th>0.17&lt;x&lt;=0.75</th>
<th>0.75&lt;x&lt;=1.5</th>
<th>1.5&lt;x&lt;=3.0</th>
<th>3.0&lt;x&lt;=6.0</th>
<th>6.0&lt;x&lt;=10</th>
<th>10&lt;x</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>3589</td>
<td>394</td>
<td>64</td>
<td>23</td>
<td>17</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Female</td>
<td>3258</td>
<td>359</td>
<td>36</td>
<td>10</td>
<td>6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>6847</td>
<td>753</td>
<td>100</td>
<td>33</td>
<td>23</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>
## Dose distribution by job types

<table>
<thead>
<tr>
<th></th>
<th>x≤0.17 mSv</th>
<th>0.17&lt;x ≤ 0.75</th>
<th>0.75&lt;x ≤ 1.5</th>
<th>1.5&lt;x ≤ 3.0</th>
<th>3.0&lt;x ≤ 6</th>
<th>6&lt;x ≤ 10</th>
<th>10&lt;x</th>
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</thead>
<tbody>
<tr>
<td>Consultant</td>
<td>52</td>
<td>6</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Delivery</td>
<td>11</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Dentist</td>
<td>354</td>
<td>23</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Dental assistant</td>
<td>310</td>
<td>14</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Industrial radiographer</td>
<td>27</td>
<td>18</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Medical officer</td>
<td>755</td>
<td>106</td>
<td>14</td>
<td>6</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
## Dose distribution by job types

<table>
<thead>
<tr>
<th></th>
<th>x≤0.17 mSv</th>
<th>0.17&lt;x ≤ 0.75</th>
<th>0.75&lt;x ≤ 1.5</th>
<th>1.5&lt;x ≤ 3.0</th>
<th>3.0&lt;x ≤ 6</th>
<th>6&lt;x ≤ 10</th>
<th>10&lt;x</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medical Technologist</td>
<td>35</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Nurse</td>
<td>950</td>
<td>135</td>
<td>14</td>
<td>5</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Physicist</td>
<td>37</td>
<td>7</td>
<td>7</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Diagnostic radiographer</td>
<td>1055</td>
<td>132</td>
<td>18</td>
<td>5</td>
<td>13</td>
<td>1</td>
<td>0</td>
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<tr>
<td>Therapeutic radiographer</td>
<td>92</td>
<td>20</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Radiologist</td>
<td>49</td>
<td>6</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Courtesy of Radiation Health Unit/DH/HKSAR
Personal radiation monitors record at PET/CT center / HKU

<table>
<thead>
<tr>
<th>Dose (μSv)</th>
<th>Rad 1</th>
<th>Rad 2</th>
<th>Rad 3</th>
<th>Nurse 1</th>
<th>Nurse 2</th>
<th>Nurse 3</th>
<th>Nurse 4</th>
<th>Nurse 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 07</td>
<td>117</td>
<td>159</td>
<td>170</td>
<td>12</td>
<td>63</td>
<td>17</td>
<td>45</td>
<td>36</td>
</tr>
<tr>
<td>July 07</td>
<td>114</td>
<td>156</td>
<td>118</td>
<td>14</td>
<td>25</td>
<td>12</td>
<td>44</td>
<td>61</td>
</tr>
<tr>
<td>Aug 07</td>
<td>129</td>
<td>190</td>
<td>195</td>
<td>33</td>
<td>38</td>
<td>21</td>
<td>41</td>
<td>45</td>
</tr>
</tbody>
</table>

Courtesy of staff from PET/CT HKU
## Summary on occupational exposure

**PET/CT HKU**

<table>
<thead>
<tr>
<th></th>
<th>Average monthly occupational exposure (μSv)</th>
<th>Projected annual occupational exposure (μSv)</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doctor</td>
<td>0</td>
<td>0</td>
<td>Doctors not involved in dose injection and scanning.</td>
</tr>
<tr>
<td>Nurse</td>
<td>34</td>
<td>408</td>
<td>1 out of 5 nurses on rotation basis</td>
</tr>
<tr>
<td>Radiographer</td>
<td>150</td>
<td>1800</td>
<td>3 radiographers worked on full time basis</td>
</tr>
</tbody>
</table>

21/09/2007

**Courtesy of staff from PET/CT HKU**
# Summary on occupational exposure

## PET/CT HKU

<table>
<thead>
<tr>
<th></th>
<th>Projected annual occupational exposure (μSv)</th>
<th>Radiation risk to the staff</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nurse</td>
<td>408</td>
<td>$2.3 \times 10^{-5}$</td>
<td>1 out of 5 nurses on rotation basis</td>
</tr>
<tr>
<td>Radiographer</td>
<td>1800</td>
<td>$1.0 \times 10^{-4}$</td>
<td>3 radiographers worked on full time basis</td>
</tr>
</tbody>
</table>

Reference in ICRP 1991: Total risk of cancer and hereditary effects for work force = 5.6% Sv\(^{-1}\)
## Typical risks from well known activities

<table>
<thead>
<tr>
<th>Activity</th>
<th>Risk of death per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travelling 300 miles by car</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>Work accidents</td>
<td>$2 \times 10^{-5}$</td>
</tr>
<tr>
<td>Home accidents</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>Smoking 10 cigarettes a day</td>
<td>$1.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>Coal mining</td>
<td>$1.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>Deep sea fishing</td>
<td>$2 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Reference from Dendy, p297 Physics for Diagnostic Radiology

21/09/2007
Thank you.