The Public Health Impact of Radon Exposure: Sources, Prevalence, and Mitigation

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Outline

• NORM
• Radiation Health Effects
• Radon Prevalence and Impact
• Radon Migration
• Radon Testing and Mitigation
• Highlighted Studies
Radiation Basics

• Spontaneous decay of a nucleus
• Three main types of natural radiation emitted
  – Alpha particles – Helium nucleus, positively charged
    • Significant momentum, no penetrating power
  – Beta particles – electron or position
    • Mostly negatively charged in NORM
  – Photons – gamma or x-rays
    • No mass or charge, electromagnetic radiation
NORM

• Nearly all terrestrial radionuclides are from:
  – Thorium series
  – Uranium series
  – Potassium-40

• Series parent radionuclides are primordial
  – Essentially stable in the environment
  – Likely formed via the r-process in neutron stars

• Uranium series more relevant to human health
  – Physiochemical properties and half-lives lead to more exposure
• Uranium Series
  • Abundant in rock and soil
  • Mixture of long and short half-lives
    • Leads to complex relationships
  • Ra is especially soluble
    • Ra-226 is usually most concerning in water
  • Rn is a noble gas, low adsorption, non-reactive
NORM

• Thorium Series
  • Th is more abundant than U
  • Ra especially soluble
    • Ra-228 usually most concerning in water
  • Half-lives are very different than U series
Properties of Radon

- Noble gas
- Decays via alpha emission
- Three natural isotopes
  - $^{222}\text{Rn}$ (often referred to as “Radon”), Progeny of $^{226}\text{Ra}$ in Uranium series
    - $t_{1/2} = 3.8$ days
  - $^{220}\text{Rn}$ (often referred to as “Thoron”), Progeny of $^{224}\text{Ra}$ in Thorium series
    - $t_{1/2} = 55.6$ sec
  - $^{219}\text{Rn}$ (often referred to as “Actinon”), Progeny of $^{223}\text{Ra}$ in the Actinium series
    - $t_{1/2} = 3.96$ sec
    - Not a major contributor to radon exposure
Radioactive Equilibrium

Secular Equilibrium, daughter $t_{1/2} \llll \text{parent } t_{1/2}$

Transient Equilibrium, daughter $t_{1/2} < \text{parent } t_{1/2}$
Radiation Effects

• Stochastic Effects
  – Based on probability
  – Generally no threshold for effect
  – Likelihood of effect increases with exposure
  – Severity dose-independent
  – Ex. Cancer

• Deterministic Effects
  – Threshold for effect
    • Threshold varies person to person
  – Severity of effect is dose dependent above threshold
  – Ex. Acute radiation poisoning
    • Hair loss, erythema, death
Radiation Health Impacts
Radiation Exposure Models

- **Linear No-Threshold (LNT) Model**
  - Extrapolates through origin
  - Based on high-level exposure

- **Hormesis**
  - Beneficial effect a low exposure
  - Evidence supporting this with radiation is very weak

Radiation Carcinogenesis

- Direct vs. Indirect Effects
  - Alpha/Beta - Direct kinetic or charged particle damage to DNA
  - Gamma - Generation of free radicals, •OH, O₂⁻
- Damage can cause cancerous mutations
  - Mis-repair of damage
  - Alterations to oncogenes, tumor-suppressor genes
  - Disruption of cell cycle checkpoints, apoptotic pathways
- Ex. TP53, p53

http://bioinformatics.org/p53/gif/intro2.gif
Radiation Exposure

Routes of Exposure to NORM

• Exposure from drinking water
  – Mostly uranium, radium, and their decay products
• Ground-shine from the environment
  – External exposure to gamma rays from NORM
• Cosmic radiation from space and the upper atmosphere
  – External exposure to gamma and neutrons
• Exposure in Air
  – From radon and thoron and their decay products
Disease Burden from Radon

• BEIR VI (1999)
  – Radon related deaths in US estimated based on uranium miner epidemiological studies
  – Two models used to estimate excess risk from radon
  – 15,400 or 21,800 death per year attributed to Radon exposure the the US
    • (3,000 to 33,000) 95% CI
Radon in Air Prevalence

EPA Map of Radon Zones

https://www.epa.gov/radon/epa-map-radon-zones
Radon in Water Prevalence

General Patterns of Radon Occurrence in Groundwater in the United States

Source: USEPA NIRS Survey, 1985
Note: State averaging of data may obscure local variations in radon levels.

Radon Action Levels

• Radon in Air
  – EPA set an action level of 4 pCi/L in air for indoor air
  – Not a risk based limit, but a practical one
  – 1:10,000 lifetime cancer risk limit is infeasible
  – Outdoor air averages 0.4 pCi/L

• Radon in Drinking Water
  – EPA proposed two limits
    • 4,000 pCi/L for states with radon air mitigation programs
    • 300 pCi/L for states without radon air mitigation programs
    • Based on 1:10,000 dilution factor in the average home
Radon Migration

- Radon moves via two main processes
  - Passive diffusion
    - Migration from high [Rn] to low [Rn]
  - Flow
    - Movement of gas from high pressure to low pressure
    - Primary movement of radon in environment

*Fig. 2. Mechanisms of exhalation of radon and thoron from soil (Wicke, 1979).*
Radon in Buildings

- Radon enters through crack/gaps in foundation
  - Sump pits of particular concern
- Radon can also enter dissolved in water
  - Most radon is liberated into air, small amounts remain in water
  - Concentrations are highly variable depending on geologic composition

http://www.lifetimeradon.com/Content/files/radonEntry.png
Stack Effect

- Warm air rises and exits structure
- Pressure is lowered in lower levels
- Negative pressure gradient created between foundation and surrounding soil
- Radon gas flows into structure
Structures at Risk

• Homes with basements
  – Older homes with compromised foundations
  – Homes with porous foundations
  – Poorly sealed structures, exacerbates stack effect

• Forced air systems in basements
  – Lowers basement pressure, increased stack effect
  – Circulates basement air throughout the home
Radon Testing

• Short-term testing (Several Days)
  – Inexpensive kits can be purchased and placed throughout the home
    • Kits are mailed away and tested
  – Real-time monitors are also used
    • Give graphical results, show variability over time
    • Must be operated by a technician
Radon Testing

• Long-term testing (months)
  – Longer term tests can look at seasonal variability
  – Help to evaluate and monitor efficacy of mitigation
  – More accurate than short term tests
Radon Testing

• Radon in Water
  – Collection without faucet aerator
  – Must be sealed with no headspace
  – Testing done by liquid scintillation
Radon Mitigation

• Cannot simply vent indoor air outside
• Radon mitigation lower pressure of surrounding soil
  – Provides a pathway for radon escape
  – Reduces pressure differential between soil and structure
• Passive vs Active

Radon Mitigation

• Radon in water can be removed
  – Usually via carbon filtration or aeration
  – Concentrations impacts method
• Aeration must be done outside the home prior to water entry or must be vented

https://www.wpb-radon.com/waterPhotos/shallowTray.jpg
Important Studies
Uranium Miners and Cancer

- Retrospective cohort study of Colorado uranium miners
- SMR standardized to similar white males in the region
- One of a number of studies to show strong evidence for radon causing lung cancer

An Update of Mortality from All Causes Among White Uranium Miners from the Colorado Plateau Study Group

Robert J. Roscoe, MS*

To place previously recognized mortality risks into the context of the total mortality from all causes, an updated retrospective cohort mortality study was conducted on 3,238 white males from the US Public Health Service cohort of Colorado Plateau uranium miners. Vital status was followed from 1960 through 1990. Life-table analyses used combined New Mexico, Arizona, Utah, and Colorado mortality rates for external comparison and mortality risks within the lowest radon-exposure or duration-employed category for internal comparison. Significantly elevated SMRs were found for pneumoconioses (SMR = 24.1, 95% CI 16.0–33.7), lung cancer (SMR = 5.8, 95% CI 5.2–6.4), tuberculosis (SMR = 3.7, 95% CI 1.9–6.2), chronic obstructive respiratory diseases (SMR = 2.8, 95% CI 2.2–3.5), emphysema (SMR = 2.5, 95% CI 1.9–3.2), benign and unspecified tumors (SMR = 2.4, 95% CI 1.0–4.6), and diseases of the blood and blood-forming organs (SMR = 2.4, 95% CI 1.0–5.0). No significantly lowered SMRs were found for any disease. For lung cancer and pneumoconioses, standardized rate ratios increased with increasing exposure to radon progeny or duration of employment. Most findings from this update are consistent with previous studies. Not observed were previously elevated SMRs for chronic nephritis and for acute alcoholism. New findings observed were elevated SMRs for benign and unspecified tumors and for diseases of the blood and blood-forming organs. The most important long-term mortality risks for the white uranium-miners continue to be lung cancer and pneumoconioses, for which SMRs remain significantly elevated after a mean period of 22.4 years since last uranium mining. Am. J. Ind. Med. 31:211–222, 1997. © 1997 Wiley-Liss, Inc.
# Uranium Miners and Cancer

## Exposure to radon progeny from uranium mining

<table>
<thead>
<tr>
<th>Disease</th>
<th>&lt;120 WLM</th>
<th>120–399 WLM</th>
<th>400–1000 WLM</th>
<th>&gt;1000 WLM</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lung cancer (5-yr lag)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>p = 0.002</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Obs/exp</td>
<td>25/14.5</td>
<td>54/16.8</td>
<td>107/16.8</td>
<td>184/15.7</td>
<td>370/63.8</td>
</tr>
<tr>
<td>SMR</td>
<td>1.7</td>
<td>3.3</td>
<td>6.4</td>
<td>11.7</td>
<td>5.8</td>
</tr>
<tr>
<td>95% CI</td>
<td>1.1–2.5</td>
<td>2.4–4.2</td>
<td>5.2–7.7</td>
<td>10.1–13.5</td>
<td>5.2–6.4</td>
</tr>
<tr>
<td>SRR</td>
<td>1.0</td>
<td>1.9</td>
<td>3.6</td>
<td>7.2</td>
<td>4.0</td>
</tr>
<tr>
<td>95% CI</td>
<td>—</td>
<td>1.2–3.0</td>
<td>2.3–5.6</td>
<td>4.7–11.0</td>
<td>2.6–6.0</td>
</tr>
<tr>
<td>All cancer except lung (5-yr lag)</td>
<td>37/31.1</td>
<td>40/35.0</td>
<td>48/35.0</td>
<td>45/33.3</td>
<td>170/134.4</td>
</tr>
<tr>
<td><strong>p = 0.506</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Obs/exp</td>
<td>1.2</td>
<td>1.1</td>
<td>1.4</td>
<td>1.4</td>
<td>1.3</td>
</tr>
<tr>
<td>SMR</td>
<td>0.8–1.6</td>
<td>0.8–1.6</td>
<td>1.0–1.8</td>
<td>1.0–1.8</td>
<td>1.1–1.5</td>
</tr>
<tr>
<td>SRR</td>
<td>1.0</td>
<td>0.9</td>
<td>1.1</td>
<td>1.1</td>
<td>1.0</td>
</tr>
<tr>
<td>95% CI</td>
<td>0.6–1.4</td>
<td>0.7–1.8</td>
<td>0.7–1.7</td>
<td>0.7–1.5</td>
<td></td>
</tr>
</tbody>
</table>

- **Obs/exp** = Observed over expected deaths.
- **SMR** = Standardized mortality ratio, **SRR** = Standardized rate ratio, **95% CI** = 95% confidence interval.
- **p** value for test for trend in SRRs over exposure categories.
- 1 observed and 0.6 expected lung cancer deaths in unexposed 5-year lag category.
- 1 observed and 0.6 expected lung cancer deaths in unexposed 5-year lag category.
- The unexposed (5-year lag) category contained 3,583 PYAR, 25 observed and 17.2 expected deaths.
Iowa Radon Lung Cancer Study

- Case-control study
- Reconstructed dose
  - Included home, work, other areas
- Validated exposure assessments with field measurements
- Kriged outdoor radon concentrations
Iowa Radon Lung Cancer Study

**TABLE 4. Estimated odds ratios* for lung cancer and tests of a linear trend for WLM_{5-19}† cumulative radon exposure, IRLCS†, Iowa, 1993–1997**

<table>
<thead>
<tr>
<th>WLM_{5-19} cumulative radon exposure‡</th>
<th>Median</th>
<th>OR†</th>
<th>95% CI†</th>
<th>Cases/controls</th>
<th>OR</th>
<th>95% CI</th>
<th>Cases/controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–4.23</td>
<td>3.16</td>
<td>1.00</td>
<td></td>
<td>56/104</td>
<td>1.00</td>
<td></td>
<td>37/104</td>
</tr>
<tr>
<td>4.24–8.47</td>
<td>6.18</td>
<td>1.34</td>
<td>0.81, 2.22</td>
<td>147/229</td>
<td>1.31</td>
<td>0.75, 2.31</td>
<td>98/229</td>
</tr>
<tr>
<td>8.48–12.70</td>
<td>10.50</td>
<td>1.73</td>
<td>0.99, 3.04</td>
<td>87/118</td>
<td>1.79</td>
<td>0.97, 3.33</td>
<td>61/118</td>
</tr>
<tr>
<td>12.71–16.94</td>
<td>14.58</td>
<td>1.62</td>
<td>0.88, 2.99</td>
<td>56/75</td>
<td>1.74</td>
<td>0.88, 3.43</td>
<td>39/75</td>
</tr>
<tr>
<td>&gt;16.95</td>
<td>21.16</td>
<td>1.79</td>
<td>0.99, 3.26</td>
<td>67/88</td>
<td>2.14</td>
<td>1.12, 4.15</td>
<td>48/88</td>
</tr>
</tbody>
</table>

* Estimates are adjusted for age, active smoking, and education.
† WLM_{5-19}, working-level months for exposures that occurred 5–19 years prior to diagnosis for cases or time of interview for controls (1 working-level month is equivalent to $3.5 \times 10^{-5}$ Jh/m²); IRLCS, Iowa Radon Lung Cancer Study; OR, odds ratio; CI, confidence interval.
‡ The temporally and spatially weighted median WLM cumulative exposure over 5–19 years was 7.9 WLM and 8.6 WLM for all controls and cases, respectively.

- Odds ratios approaching significance
- p-trend statistically significant
The Story of Stanley Watras

• 1984
• Nuclear power plant worker in PA
• Set off radiation monitors at his the plant
  – No obvious source of contamination
• Investigations found radon concentrations of 2,700 pCi/L in his home
• Without testing, his family would never have known

Can You Answer the Public’s Questions About Radon?

• Does your state have a radon control program?
• Do you know where to refer the public if they call with questions about radon?
• Do you know if your state has a radon problem?
• Does your state have problems with radon in water?
Thank you

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Mission: The State Hygienic Laboratory at the University of Iowa protects and improves quality of life by providing reliable environmental and public health information through the collective knowledge and capabilities of our organization.