R. William Field, PhD, MS
College of Public Health
Department of Occupational and Environmental Health
Department of Epidemiology
University of Iowa

Residential Radon Epidemiology

Example - Case-Control Epidemiologic Study

"Statistics are people with the tears wiped away."

Irving Selikoff
## Cancer Statistics, 2012

**Estimated New Cases**

<table>
<thead>
<tr>
<th>Cancer Type</th>
<th>Males</th>
<th>Females</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prostate</td>
<td>241,740</td>
<td></td>
</tr>
<tr>
<td>Lung &amp; Bronchus</td>
<td>115,470</td>
<td></td>
</tr>
<tr>
<td>Colorectal</td>
<td>75,620</td>
<td></td>
</tr>
<tr>
<td>Urinary Bladder</td>
<td>55,830</td>
<td></td>
</tr>
<tr>
<td>Melanoma of the Skin</td>
<td>44,290</td>
<td></td>
</tr>
<tr>
<td>Kidney &amp; Renal Pelvis</td>
<td>40,290</td>
<td></td>
</tr>
<tr>
<td>Non-Hodgkin Lymphoma</td>
<td>38,160</td>
<td></td>
</tr>
<tr>
<td>Oral Cavity &amp; Pharynx</td>
<td>26,540</td>
<td></td>
</tr>
<tr>
<td>Leukemia</td>
<td>26,830</td>
<td></td>
</tr>
<tr>
<td>Pancreas</td>
<td>22,090</td>
<td></td>
</tr>
<tr>
<td>All Sites</td>
<td>848,170</td>
<td></td>
</tr>
</tbody>
</table>

**Estimated Deaths**

<table>
<thead>
<tr>
<th>Cancer Type</th>
<th>Males</th>
<th>Females</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lung &amp; Bronchus</td>
<td>87,750</td>
<td></td>
</tr>
<tr>
<td>Prostate</td>
<td>28,170</td>
<td></td>
</tr>
<tr>
<td>Colorectal</td>
<td>26,470</td>
<td></td>
</tr>
<tr>
<td>Pancreas</td>
<td>18,850</td>
<td></td>
</tr>
<tr>
<td>Liver &amp; Intrahepatic Bile Duct</td>
<td>13,960</td>
<td></td>
</tr>
<tr>
<td>Leukemia</td>
<td>13,850</td>
<td></td>
</tr>
<tr>
<td>Esophagus</td>
<td>12,040</td>
<td></td>
</tr>
<tr>
<td>Uterine Corpus</td>
<td>10,570</td>
<td></td>
</tr>
<tr>
<td>Non-Hodgkin Lymphoma</td>
<td>10,320</td>
<td></td>
</tr>
<tr>
<td>Kidney &amp; Renal Pelvis</td>
<td>8,630</td>
<td></td>
</tr>
<tr>
<td>All Sites</td>
<td>391,820</td>
<td></td>
</tr>
</tbody>
</table>

Trends in Death Rates Among **Males** for Selected Cancers, United States, 1930 to 2008. Rates are age adjusted to the 2000 US standard population.

---

Radon Resistant New Construction (RRNC) Workshop

Residential Studies


Radon Resistant New Construction (RRNC) Workshop
Residential Studies

RISK PERCEPTION: Why is the evidence ignored or not accepted??

- Invisible, odorless, colorless
- Naturally occurring outdoors
- Can not link an individual death to radon exposure
- Long latency period
- Not a dread hazard
- Cancers occur one at a time
- Lung cancer does not occur in children
- Voluntary risk
- Lack of press – no sensational story
- No sensory reminders to repetitively stimulate us to think about it
Scientific Evidence
Cause and Effect

- Biological credibility (plausibility)
- Validity of study design
- Consistency across investigations
- Evidence of dose-response relationship
**U.S. Radon Potential**

- Based on geology and surveys
- Expected closed building radon (pCi/L):
  - Zone 1: 4.0 and above
  - Zone 2: between 2.0 & 4.0
  - Zone 3: 2.0 and lower

---

**Tobacco Use and Cancer**

Some Cancer-Causing Chemicals in Tobacco Smoke

- aminostilbene
- arsenic
- benz[a]anthracene
- benz[a]pyrene
- benzene
- benzo[b]fluoranthene
- benzo[c]phenanthrene
- benzo[g,h,i]perylene
- cadmium
- chrysene
- dibenz[a]anthracene
- dibenzo[a,e]fluoranthene
- dibenz[a]h[acridine
- dibenz[a]i[acridine
- dibenz[c,e]carbazole
- N-dibutyl-nitrosamine
- 2,3-dimethylchrysenes
- indeno[1,2,3-c,d]pyrene
- S-methylchrysene
- S-methylfluoranthene
- alpha-naphthylamine
- nickel compounds
- N-nitrosodimethylamine
- N-nitrosomethylamine
- N-nitrosodiethylamine
- N-nitrosonornicotine
- N-nitrosoanabasine
- N-nitrosopiperidine
- polonium-210

---

Radon Resistant New Construction (RRNC) Workshop
Residential Studies
Nature. 1974 May
17:249(454): 215-7
Radioactivity of tobacco
trichomes and insoluble
cigarette smoke particles.
Martell EA
# CANCER MORTALITY - 2012

<table>
<thead>
<tr>
<th>CANCER TYPE</th>
<th>ESTIMATED U.S. DEATHS/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Lung and Bronchus</td>
<td>160,340</td>
</tr>
<tr>
<td>2. Colon and Rectum</td>
<td>51,690</td>
</tr>
<tr>
<td>3. Breast Cancer</td>
<td>39,920</td>
</tr>
<tr>
<td>4. Pancreas</td>
<td>37,390</td>
</tr>
<tr>
<td>5. Prostate</td>
<td>28,170</td>
</tr>
<tr>
<td>6. Leukemia</td>
<td>23,540</td>
</tr>
<tr>
<td>7. Liver and Bile Duct</td>
<td>20,550</td>
</tr>
<tr>
<td>8. Non-Hodgkin Lymphoma</td>
<td>18,940</td>
</tr>
<tr>
<td>9. Ovary</td>
<td>15,500</td>
</tr>
<tr>
<td>10. Esophagus</td>
<td>15,070</td>
</tr>
<tr>
<td>11. Urinary Bladder</td>
<td>14,880</td>
</tr>
<tr>
<td>12. Kidney and Renal Pelvis</td>
<td>13,570</td>
</tr>
<tr>
<td>13. Myeloma</td>
<td>10,710</td>
</tr>
<tr>
<td>14. Stomach</td>
<td>10,540</td>
</tr>
<tr>
<td>15. Melanoma</td>
<td>9,180</td>
</tr>
</tbody>
</table>

## Radon Epidemiology

- 1556 Agricola - Miners in Europe
- 1879 Harting & Hesse - Lung Cancer in Miners
- 1921 Uhlig - Radium Emanations & Lung Cancer
- 1950s Peller - First Review of Mining Related Cancers
- 1970s Studies of Underground Miners (ongoing)
- 1990s Residential Radon Studies
- 1994 NCI Pooled Analyses of Miners
- 1999 NAS BEIR VI Report
- 2005 North American and European Pooled Residential Radon Studies
- 2007 Global Pooling of Residential Radon Studies
- 2007 Pooling of Glass-based Residential Radon Studies

*Radon Resistant New Construction (RRNC) Workshop*

*Residential Studies*
Radon Resistant New Construction (RRNC) Workshop

Residential Studies

National Academy of Sciences
BEIR VI  1999

- Risk estimates based primarily on radon-exposed miners

- Estimated 18,600 lung cancer deaths each year in the U.S. from residential radon exposure

In 2003, the EPA updated the BEIR VI risk estimates to 21,000 radon-related lung cancer deaths each year in the United States.

http://www.epa.gov/radon/risk_assessment.html

Based on its analysis, EPA estimates that out of a total of 146,400 lung cancer deaths nationally in 1995, 21,100 (14.4%) were radon related. Although it is not feasible to totally eliminate radon from the air, it is estimated that about one-third of the radon-related lung cancers could be averted by reducing radon concentrations in homes that exceed EPA’s recommended 4 picocurie per liter (pCi/L) action level (NAS 1999).
CANCER MORTALITY - 2012

<table>
<thead>
<tr>
<th>CANCER TYPE</th>
<th>ESTIMATED U.S. DEATHS/yr</th>
</tr>
</thead>
<tbody>
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<tr>
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<td>23,540</td>
</tr>
<tr>
<td>7. Liver and Bile Duct</td>
<td>21,000</td>
</tr>
<tr>
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<tr>
<td>14. Stomach</td>
<td>10,540</td>
</tr>
</tbody>
</table>

Published Online: 27 May 2009
Copyright © 2009 American Cancer Society
CA: A Cancer Journal for Clinicians
Volume 62, Issue 1, pages 10-29, 4 JAN 2012 DOI: 10.3322/caac.20138

Epidemiology Study Designs

- Ecological
  - Compares level of disease & exposure in groups
  - Cannot correlate exposure to sick individuals
  - Cannot control for confounders

- Cohort
  - Identify populations based on exposure
  - Follow for disease occurrence

- Case-Control
  - Identify Individuals with disease & individuals without disease
  - Look at and compare exposures

Radon Resistant New Construction (RRNC) Workshop
Residential Studies
Residential Radon Case-Control Around the World

European Pooling

13 Studies from 9 Countries
- Austria
- Czech Republic
- Finland [nationwide]
- Finland [south]
- France
- Germany [eastern]
- Germany [western]
- Italy
- Spain
- Sweden [nationwide]
- Sweden [never smokers]
- Sweden [Stockholm]
- United Kingdom

Total 7,148 cases and 14,208 controls

North American Pooling

7 Studies from 2 countries:
- New Jersey
- Winnipeg
- Missouri I [non-smoking women]
- Missouri II [women]
- Iowa
- Connecticut
- Utah-South Idaho

Total 3,622 cases and 4,966 controls

Basement and Living Area Radon Concentrations for U.S. Residential Radon Studies.

<table>
<thead>
<tr>
<th>Study Location</th>
<th>Geometric Mean in pCi/L</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Basement</td>
<td>Level 1</td>
<td>Level 2</td>
</tr>
<tr>
<td>New Jersey</td>
<td></td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>Missouri-I</td>
<td>2.4</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Missouri-II</td>
<td>2.4</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Iowa</td>
<td>4.6</td>
<td>2.5</td>
<td>2.0</td>
</tr>
<tr>
<td>Connecticut, Utah</td>
<td>1.5</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Southern Idaho²</td>
<td>1.8</td>
<td>1.2</td>
<td>1.0</td>
</tr>
</tbody>
</table>

1 Summary data represent those homes that were measured with no imputed (values added to replace missing values) values.
THE IOWA RADON LUNG CANCER STUDY (IRLCS)

Overview and Example

RADON EXPOSURE ASSESSMENT CHALLENGES

- Quality Assurance/Quality Control
- Temporal and Spatial Radon Variation
- Missing Data Due to Inability to Measure Previous Homes
- Estimating Non-Residential Radon Exposure
- Measuring Radon Gas a Surrogate for Radon Progeny

Radon Resistant New Construction (RRNC) Workshop
Residential Studies
Residential Radon Gas Exposure and Lung Cancer: The Iowa Radon Lung Cancer Study (IRLCS)


American Journal of Epidemiology,

Differences Between the Other Case-Control Studies and the Iowa Study

- Performed in areas with low or average radon concentrations
- Had 30% - 60% percent missing radon data for previous 20 years which required imputation
- Did not account for where subjects spent time
- Did not link radon concentrations (within the home and outside the home) with where the subject spent time
- Measurements were limited to radon gas only
- Poor dosimetry quality control

STUDY DESIGN

- Population-based case-control study
- Geographic area: state of Iowa
- 413 female cases/614 female controls
- Study period: 10/92 to 10/97
IRLCS sites

MAJOR COMPONENTS

Rapid-reporting of cases: 93%
Median time diagnosis to ascertainment: 20 days
- Detailed questionnaires:
  health, diet, home characteristics, mobility
- 1 Year home radon measurements
- Histopathologic review of lung tissue:
  96% of cases

Journal of Exposure Analysis and Environmental Epidemiology, Field et al. 1996
Case Eligibility/Ascertainment

Female Iowa resident
No prior malignant lung cancer
Ages 40 - 84
Alive or deceased at initial contact
Newly diagnosed invasive lung cancer
without prior invasive lung cancer;
histologically-confirmed
Reside in current home ≥ 20 years
No history of residential radon mitigation

Geographic Coverage

Original SEER
Registries

SEER Registries
Added in 1992

SEER Registries
Added in 2000

Radon Resistant New Construction (RRNC) Workshop
Residential Studies
Control Eligibility/Ascertainment

- Female Iowa resident
- No prior malignant lung cancer
- Ages 40 - 84
- Alive at initial contact
- Reside in current home ≥ 20 years
- No history of residential radon mitigation

IRLCS Inclusion Criteria

20-year residency criteria in current home avoids imputation of data

Previous studies imputed 20% - 58% of data because of the inability to measure radon in previous homes
**Histopathologic Review**

- Blinded review by two surgical pathologists
- Consensus diagnosis based on World Health Organization 1981 (WHO) histologic type
- 72% agreement between Iowa Cancer Registry and consensus histologic type

The relative odds of misclassification for samples collected using cytology and biopsy as compared to resection was 2.4 (CI; 1.1-5.2) and 2.2 (CI; 1.1-4.2), respectively. JNCI 2004.

**Morphologic Distribution of 413 Lung Cancers**

<table>
<thead>
<tr>
<th>Morphology</th>
<th>Number</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adenocarcinoma</td>
<td>175</td>
<td>42.4</td>
</tr>
<tr>
<td>Squamous Cell</td>
<td>82</td>
<td>19.9</td>
</tr>
<tr>
<td>Small Cell</td>
<td>74</td>
<td>17.9</td>
</tr>
<tr>
<td>Large Cell</td>
<td>32</td>
<td>7.7</td>
</tr>
<tr>
<td>Carcinoma, NOS</td>
<td>50</td>
<td>12.1</td>
</tr>
</tbody>
</table>
CONTROL SELECTION

Age 40-64: from Driver’s License Tapes

Age 65-84: from HCFA Records

STUDY DEMOGRAPHICS

<table>
<thead>
<tr>
<th></th>
<th>Cases</th>
<th>Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>413</td>
<td>614</td>
</tr>
<tr>
<td>Age in yrs. (median)</td>
<td>68</td>
<td>67</td>
</tr>
<tr>
<td>Residency in yrs. (median)</td>
<td>33</td>
<td>31</td>
</tr>
<tr>
<td>Alive at interview</td>
<td>69%</td>
<td>100%</td>
</tr>
<tr>
<td>Ever-smokers</td>
<td>86%</td>
<td>33%</td>
</tr>
<tr>
<td>Previous lung disease</td>
<td>44%</td>
<td>27%</td>
</tr>
<tr>
<td>At least H.S. Education</td>
<td>90%</td>
<td>92%</td>
</tr>
</tbody>
</table>
### HOUSING CHARACTERISTICS

<table>
<thead>
<tr>
<th></th>
<th>Cases</th>
<th>Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age of Home</td>
<td>62 yrs</td>
<td>56 yrs</td>
</tr>
<tr>
<td>Square Footage</td>
<td>1,879</td>
<td>1,990</td>
</tr>
<tr>
<td>Central AC</td>
<td>60.7%</td>
<td>64.7%</td>
</tr>
<tr>
<td>Window AC only</td>
<td>32.8%</td>
<td>29.9%</td>
</tr>
<tr>
<td>Forced air (1 Story)</td>
<td>91.8%</td>
<td>90.4%</td>
</tr>
<tr>
<td>Forced air (2 Story)</td>
<td>82.8%</td>
<td>80.4%</td>
</tr>
</tbody>
</table>

### LEVELS OF HOME

<table>
<thead>
<tr>
<th></th>
<th>Cases</th>
<th>Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 story home</td>
<td>49.4%</td>
<td>51.5%</td>
</tr>
<tr>
<td>2 story home</td>
<td>48.0%</td>
<td>44.1%</td>
</tr>
<tr>
<td>3 story home</td>
<td>2.6%</td>
<td>4.1%</td>
</tr>
<tr>
<td>4 story home</td>
<td>0%</td>
<td>0.3%</td>
</tr>
</tbody>
</table>
COMPREHENSIVE $^{222}\text{Rn}$ EXPOSURE ASSESSMENT

Home: Temporally and spatially weighted radon exposure

Outside: Temporally weighted outdoor radon exposure derived from kriged data from outdoor radon monitoring network

Building: Temporally weighted estimated value representing 50% of kriged 1st floor radon concentration
HOME $^{222}$Rn EXPOSURE

REQUIRES KNOWLEDGE OF:

- Time spent at home
  (Cases 73.2% Controls 72.1%)
- Subject mobility while at home
- Radon concentrations in various parts of the home

HOME RADON EXPOSURE

SUBJECT MOBILITY INTERVIEW
Obtains mobility patterns within/outside the home using seasonally adjusted task linkage

- Identifies temporal periods when mobility remains fairly constant
- Permits linkage of mobility information to radon measurements
SUBJECT MOBILITY INFORMATION

- **Hours in-home**: Bedroom, home work area, basement, upper level, kitchen/dining room
- **Hours in another building**: Type of activities (work, church, recreation), seasonal variation
- **Hours outdoors**: Type of activities (gardening, walking, work), seasonal variation

SPATIAL HOME MOBILITY

**One Story Homes** (N=494)
- Basement: 6.4%
- 1st Story: 93.6%

**Two Story Homes** (N=437)
- Basement: 3.2%
- 2nd Story: 21.8%
- 1st Story: 75.0%

PERCENT OF TIME IN HOME BY AGE


Radon Measurement

Continuous Radon Monitors
- Labor intensive
- Time consuming
- Expensive

Short-Term Radon Monitoring
- Fast
- Cheap
- Do not allow for estimates of yearly radon variation
RADON GAS DETECTORS

Alpha track detectors (ATDs)

-- yearly integrated mean radon measurement

-- up to 7 ATDs per home

-- second year measurements

Alpha Track Detectors (ATDs)
PLACEMENT OF ATDs

- Bedroom (and historic bedroom)
- 1 ATD per level of home with placement weighted by participant occupancy time
- 1 ATD in home work area
Quality Assurance/Quality Control

- Spiked Samples (5%)
- Field Duplicates (12%)
- Field Control Detectors (5%)
- Strictly Adhered to Written QA Plan
- Oversight by QA Officer


Radon Measurement Devices (ATDs) Installed

- Total ATDs placed: 4,626
- Mean number/home: 4.0
- Percent retrieved: 97.2%

- Duplicates placed: 515
- Percent duplicates: 12.5%
- Mean COV (S.D.): 6.9%(7.2)
Collocated Radon Gas Measurements

Detector Accuracy and Precision
“Spiked Detectors”

<table>
<thead>
<tr>
<th>Exposure Equivalent</th>
<th>MARE</th>
<th>COV</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 pCi/L</td>
<td>12.8 %</td>
<td>8.3 %</td>
</tr>
<tr>
<td>4 pCi/L</td>
<td>11.4 %</td>
<td>7.5 %</td>
</tr>
<tr>
<td>6 pCi/L</td>
<td>8.6 %</td>
<td>5.7 %</td>
</tr>
</tbody>
</table>

COMPREHENSIVE RADON EXPOSURE

Home Exposure

Outdoor Exposure

Other Building Exposure

Outdoor $^{222}$Rn Concentrations

Radon Resistant New Construction (RRNC) Workshop

Residential Studies
OUTDOOR $^{222}$Rn EXPOSURE

REQUIRES KNOWLEDGE OF:

- Time spent outdoors  
  (Cases 7.6% Controls 8.5%)
- Radon concentrations outdoors

OUTDOOR RADON MEASUREMENTS

111 Outdoor $^{222}$Rn gas and $^{222}$Rn progeny measurements have been made in over 70 Iowa counties during 1995, 1996 and 1997.

Geometric mean (GSD) = 0.8 pCi/L (1.4)

Outdoor Radon in Iowa

Radon Resistant New Construction (RRNC) Workshop
Residential Studies
OUTDOOR $^{222}\text{Rn}$ EXPOSURE

- The mean outdoor kriged radon concentration within 1 mile of the home is weighted at 50%.

- The mean outdoor kriged radon concentration from 1 to 20 miles away from the home is weighted at 50% with decreasing weight as you progress from 1 to 20 miles away.
COMPREHENSIVE RADON EXPOSURE

- Home Exposure
- Outdoor Exposure
- Other Building Exposure

OTHER BUILDING $^{222}$Rn EXPOSURE

Time spent in other building
(Cases 14.2% Controls 14.4 %)
Linked to
50% of kriged radon value for the
1st floor measurements (from
control homes) weighted for
surrounding 20 miles

Radon Resistant New Construction (RRNC) Workshop
Residential Studies
FIRST STORY $^{222}$Rn CONCENTRATIONS

$^{222}$Rn Exposure Occurring Away on Vacation or Business

Case 5.0%, Control 4.9%

The average of the national mean indoor $^{222}$Rn concentration (1.5 pCi/L) and national mean outdoor $^{222}$Rn concentration (0.4 pCi/L).
Exposure Model Combining Radon Levels and Subject Mobility

Working level month cumulative exposure model:

\[ \text{WLM}_{5-19} \propto \sum \text{time}_i \times \text{radon}_i \]

where the sum is over the years 5-19 prior to enrollment and includes the following locations:

Home (individual floors, bedrooms, work area), Outside, Another Building, Away on Vacation/Business

**IMPUTED VALUES**

<table>
<thead>
<tr>
<th>Time Period</th>
<th>% Population</th>
<th>% Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imputed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 - 20 Years</td>
<td>100 %</td>
<td>0 %</td>
</tr>
<tr>
<td>0 - 30 Years</td>
<td>58 %</td>
<td>0 %</td>
</tr>
<tr>
<td></td>
<td>42 %</td>
<td>18 %</td>
</tr>
</tbody>
</table>
LOGISTIC REGRESSION RISK MODEL

VARIABLES INCLUDED IN MODEL
- Age (Dx or enrollment)
- Education (yrs. attained)
- Active smoking
  -- Pack-year rate
  -- Year since quit smoking or never smoker
- Radon (continuous and categorical)

OTHER VARIABLES CONSIDERED
- Pre-existing lung disease
- Number of children
- Urban/rural status
- Asbestos exposure
- Family history of cancer

Design of a Case-Control Study

Exposed | Not Exposed | Exposed | Not Exposed
---------|------------|---------|------------
Disease  |            | No Disease |  
Lung Cancer Cases | Controls
Odds Ratio

\[
\frac{a}{c} = \frac{ad}{bc}
\]

Case Control

<table>
<thead>
<tr>
<th>Type of Smoker</th>
<th>E+</th>
<th>E-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Never</td>
<td>a</td>
<td>c</td>
</tr>
<tr>
<td>Light</td>
<td>b</td>
<td>d</td>
</tr>
<tr>
<td>Heavy</td>
<td>8.1</td>
<td>29.0</td>
</tr>
<tr>
<td>95% CI</td>
<td>--</td>
<td>5.6-11.7</td>
</tr>
<tr>
<td></td>
<td>19.1-43.9</td>
<td></td>
</tr>
</tbody>
</table>

Light and heavy smokers were divided by the median pack-year rate. Odds ratios adjusted for age, education, and cumulative radon exposure.

Radon Resistant New Construction (RRNC) Workshop
Residential Studies
Distribution of Cases and Controls by Exposure Category

<table>
<thead>
<tr>
<th>Cumulative Radon Exposure</th>
<th>0-4.23</th>
<th>4.24-8.47</th>
<th>8.48-12.70</th>
<th>12.71-16.94</th>
<th>16.95+</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cases</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Live)</td>
<td>56</td>
<td>147</td>
<td>87</td>
<td>56</td>
<td>67</td>
<td>413</td>
</tr>
<tr>
<td><strong>Controls</strong></td>
<td>104</td>
<td>229</td>
<td>118</td>
<td>75</td>
<td>88</td>
<td>614</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>160</td>
<td>376</td>
<td>205</td>
<td>131</td>
<td>155</td>
<td>1027</td>
</tr>
</tbody>
</table>

Radon-Lung Cancer Association

<table>
<thead>
<tr>
<th>WLM_{5-19} Cumulative Radon Exposure</th>
<th>0-4.23</th>
<th>4.24-8.47</th>
<th>8.48-12.70</th>
<th>12.71-16.94</th>
<th>16.95+</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cases</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All:</td>
<td>1.00</td>
<td>1.34</td>
<td>1.73</td>
<td>1.62</td>
<td>1.79</td>
</tr>
<tr>
<td>OR</td>
<td></td>
<td>1.34</td>
<td>1.73</td>
<td>1.62</td>
<td>1.79</td>
</tr>
<tr>
<td>95% CI</td>
<td>0.81-2.22</td>
<td>0.99-3.04</td>
<td>0.88-2.99</td>
<td>0.99-3.26</td>
<td></td>
</tr>
<tr>
<td>Live:</td>
<td>1.00</td>
<td>1.31</td>
<td>1.79</td>
<td>1.74</td>
<td>2.14</td>
</tr>
<tr>
<td>OR</td>
<td></td>
<td>1.31</td>
<td>1.79</td>
<td>1.74</td>
<td>2.14</td>
</tr>
<tr>
<td>95% CI</td>
<td>0.75-2.31</td>
<td>0.97-3.33</td>
<td>0.88-3.43</td>
<td>1.12-4.15</td>
<td></td>
</tr>
</tbody>
</table>

*Estimates are adjusted for age, active smoking and education.*
The estimated excess risk was approximately 50% higher (0.24 – 0.80) for an exposure to 4 pCi/L for 15 years.

### Odds Ratios by Histologic Cancer Type

<table>
<thead>
<tr>
<th>Cases (n)</th>
<th>Squamous (82)</th>
<th>Small Cell (74)</th>
<th>Adeno CA (175)</th>
<th>Large Cell (32)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>2.06</td>
<td>1.16</td>
<td>1.21</td>
<td>1.13</td>
</tr>
<tr>
<td></td>
<td>2.20</td>
<td>1.83</td>
<td>1.57</td>
<td>1.87</td>
</tr>
<tr>
<td></td>
<td>2.40</td>
<td>1.36</td>
<td>1.86</td>
<td>1.99</td>
</tr>
<tr>
<td></td>
<td>3.17</td>
<td>1.44</td>
<td>1.35</td>
<td>3.42</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.79-5.90</td>
<td>0.79-4.95</td>
<td>0.67-2.24</td>
<td>0.33-4.51</td>
</tr>
<tr>
<td></td>
<td>0.81-6.75</td>
<td>0.70-4.95</td>
<td>0.81-3.09</td>
<td>0.50-7.90</td>
</tr>
<tr>
<td></td>
<td>0.77-7.90</td>
<td>0.49-4.44</td>
<td>0.90-3.86</td>
<td>0.42-9.56</td>
</tr>
<tr>
<td></td>
<td>1.06-10.96</td>
<td>0.47-4.35</td>
<td>0.64-2.83</td>
<td>0.93-14.53</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.18</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.06</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.03</td>
<td></td>
</tr>
</tbody>
</table>

Estimates are adjusted for age, active smoking and education.
SUMMARY

- The Iowa Radon Lung Cancer Study found a statistically significant association between residential radon exposure and lung cancer.

- The findings suggest that prolonged exposure to radon, even at 4 pCi/L, increases lung cancer risk.

- These findings suggest that radon is a major environmental carcinogen.

Have Previous Residential Radon Studies Underestimated Risk?

*The evidence indicates that they have underestimated risk.*
Pooled Analyses Agreement ??

New Jersey, Missouri I, Canada, Iowa, Missouri II, a combined study from Connecticut, Utah and S. Idaho

Shenyang, China, Stockholm, Sweden, Swedish nationwide, Winnipeg, Canada, S. Finland, Finnish nationwide, SW England, W. Germany, Sweden, Czech Republic, Italy-Trento, Spain, Austria, France, China - Gansu Province, E. Germany

Why have the risks been under reported in residential radon studies?

Major Reasons for Poor Exposure Assessment
  ➢ Missing radon measurements in previous homes
  ➢ Failure to link radon concentrations with where people spent time
  ➢ Poor QA/QC
  ➢ Studies performed in low radon areas
  ➢ Inadequate consideration of temporal radon variations
  ➢ High percentage of proxy respondents
We have “demonstrated that empiric models with improved retrospective radon exposure estimates were more likely to detect an association between prolonged residential radon exposure and lung cancer.”

Therefore, estimated pooled risk estimates are likely low.


Risk estimates *decrease* when one fails to link radon concentrations with where the subject spends time.

Random misclassification of radon exposure tends to bias studies toward finding no association between radon concentrations and lung cancer.
Risk Estimates for Alternative Models

(all subjects)

Exposure Percentile Categories

Risk Estimates for Alternative Models

(live cases and controls)


Radon Resistant New Construction (RRNC) Workshop
Residential Studies
RESIDENTIAL RADON EPIDEMIOLOGY - Future Activities

- World pooling of residential radon studies
- Complete radon progeny-based study
- Occupational exposures
- Promote awareness of radon and RRNC
- Radon related gene studies
- Explore avenues to evaluate the possible association between radon exposure and other possible adverse health outcomes, e.g., leukemia
Radon Resistant New Construction (RRNC) Workshop

Residential Studies

Retrospective Radon Measurements

- $^{218}\text{Po}$ and $^{214}\text{Po}$ deliver the radiologically significant dose to the respiratory epithelium.

- Long residency in glass
- Decay easy to measure

HRD schematic

Radon Resistant New Construction (RRNC) Workshop

Residential Studies
HISTORIC RECONSTRUCTION DETECTOR (HRD)

- Glass-based radon progeny measurement
- Measures contemporary radon gas concentration
- Measures contemporary radon progeny deposition
- Measures retrospective deposition of radon progeny in glass surfaces via implanted Polonium-210.
- Reconstruction of airborne concentrations using a semi-empirical model

RESIDENTIAL RADON EPIDEMIOLOGY - Future Activities

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Occupational Exposure to Radon – Very Common

- Mine workers, including uranium, hard rock, and vanadium
- Workers remediating radioactive contaminated sites, including uranium mill sites and mill tailings
- Workers at underground nuclear waste repositories
- Radon mitigation contractors and testers
- Employees of natural caves
- Phosphate fertilizer plant workers
- Oil refinery workers
- Utility tunnel workers

- Subway tunnel workers
- Construction excavators
- Power plant workers, including geothermal power and coal
- Employees of radon health mines
- Employees of radon balneotherapy spas (waterborne radon source)
- Water plant operators (waterborne radon source)
- Fish hatchery attendants (waterborne radon source)
- Employees who come in contact with technologically enhanced sources of naturally occurring radioactive materials
- Incidental exposure in almost any occupation from local geologic radon sources
- Farming related activities
RESIDENTIAL RADON EPIDEMIOLOGY - Future Activities

- Complete radon progeny-based study
- World pooling of residential radon studies
- Occupational exposures
- Promote awareness of radon and RRNC
- **Radon related gene studies**
- Explore avenues to evaluate the possible association between radon exposure and other possible adverse health outcomes, e.g., leukemia

What Happens When Radon Decay Products Are Inhaled?

- Highly radioactive particles adhere to lung tissue, where they can irradiate sensitive cells.
- Radiation can alter the cells, increasing the potential for cancer.

*Double Strand Breaks*
Ionizing radiation can directly and indirectly damage DNA

Defects in tumor suppressor genes – p53

At risk individuals–GSTM$_1$
(glutathione S-transferase M1)

RESIDENTIAL RADON EPIDEMIOLOGY - Future Activities

- Complete radon progeny-based study
- World pooling of residential radon studies
- Occupational exposures
- Promote awareness of radon and RRNC
- Radon related gene studies
- Explore avenues to evaluate the association between radon exposure and other possible adverse health outcomes, e.g., leukemia
Residential radon epidemiology has made major advances the past 10 years.

The residential radon studies have provided direct evidence that prolonged residential radon is one of our leading public health risks and major cause of cancer mortality.

Radon is our leading environmental cause of cancer mortality and seventh leading cause of cancer mortality overall.
6. National radon programmes

**KEY MESSAGES**

- National radon programmes should aim to reduce the overall population risk and the individual risk for people living with high radon concentrations.
- To limit the risk to individuals, a national reference level of 100 Bq/m² is recommended. Wherever this is not possible, the chosen level should not exceed 300 Bq/m².
- To reduce the risk to the overall population, building codes should be implemented that require radon prevention measures in homes under construction. Radon measurements are needed because building codes alone cannot guarantee that radon concentrations will be below the reference level.
- Detailed national guidance on radon measurement protocols is essential to ensure quality and consistency in radon testing. A national radon database that monitors the measurement results over time can be used to evaluate the effectiveness of a national radon programme.
- An effective national radon programme requires input from several agencies within a country. One agency should lead the implementation and coordination and ensure linkage with tobacco control and other health promotion programmes.
Availability of WHO Handbook

• WHO Handbook on Indoor Radon: A Public Health Perspective:

• WHO Radon Webpage:
The two-member panel – Dr. LaSalle D. Lefall, Jr., a professor of surgery at Howard University and Margaret Kripke, a professor at University of Texas’ M.D. Anderson Cancer Center – was appointed by President Bush to three-year terms.

The two panelists met with nearly 50 medical experts in late 2008 and early 2009 before writing their report to the president.

Annual Effective Dose Equivalent to Member of the U.S. Population
NCRP 93 (1987)

<table>
<thead>
<tr>
<th>Source</th>
<th>% of Natural Dose Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radon</td>
<td>200</td>
</tr>
<tr>
<td>Cosmic</td>
<td>27</td>
</tr>
<tr>
<td>Medical X-rays</td>
<td>11%</td>
</tr>
<tr>
<td>Nuclear Medicine</td>
<td>4%</td>
</tr>
<tr>
<td>Consumer Products</td>
<td>3%</td>
</tr>
<tr>
<td>Other</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Artificial</td>
<td>18%</td>
</tr>
<tr>
<td>Occupational Radiation</td>
<td>0.3%</td>
</tr>
<tr>
<td>Nuclear Power</td>
<td>0.1%</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>0.1%</td>
</tr>
<tr>
<td>TOTAL</td>
<td>~360</td>
</tr>
</tbody>
</table>

Radon Resistant New Construction (RRNC) Workshop
Residential Studies
Medical Radiation

• The Panel urged physicians to use caution in prescribing CT scans and other medical imaging tests that expose patients to large amounts of radiation.

• In 2007, 69 million CT scans were performed, compared with 18 million in 1993. As noted in the report, patients who have a chest CT scan receive a dose of radiation in the same range as survivors of the Hiroshima atomic bomb attacks who were less than half a mile from ground zero.

Exposure to Environmental Hazards from Natural Sources

As the preceding chapters indicate, most environmental hazards with the potential to cause cancer risk are the product of human activity. Some environmental carcinogens, however, come from natural sources.

Radon

Radon is an inert gas (i.e., not chemically reactive), colorless, odorless gas, one in a chain of naturally produced uranium decay.²³ Radon is produced from the decay of radium located at uranium ore, which is ubiquitous in soil and rock worldwide. As radon forms in the earth, it rises to the surface where it dissipates rapidly in the air. However, when radon enters a residential and other tightly enclosed structures, its concentration can rise to levels that increase cancer risk, particularly when inhabitants of homes with higher radon levels are exposed over a period of years. Inhaled radioactive alpha particles produced by radon’s two short-lived decay products can directly or indirectly damage DNA in lung cells.⁴³

Miners who frequently work underground are exposed to high levels of radioactive radon, which is associated with elevated lung cancer risk. Miners who smoke are at particularly high risk. People also can be exposed to workroom radon, these exposures usually occur among workers such as water plant operators, and fish hatchery attendants⁴⁴ and among people whose drinking water comes from deeply drilled wells.⁴⁵ Little research has been conducted on radon workplace or drinking water exposures.

Comparative risk assessments by EPA’s Environmental Protection Agency and its Science Advisory Board have consistently ranked radon among the top four environmental risks to the public.

GUS WEHNER
U.S. ENVIRONMENTAL PROTECTION AGENCY

Although some recent studies suggest there could be a harmful but potentially beneficial stimulatory effect from low-dose residential radon exposure,⁴⁶ numerous human cohort and case-control studies have concluded that radon causes lung cancer.⁴⁷ Radon is the second leading cause of lung cancer in the United States and the leading cause of lung cancer among people who have never smoked. Radon-related lung cancer is responsible for an estimated average of 21,000 deaths annually, though scientists believe the range could be as wide as 6,000-50,000 radon deaths per year.⁴⁸ People who smoke and also are exposed to radon have a higher risk of lung cancer than from either exposure alone.

Table 7

<table>
<thead>
<tr>
<th>Radon Level</th>
<th>SHORT-TERM</th>
<th>CURRENT</th>
<th>LIFETIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>15 µatm</td>
<td>10 µatm</td>
<td>15 µatm</td>
</tr>
<tr>
<td>10</td>
<td>15 µatm</td>
<td>10 µatm</td>
<td>10 µatm</td>
</tr>
<tr>
<td>5</td>
<td>10 µatm</td>
<td>5 µatm</td>
<td>10 µatm</td>
</tr>
<tr>
<td>4</td>
<td>7 µatm</td>
<td>4 µatm</td>
<td>7 µatm</td>
</tr>
<tr>
<td>2</td>
<td>5 µatm</td>
<td>2 µatm</td>
<td>5 µatm</td>
</tr>
<tr>
<td>1</td>
<td>2.5 µatm</td>
<td>1.25 µatm</td>
<td>2.5 µatm</td>
</tr>
<tr>
<td>0.5</td>
<td>1.25 µatm</td>
<td>0.625 µatm</td>
<td>1.25 µatm</td>
</tr>
</tbody>
</table>

Current risk projection (mass) is based on a paradigm in radon risk assessment developed in the 1970s. The Indoor Radon Abatement Act (HR 1070) was a national long-term goal of reducing radon levels in buildings to the levels expected in a natural setting. The Indoor Radon Abatement Act (HR 1070) was signed into law in 1986. The U.S. Environmental Protection Agency’s (EPA) determination was that the level of radon in and around most homes is not a significant public health hazard. The Indoor Radon Abatement Act (HR 1070) was signed into law in 1986. The U.S. Environmental Protection Agency’s (EPA) determination was that the level of radon in and around most homes is not a significant public health hazard. The Indoor Radon Abatement Act (HR 1070) was signed into law in 1986. The U.S. Environmental Protection Agency’s (EPA) determination was that the level of radon in and around most homes is not a significant public health hazard. The Indoor Radon Abatement Act (HR 1070) was signed into law in 1986. The U.S. Environmental Protection Agency’s (EPA) determination was that the level of radon in and around most homes is not a significant public health hazard.
Radon Resistant New Construction (RRNC) Workshop

Residential Studies

Radon in U.S.

EPA action level

0.00 0.05 0.10 0.15

Attributable risk

0 5 10 15 20

AR = 0.14

~ 1/3 of lung cancers from homes above EPA action level
(or 5-8K lung cancer deaths/yr)

Radon concentration, pCi/L

AR for Radon

Radon in U.S.

EPA action level

0 5 10 15 20

Attributable risk

While the public may know that radon kills, relatively few people are aware of the level at which radon concentrations should be monitored and remediated. In 1980, the EPA established an action level of 4 pCi/L above which remediation was recommended. According to the Centers for Disease Control and Prevention, radon is responsible for approximately 20,000 lung cancer deaths per year in the United States, with 15,000 of those deaths occurring in homes at levels above the EPA action level.

It's important to know that radon is a naturally occurring gas, but in some homes, it is not naturally occurring. We can build homes that are radon resistant. We just choose not to do so.

William Held
University of Iowa

EPA Map of Radon Zones

Radon concentrations vary greatly across the United States. In some areas, radon levels are naturally high, but in other areas, they are very low or non-existent. The EPA has developed a map of radon zones to help homeowners understand their risk.

Radon Resistant New Construction (RRNC) Workshop

Residential Studies

It's important to know that radon is a naturally occurring gas, but in the homes it's not naturally occurring, it's enhanced. We can build homes that are radon resistant. We just choose not to do so.
We have to go beyond a voluntary program for radon mitigation at this point. You can see all these homes in the future with no mitigation and it’s going to be three times, four times more expensive than doing it when we first build the homes.

MILLIEN FIELD
UNIVERSITY OF KANSAS

Based on its conclusions, the Panel recommends:

**RECOMMENDATION**

The cancer risk attributable to residential radon exposure has been clearly demonstrated and must be better addressed. The following are needed:

- The Environmental Protection Agency (EPA) should consider lowering its current action level (14 pCi/L) for radon exposure, taking into account data on radon-related cancer risk developed since the existing action level was established.
- Public and health care provider education should be developed and broadly disseminated to raise awareness of radon-related cancer risk.

**RESPONSIBLE AGENCIES, STAKEHOLDERS, AND OTHER ENTITIES**

- EPA
- HHS
- Health care provider professional organizations
- Media

Radon Resistant New Construction (RRNC) Workshop

Residential Studies
Based on its conclusions, the Panel recommends:

<table>
<thead>
<tr>
<th>RECOMMENDATION</th>
<th>RESPONSIBLE AGENCIES, STAKEHOLDERS, AND OTHER ENTITIES*</th>
</tr>
</thead>
</table>
| • Improved testing methods for residential radon exposure and better methods for assessing cumulative exposure should be developed. Tax deductions or other incentives should be implemented to encourage radon mitigation retrofitting of existing housing. Building code changes should be made to require radon reduction venting in new construction. | Industry  
Congress  
Internal Revenue Service  
State and local governments |
| • All schools, day care centers, and workplaces should be tested at regular intervals for radon. Radon level data must be made available to the public. Buildings found to have levels in excess of the EPA action level should be mitigated. | State and local governments |
Radon Professionals Listserv
http://list.uiowa.edu/archives/radonprofessionals.html