Thirty-Third Lauristion S. Taylor Lecture on Radiation Protection and Measurements

2 March 2009
John D. Boice, Jr.

Radiation Epidemiology: The Golden Age and Future Challenge
Laurie Taylor and First Taylor Lecture 1977
Lauriston S. Taylor  Lecturers (1977-2008)
Colleagues Over the Years

- Seymour Jablon (1987)
- Bo Lindell (1988)
- Vic Bond (1991)
- Ted Webster (1992)
- Warren Sinclair (1993)
- Michael Fry (1994)
- Albrecht Kellerer (1995)
- Seymour Abrahamson (1996)
- Eric Hall (1998)
- Naomi Harley (1999)
- Jim Adelstein (2000)
- Julian Preston (2002)
- Jack Little (2005)
- Bob Brent (2006)
- Dade Moeller (2008)
Epidemiology is the study of the distribution and causes of disease in humans.

- Studies of human populations exposed to ionizing radiation have been conducted for nearly 100 years (the GOLDEN AGE).

- Radiation epidemiology is now so sophisticated that human studies are the basis for radiation protection standards and for compensation schemes in response to claims of ill health from prior exposures.
The Golden Age
Epidemiologic Studies of Exposed Human Populations

√ JAPANESE ATOMIC BOMB SURVIVORS

RADIOTHERAPY - CANCER
√ Cervical
√ Endometrial
√ Childhood
√ Breast
√ Hodgkin Lymphoma

RADIOTHERAPY - NON-MALIGNANT DISEASE
√ Spondylitis
√ Mastitis
√ Thymus
√ Infertility
√ Tonsils
√ Otitis Media
√ Menstrual Disorders
√ Ulcer
√ Scalp Ringworm
√ Hemangiomata

DIAGNOSTIC
√ TB - Fluoroscopy
√ Scoliosis
√ Pelvimetry
√ General

RADIONUCLIDES
√ Thorotrast
√ I-131
√ Uranium
P-32
Ra-224
Plutonium

OCCUPATION
Ra Dial Painters
Miners (Radon)
Radiologists
Technologists
Nuclear Workers
Atomic Veterans

ENVIRONMENT
√ Chernobyl
Weapons Fallout
Natl Background
Techa River

Vanderbilt-Ingram Cancer Center
A Comprehensive Cancer Center Designated by the National Cancer Institute
A Few Golden Studies

Medical
- Diagnostic fluoroscopic X-rays for tuberculosis
- Radiotherapy for cervical cancer
- Prenatal and preconception exposures

Environmental
- Radon
- Nuclear Facilities

Occupational
- Rocketdyne – Atomics International
Studies of Low-Dose Exposures Accumulating to High Dose

Lung collapse therapy for tuberculosis and associated multiple chest fluoroscopic x-rays (1930-1954)
## Breast Cancer
### TB - Fluoroscopy, Massachusetts

<table>
<thead>
<tr>
<th></th>
<th>Exposed</th>
<th>Nonexposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of women</td>
<td>2,573</td>
<td>2,367</td>
</tr>
<tr>
<td>No. chest fluoroscopies (ave)</td>
<td>88</td>
<td>--</td>
</tr>
<tr>
<td>Dose (ave)</td>
<td>79 cGy</td>
<td>--</td>
</tr>
<tr>
<td>Breast cancers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Observed (O)</td>
<td>147</td>
<td>87</td>
</tr>
<tr>
<td>Expected (E)</td>
<td>113.6</td>
<td>100.9</td>
</tr>
<tr>
<td>O/E</td>
<td>1.29</td>
<td>0.86</td>
</tr>
</tbody>
</table>

**29% Excess**

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Dose Response – Pooled Analysis of Breast Cancer Studies

Breast Cancer

Consistent with linearity

(67) … the adoption of the LNT model combined with a judged value of a dose and dose rate effectiveness factor (DDREF) provides a prudent basis for the practical purposes of radiological protection, i.e., the management of risks from low-dose radiation exposure. (ICRP Publ 103, 2007)
Lung and Leukemia
TB - Fluoroscopy, Massachusetts

<table>
<thead>
<tr>
<th></th>
<th>Lung</th>
<th>Leukemia</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. exposed</td>
<td>6,285</td>
<td></td>
</tr>
<tr>
<td>No. unexposed</td>
<td>7,100</td>
<td></td>
</tr>
<tr>
<td>No. chest fluoroscopies (ave)</td>
<td>77</td>
<td></td>
</tr>
<tr>
<td>Dose to lung or marrow</td>
<td>84 cGy</td>
<td>9 cGy</td>
</tr>
<tr>
<td>Observed (O)</td>
<td>69</td>
<td>17</td>
</tr>
<tr>
<td>Expected (E)</td>
<td>86</td>
<td>19</td>
</tr>
<tr>
<td>RR (95% CI)</td>
<td>0.8 (0.6-1.0)</td>
<td>0.9 (0.5-1.8)</td>
</tr>
</tbody>
</table>

No excess lung or leukemia
Not all tissues respond similarly to fractionation.

Davis et al, Cancer Res 49:6130, 1989

A Comprehensive Cancer Center Designated by the National Cancer Institute
Heart Disease
TB – Fluoroscopy, Massachusetts

Number exposed 6,285
Number unexposed 7,100
Heart dose ~90 cGy
Observed heart disease (O) 826
Expected (E) 908
RR (95% CI) 0.9 (0.8-1.0)

Davis et al, Cancer Res 49:6130, 1989

No excess heart
A Few Golden Nuggets
TB Fluoroscopy

- Low-dose fractions increase breast cancer
- Linearity fits the breast data
- Low-dose fractions NOT found to increase
  - Lung cancer
  - Leukemia
  - Heart disease
- Be cautious when generalizing
Treating Breast Cancer
Radiotherapy Dose to Contralateral Breast

200 cGy (ave)
Radiotherapy for Breast Cancer
All Breast Cancers in Connecticut (1935-82) – Second Breast Cancer

<table>
<thead>
<tr>
<th></th>
<th>RR</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Subjects*</td>
<td>1.19</td>
<td>0.9-1.5</td>
</tr>
<tr>
<td>Time After Exposure (Yr)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-9</td>
<td>0.99</td>
<td>0.7-1.4</td>
</tr>
<tr>
<td>&gt;10</td>
<td>1.33</td>
<td>1.0-1.8</td>
</tr>
<tr>
<td>Age at Exposure (Yr)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;35</td>
<td>2.26</td>
<td>0.9-5.7</td>
</tr>
<tr>
<td>35 -</td>
<td>1.46</td>
<td>0.9-2.3</td>
</tr>
<tr>
<td>&gt;45</td>
<td>1.01</td>
<td>0.8-1.4</td>
</tr>
</tbody>
</table>

*655 Cases, 1,189 Controls


Risk after 10 years among young. Example of age modification.
Unanswered Question
Genetic Susceptibility?
Second Breast Cancer

WECARE, 2\textsuperscript{nd} breast (n=800) to study
Interaction Between Radiation and Genes*

<table>
<thead>
<tr>
<th>Exposure</th>
<th>RR</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRCA1 mutation</td>
<td>4.5</td>
<td>2.8-7.1</td>
</tr>
<tr>
<td>BRCA2 mutation</td>
<td>3.4</td>
<td>2.0-5.8</td>
</tr>
<tr>
<td>1 Gy (&lt;40 y)</td>
<td>1.6</td>
<td>1.1-2.5</td>
</tr>
<tr>
<td>1 Gy (&gt;45 y)</td>
<td>1.0</td>
<td>0.9-1.3</td>
</tr>
</tbody>
</table>

*BRCA\textit{s}, ATM, CHEK2\textit{*1100delC}

Stovall, *IJROBP*, 2008
A Few Golden Nuggets
Breast Cancer Treatment

- Long latency (time) for second cancers to occur

- Age at exposure can have a profound effect – little risk for exposures over 45 y

- Genetic susceptibility at low doses is uncertain
Radiation Treatments
Multiple Primary Cancers

Warren and Gates, 1932, Definitions

Risk Quantification
Study of Leukemia
Radiotherapy for Cervical Cancer

Third study in 1960s designed to quantify risk of leukemia
Cervical Cancer and Leukemia
Large Doses, No Chemotherapy, Good Survival
### Cervical Cancer and Leukemia
Blood Studies and Clinical Follow-up
30 Radiotherapy Centers in 9 Countries

<table>
<thead>
<tr>
<th>Number</th>
<th>30,000 women</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dose</td>
<td>5-15 Gy (marrow)</td>
</tr>
<tr>
<td>Leukemia</td>
<td></td>
</tr>
<tr>
<td>Observed</td>
<td>13</td>
</tr>
<tr>
<td>Expected</td>
<td>15.5</td>
</tr>
</tbody>
</table>

**Risk:** No excess

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Boice & Hutchison, *JNCI* 65:115, 1980

Huge dose but no risk

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Vanderbilt-Ingram Cancer Center

A Comprehensive Cancer Center Designated by the National Cancer Institute
International Cervical Cancer Study Expansion – 16 Radiotherapy Centers and 17 Cancer Registries in 14 Countries

200,000 women
Characteristic Wave-like Pattern for Radiation-Induced Leukemia

Boice, JNCI, 74:955, 1985
Bone Marrow Dosimetry
Downturn at High Doses

Solid Cancers After Radiotherapy
Long Minimum Latency

Boice, JNCI 74:955, 1985
Not all cancers have been convincingly increased following radiation in human studies (UNSCEAR 2008)

There is **little evidence** for an association with radiation for:

- chronic lymphocytic leukaemia
- pancreatic cancer
- prostate cancer
- cervical cancer
- testicular cancer
- uterine cancer
- non-Hodgkin’s lymphoma
- Hodgkin’s disease
- multiple myeloma
- small intestine
- rectum
- uterus
- kidney

And other associations have only been seen following **very high doses** (radiotherapeutic):
## Opportunities for Low-Dose Studies

### Cervical Cancer - Lightly Irradiated Sites

<table>
<thead>
<tr>
<th>Second Cancer</th>
<th>Number Cases</th>
<th>Organ Dose (ave. GY)</th>
<th>RR at 1 Gy (90% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stomach</td>
<td>338</td>
<td>2.0</td>
<td>1.69 (1.0 - 3.3)</td>
</tr>
<tr>
<td>Pancreas</td>
<td>211</td>
<td>1.9</td>
<td>1.00 (0.7 - 1.6)</td>
</tr>
<tr>
<td>Kidney</td>
<td>134</td>
<td>2.0</td>
<td>1.71 (1.0 - 3.2)</td>
</tr>
<tr>
<td>Thyroid</td>
<td>43</td>
<td>0.1</td>
<td>2.35 (0.6 – 8.7)</td>
</tr>
<tr>
<td>Breast</td>
<td>838</td>
<td>0.3</td>
<td>1.03 (0.1 - 2.3)</td>
</tr>
</tbody>
</table>

Golden Nuggets
Cancer Treatments

- High dose to small volumes may kill rather than transform most cells
- Long latency for solid cancers to develop
- Short latency for leukemia to develop
- Opportunity for low-dose studies - scatter
- Caution – new technologies (IMRT, Intensity-Modulated Radiation Therapy) result in increased dose to all normal tissue
Pregnancy and Medical Radiation

Is the low-dose association causal?
## Oxford Prenatal X-ray Survey

<table>
<thead>
<tr>
<th>Childhood cancer</th>
<th>Cases</th>
<th>% X-ray</th>
<th>RR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leukemia</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lymphatic</td>
<td>2,007</td>
<td>14</td>
<td>1.5</td>
</tr>
<tr>
<td>Myeloid</td>
<td>866</td>
<td>14</td>
<td>1.5</td>
</tr>
<tr>
<td>Lymphoma</td>
<td>719</td>
<td>13</td>
<td>1.4</td>
</tr>
<tr>
<td>All leukemia/lymphoma</td>
<td>4,771</td>
<td>14</td>
<td>1.47</td>
</tr>
<tr>
<td>Wilms</td>
<td>590</td>
<td>15</td>
<td>1.6</td>
</tr>
<tr>
<td>CNS</td>
<td>1,332</td>
<td>13</td>
<td>1.4</td>
</tr>
<tr>
<td>Neuroblastoma</td>
<td>720</td>
<td>14</td>
<td>1.5</td>
</tr>
<tr>
<td>Bone</td>
<td>244</td>
<td>11</td>
<td>1.1</td>
</tr>
<tr>
<td>Other solid</td>
<td>856</td>
<td>15</td>
<td>1.6</td>
</tr>
<tr>
<td>All solid</td>
<td>3,742</td>
<td>14</td>
<td>1.47</td>
</tr>
</tbody>
</table>


Biologically plausible to have same RR?
Biological Plausibility Questioned

“... the equality of relative risks associated with obstetric x-rays for leukemia and solid tumors is perplexing given the variability in tissue radiosensitivity, dissimilar origins, and different incidence patterns.”

Association does not mean causation.

Miller, NCRP Proc 6 (Apr), 1984
Boice and Miller, Teratology 59:227, 1999
Sir Richard Doll – Causal Interpretation
# Prenatal X-ray – Leukemia

Sweden, 1973-87, Medical Records

<table>
<thead>
<tr>
<th>Leukemia cases (578)</th>
<th>Controls (578)</th>
<th>RR</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>All exposed</td>
<td>121</td>
<td>113</td>
<td>1.11</td>
</tr>
<tr>
<td>No. x-rays</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>503</td>
<td>511</td>
<td>1.00</td>
</tr>
<tr>
<td>1</td>
<td>113</td>
<td>101</td>
<td>1.16</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>12</td>
<td>0.72</td>
</tr>
<tr>
<td>Type x-ray</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abdominal</td>
<td>68</td>
<td>61</td>
<td>1.14</td>
</tr>
<tr>
<td>Other</td>
<td>34</td>
<td>32</td>
<td>1.04</td>
</tr>
</tbody>
</table>

Golden Nuggets
Prenatal X-ray and Cancer

- Many associations – but all in case-control studies (possible biases in selection and recall)
- No cohort studies positive, including atomic bomb survivors
- Biological plausibility questioned
- Causal nature of low-dose association questioned, particularly for solid cancers
Preconception Studies
Children of Cancer Survivors
Children of Cancer Survivors
Genetic Consequences of Cancer Treatment

NIH

USA/CCSS

St. Jude MDACC U OKLA

Scientific Advisory Committee

Denmark

Danish Cancer Society

MDACC U OKLA Westlakes

Expansion

Finland Vanderbilt Young Adults 20-34-yr

## Genetic Disease in Children of Survivors and Sibling Controls

<table>
<thead>
<tr>
<th>Type of genetic disease</th>
<th>Survivors (n=4,214)</th>
<th>Controls (n=2,339)</th>
<th>RR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cancer</td>
<td>10 (0.2%)</td>
<td>4 (0.2%)</td>
<td>1.4</td>
</tr>
<tr>
<td>Cytogenetic Abnormality</td>
<td>5 (0.1%)</td>
<td>3 (0.1%)</td>
<td>0.9</td>
</tr>
<tr>
<td>Single Gene Disorder</td>
<td>25 (0.6%)</td>
<td>10 (0.4%)</td>
<td>1.4</td>
</tr>
<tr>
<td>Simple Malformation</td>
<td>117 (2.8%)</td>
<td>78 (3.3%)</td>
<td>0.8</td>
</tr>
<tr>
<td>Total</td>
<td>157 (3.7%)</td>
<td>95 (4.1%)</td>
<td>0.9</td>
</tr>
</tbody>
</table>


No increase in birth defects
Dosimetry Models

- Pituitary Gland: 5 cGy
- Thyroid: 17 cGy
- Breasts: 94 cGy R, 300 cGy L
- Ovaries: 150 cGy R, 170 cGy L

Treatement Field Wilms Tumor

Stovall et al, *IJROBP* 60, 2004
Stillbirths and Neonatal Deaths
Children of Male Cancer Survivors

Relative Risk of Stillbirth and Neonatal Death

Trend $p_1 = 0.32$ (-), Pilot
Epidemiology has not Revealed Heritable Effects in Humans

No radiation-induced genetic diseases have so far been demonstrated in humans... estimates of risk have to be based on mouse experiments. UNSCEAR 2001
Girls Treated with Radiation
High Dose to Uterus (n=386)

Dose to Uterus (cGy)

- 0 to 5
- 5 to 10
- 10 to 20
- 20 to 50
- 50 to 100
- 100 to 250
- 250 to 500
- 500 to 1000
- 1000 to 2000
- 2000 - 4000

Percent of Patients

- CCSS-US (n=358)
- Danish (n=28)
Risk of Preterm Birth Increases with Uterine Dose

Risk of Preterm Birth Increases with Uterine Dose

Relative Risk of Preterm*

<table>
<thead>
<tr>
<th>Dose to Uterus (cGy)</th>
<th>0-</th>
<th>10-</th>
<th>50-</th>
<th>250-</th>
<th>≥500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative Risk of Preterm*</td>
<td>0.9</td>
<td>1.2</td>
<td>1.8</td>
<td>2.3</td>
<td>3.5</td>
</tr>
</tbody>
</table>

*Referent: Children not treated with radiation

<table>
<thead>
<tr>
<th></th>
<th>Preterm</th>
<th>Fullterm</th>
<th>RR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Referent: Children not treated with radiation</td>
<td>121</td>
<td>496</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Similar association with low birth weight and small for gestational age

Signorello et al. *JNCI*, 2006

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Golden Nuggets
Preconception Radiation

- No genetic effects detected
- Radiotherapy to uterus can result in low birth weight and preterm babies
RADON AND LUNG CANCER RISK:
A JOINT ANALYSIS OF 11 UNDERGROUND MINERS STUDIES

NATIONAL INSTITUTES OF HEALTH
National Cancer Institute
Pooled Analysis of Underground Miner Studies
Lung Cancer Dose Responses in Miners
Consistency in the Epidemiology

Czech Uranium  Newfoundland Fluorspar  Port Radium Uranium  Chinese Tin
Beaverlodge Uranium  Ontario Uranium  Malmberget Iron  Colorado Plateau Uranium

Cumulative Working Level Months (WLM)
11 Underground Miner Studies
68,000 Miners – 2,700 Lung Cancers

RR = 1.0 + 0.0049 \times \text{WLM}

1 \text{ pCi/l} \sim 0.2 \text{ WLM / yr.}

Lubin et al, 1993
Washington Post, February 6, 1986

New Meaning to “The Nuclear Family”
# Radon Studies in Homes (Case-Control)

**United States**
- √ New Jersey
- √ Missouri
  - Iowa
  - Connecticut
  - Utah/Idaho

**Canada**
- Winnipeg

**Europe**
- Southwest England
- Western Germany
- Czech (cohort)

**Nordic Countries**
- √ Sweden
- Finland

**China**
- √ Shenyang
- √ Gansu

**Pooled**
- √ Lubin (1997, 1999)
  - North America (Krewski, 2005)
  - Europe (Darby, 2005)
  - √ China (Lubin, 2004)
  - World (Darby, in progress)

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BEIR VI, 1999; Field, *Rev Envrir Health* 16, 2001
People’s Republic of China
Gansu Province
Gansu Province
Underground Dwellings
Gansu Province
Underground Dwelling
Gansu China - Radon Study

\[ OR = 1 + 0.0032X \]

\[ OR = 1 + 0.0025X \]

\[ RR = 1 \]

Consistent with linearity

4 pCi/l = 150 Bq/m³


Lubin et al. *Int J Cancer* 109:132, 2004
Indoor Radon Meta-Analysis
Lung Cancer

Difficult to detect low-dose risks, yet significant trend when studies combined.

Lubin & Boice, JNCI, 89:49, 1997

4 pCi/l = 150 Bq/m³
Radon Interacts with Smoking to Enhance Risk

A nearly multiplicative interaction

NRC, BEIR, 1999
## Smoking Compared with Radiation/Radon

<table>
<thead>
<tr>
<th>RR</th>
<th>Cigarettes Per Day</th>
<th>A-Bomb Dose, Sv</th>
<th>Miners WLM</th>
<th>Radon Indoor Bq/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>&lt; 40</td>
</tr>
<tr>
<td>4.6</td>
<td>1-9</td>
<td>3.4</td>
<td>735</td>
<td>4,500*</td>
</tr>
</tbody>
</table>

*140 pCi/L

Smoking <10 cig/day equivalent to being high dose A-bomb survivor

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*Vanderbilt-Ingram Cancer Center*

A Comprehensive Cancer Center Designated by the National Cancer Institute
Golden Nuggets
Radon

- The epidemiology is consistent
- Linearity fits all the data
- Indoor risk low and hard to detect but case-control studies consistent with the miner study predictions
- Interaction with smoking is nearly multiplicative
- Best way to lower radon risk is to stop smoking
Descriptive Studies
Nuclear Facilities (Sellafield, U.K.)
# Overall Relative Risk

US Nuclear Facilities Study

<table>
<thead>
<tr>
<th>Disease</th>
<th>Before Startup</th>
<th>After Startup</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Leukemia</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Childhood</td>
<td>1.08</td>
<td>1.03</td>
</tr>
<tr>
<td>All Ages</td>
<td>1.02</td>
<td>0.98</td>
</tr>
</tbody>
</table>

**Time Pattern**

Risk higher before than after facilities began operating

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Golden Nuggets
Descriptive Studies

- Doses to individuals not known
- Can’t adequately control for confounding
- But large numbers and
- Great societal interest
- Be cautious, e.g., low statistical power (dose is very low) and bias can lead to spurious results
- Generate hypotheses not to test them
Radiation Worker Studies
Rocketdyne – Atomics International
Santa Susana Field Laboratory
Sodium Reactor Experiment - 1956

First commercial power reactor – provided electricity for Moonpark.
Rocketdyne Worker Population

54,384 Rocketdyne Workers from 1948-1999

46,970 Eligible Workers

6,601 Short Term (< 6 mo.)

813 Insufficient Identifying Information or Not Employee

5,801 Radiation Group *

8,372 Chemical Group (SSFL)*

32,979 Comparison Group (Canoga Park etc)

*182 workers included in both groups

99.2% of eligible workers as of 12/31/99 were traced.
Hot Laboratory (1978)

Largest at the time
**Types of Exposure**

- Gamma
- X-ray (radiographers)
- Neutrons

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**External**
- Uniform dose
- Delivered during exposure
- Film (TLD) badge reading

**Internal**
- Non uniform dose
- Protracted in time
- Bioassay measurements

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- Uranium, Plutonium
- Americium, Polonium
- Thorium, Strontium
- Cesium, Tritium

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Vanderbilt-Ingram Cancer Center

_A Comprehensive Cancer Center Designated by the National Cancer Institute_
Sources of Radiation Exposure Histories

Rocketdyne Workforce 46,970

Monitored Workers 5,801

Department of Energy 2,058
NRC – REIRS 1,039
Landauer Dosimetry Co. 1,792

Known Facilities
- Hanford (1,194)
- Idaho National Engineering Lab (237)
- Albuquerque Operation (11)
- Argonne National Lab (74)
- Brookhaven National Lab (8)
- Chicago Operations (17)
- Fermilab (8)
- Fernald (26)
- Lawrence Berkeley Lab (22)
- Lawrence Livermore National Lab (73)
- Los Alamos National Lab (92)
- Mound (13)
- Nevada Test Site (103)
- Oak Ridge Reservation (95)
- Oakland Operations (250)
- PanTex (14)
- Pittsburgh Naval Reactor (34)
- Portsmouth Gaseous Diffusion Plant (6)
- Rocky Flats (160)
- Sandia National Lab (38)
- Savannah River (72)
- Schenectady Naval Reactor (KAPL) (30)
- Stanford Linear Accelerator (12)
- West Valley (6)

Other Sources
- Oak Ridge (66)
- Malineckrodt (13)
- Ferrald (11)
- Savannah River (26)
- Rochester Files (6)
- 5 REM Study (14)
- US Army (152)
- US Air Force (152)
- US Navy (26)
Lung Dose by Dose Categories

Importance of career dose and internal dose

![Graph showing lung dose by dose categories](image)

- Rocketdyne EXT
- Total Career EXT
- Total Career EXT and Neutron
- Total EXT & INT (Lung)

Lung dose (mSv)
Little evidence that radiation increased the risk of dying from lung cancer but small numbers
Summary
Worker Study - Rocketdyne

- Importance of career dose (1 in 4 worked elsewhere)
- Importance of internal dose (41% of lung dose)
- Single study has low statistical power to reveal effects
- More (and combined) U.S. worker studies are needed
What More Could be Done
Is There More Gold to Mine?

- Occupational Studies
- Nuclear Weapons Test Participants
- Cancer Survivors – Low Dose Scatter
- Prenatal Studies – Cancer Patients Who Are Pregnant
- High Background Radiation – e.g., Tibet
Department of Energy Cohorts Could Be Extended

- **Oak Ridge Group** (N=147,134)
  - Fernald
  - K-25 (Oak Ridge Gaseous Diffusion Plant)
  - Linde Ceramics Plant
  - Mallinckrodt Chemical Works
  - Savannah River Site
  - Y-12, Tennessee Eastman (pre 1947)
  - Y-12 post 1947
  - Oak Ridge National Laboratory (X-10)
  - Other?

- **Los Alamos Group** (N=30,035)
  - Los Alamos
  - Mound
  - Rocky Flats
  - Pantex
  - Other?

- **Hanford** (N=32,643)

“... the US multi-site cohort studies seem to have petered out. This is very disappointing because if an effect of occupational exposure among nuclear industry workforces in the West is to be found then one would expect the combined workforce of the US Department of Energy nuclear sites to be the prime candidate for its manifestation. One can only hope that the results of NRRW-3 will be the spur for an increased effort from the USA.”

Wakeford, JRP, 2009
USA Occupational Studies
Early Utility Workers

- U.S. Early Utility Workers
  - large numbers, good dosimetry, range of doses
  - 600,000 workers, all years
  - early workers received the highest doses
  - 5 (N-18 years) rem “rule” allowed 3 rem per quarter (30 mSv) and up to 12 rem per year (120 mSv)
  - cumulative doses over 100 rem were possible (1000 mSv)

- Navy Shipyard Workers
- Nuclear Navy
- DOE Cohorts
Nuclear Weapons Test Participant Studies

- Large numbers (125K), complex dosimetry, DoD $300M, 60 y follow-up, radionuclides
- 451 leukemias at last follow-up
Cancer Survivor Studies
Opportunity for Low Dose Studies
Dose Outside the Treatment Field

DOSE COMPONENTS OUTSIDE THERAPY BEAM
1 = HEAD LEAKAGE
2 = COLLIMATOR SCATTER
3 = SCATTER IN PATIENT FROM USEFUL BEAM
Prenatal – Sensitive Subgroup

- Cancer patients who are pregnant at time of radiotherapy
- Fetal dose: 1-150 cGy
High Background Radiation
Example - Cosmic Rays

- Defined and stable population
- Tibet (4,230 m)
- Precise dosimetry
- 1.8 vs. 0.5 mSv/y
- 110 vs. 30 mSv/60y
- Exam thyroid
- Cataracts (NASA?)
Golden Nuggets
What Epidemiology Tells Us

- a single exposure can increase your cancer risk for life
- many small exposures can increase your cancer risk
- the young are more susceptible than the old
- the fetus, however, is not more susceptible than the child
- no genetic (heritable) effects have been found
- females are more susceptible than males
- risks differ by organ or tissue
- some cancers not convincingly increased after exposure
- high doses kill cells and result in lower risks
- there’s more to be learned
An **aging epidemiologist** has the not insignificant satisfaction of a **shelf of publications** behind him that, as they wait for their ideal readers to discover them, will outlast him for a while.

**The pleasures, for him, of research** — the first flush of inspiration, the patient years of study conduct, the final analyzes and final draft manuscript, the merry-go-round of conference presentations, the back-and-forthing with reviewers and journal publishers, the page proofs, and at last the glossy prints (now electronic pdf’s) — remain, and retain creation’s giddy bliss.

**Among those diminishing neurons there lurks the irrational hope that the last study might be his best.**
Family – Jennifer and 4 Sons 2009

Justin, Jack, Shannon, John, Jennifer, Jason, Brittin