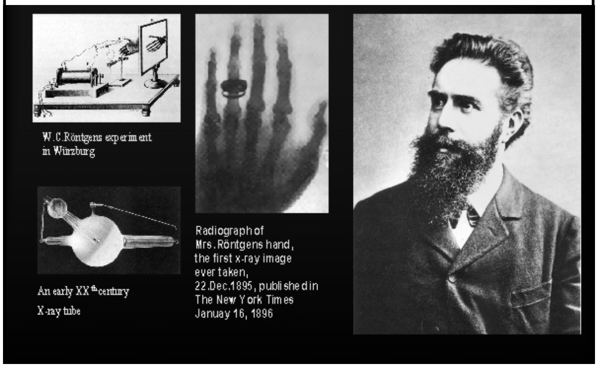
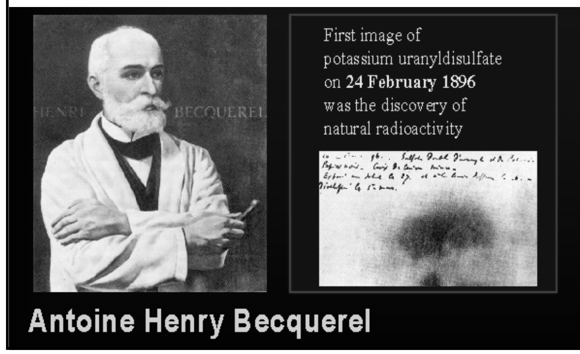
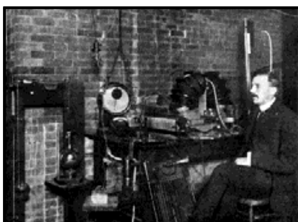
November 1895: Roentgen discovers x rays

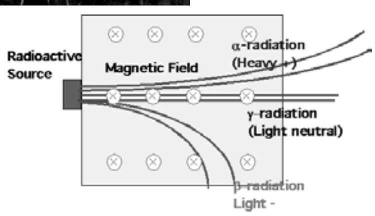


February 1896: Becquerel discovers radioactivity

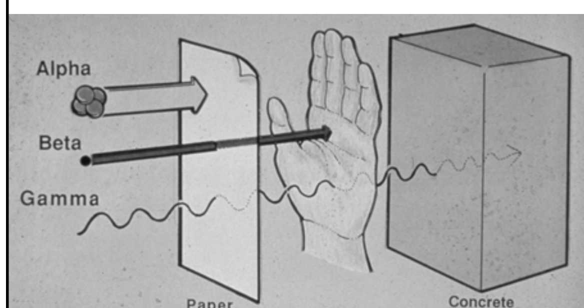


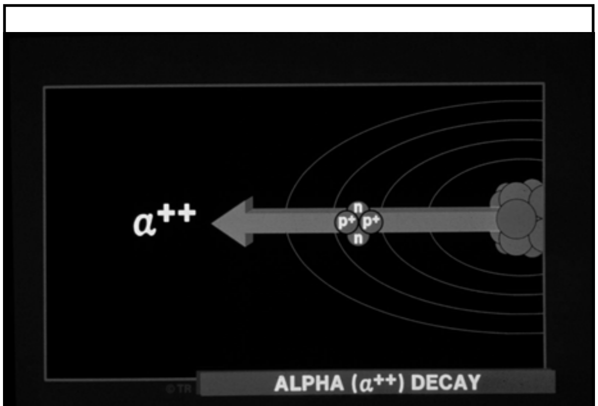


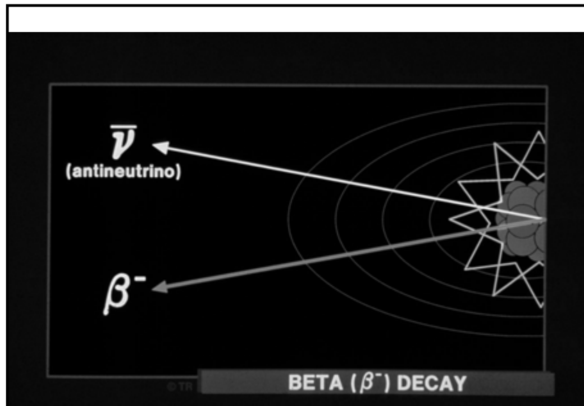
Ernest Rutherford 1898-99

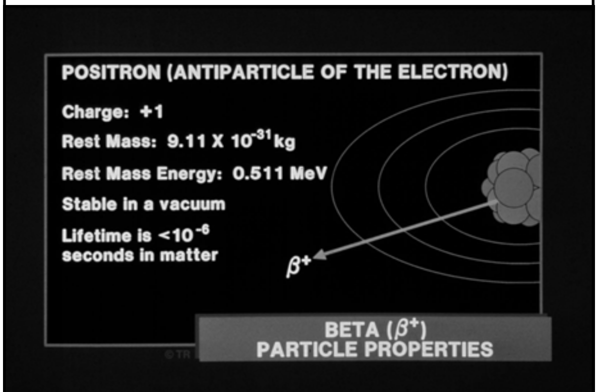


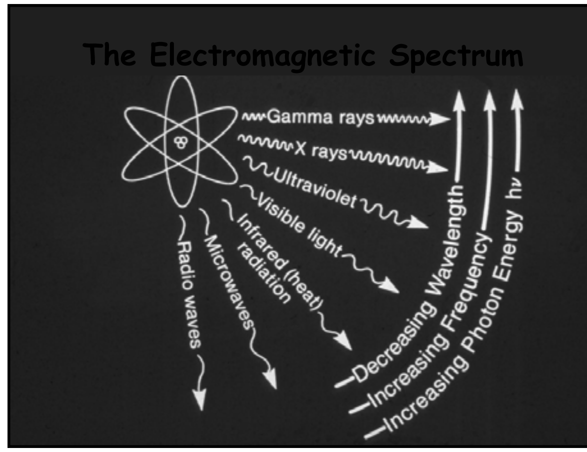
Ernest Rutherford: 1898-99

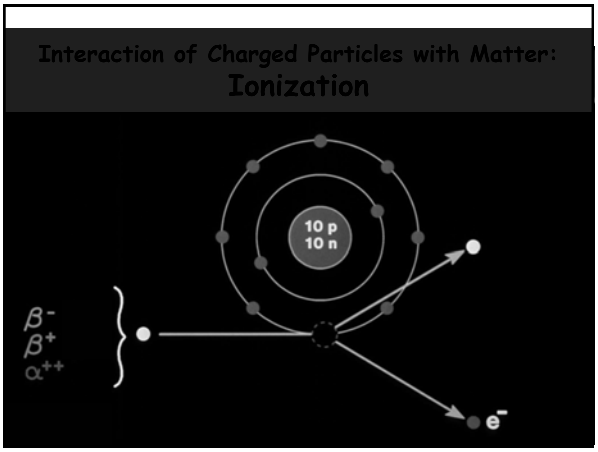


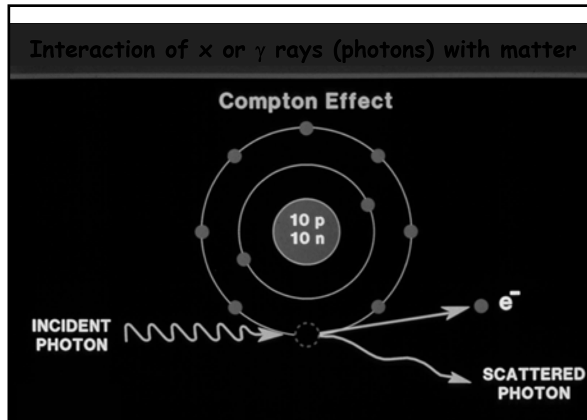








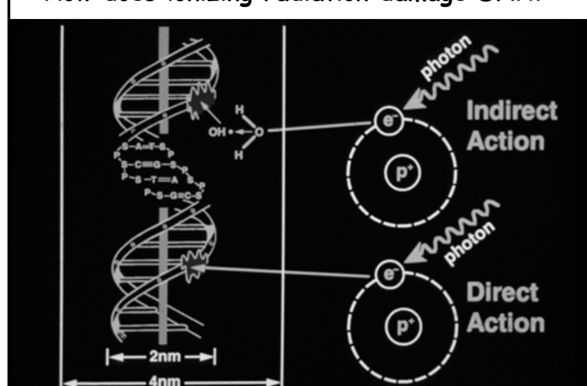




Relevant Quantities & Units – for Individuals

QUANTITY	DEFINITION	UNITS New	Old
Absorbed Dose	Energy per unit mass	Gray (Gy)	rad
Equivalent Dose	Average dose X radiation weighting factor	Sievert (Sv)	rem
Effective Dose	Sum of equivalent doses to organs and tissues exposed, each multiplied by the appropriate tissue weighting factor	Sievert	rem
Committed Equivalent Dose	Equivalent dose integrated over 50 years (relevant to incorporated radionuclides)	Sievert	rem
Committed Effective Dose	Effective dose integrated over 50 years (relevant to incorporated radionuclides)	Sievert	rem

How does ionizing radiation damage DNA?



Principal Hazards of Ionizing Radiation

- Genetic effects
- Carcinogenic effects
- Effects on the developing embryo/fetus

The Carcinogenic Effects of Radiation

Radiation and Cancer

How does radiation cause cancer?

Radiation and Cancer

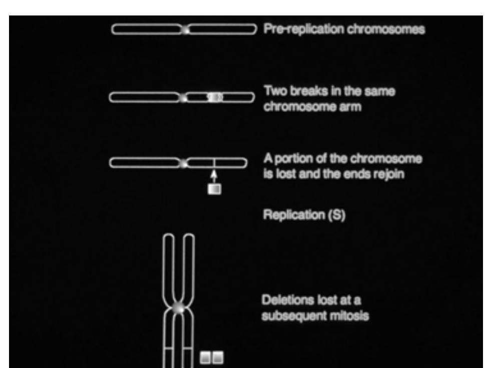
- Ionizing radiation does cause cancer
- Parts of the mechanisms are understood
- The full picture is still very unclear

Radiation and Cancer

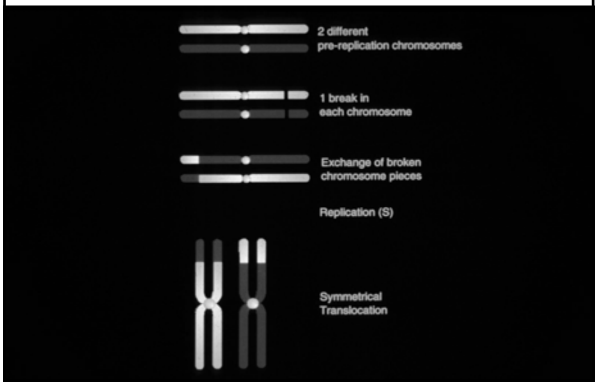
Ionizing radiation is quite efficient at inducing chromosomal aberrations such as

deletions and translocations

Chromosomal Deletions



Chromosomal Translocations



Links between chromosomal aberrations and cancer

[redacted] → [redacted]

[redacted] → [redacted]

Radiation and Cancer

What do we know *quantitatively* about the risks of radiation-induced cancer in humans?

Radiation and Cancer: Sources of Information

- ☛ Extrapolation from animal data
- ☛ Relevant human cohorts
- ☛ Mechanistic information

Radiation and Cancer: Are animal data useful?

- ☛ Useful for indicating *relative* patterns (dose, dose rate, radiation quality)
- ☛ Not useful for assessing *absolute* risk

Radiation and Cancer

What are the problems in estimating the risks of radiation-induced cancer in humans?

Problems estimating cancer risks

Many!

Problems estimating cancer risks

- ✓ Dose reconstruction
- ✓ Statistics
- ✓ Controls
- ✓ Latency

Problems estimating cancer risks

- ✓ Dose extrapolation
- ✓ Dose rate extrapolation
- ✓ Age and time dependencies
- ✓ Transfer models
- ✓ Neutrons at Hiroshima

The BIG caveat

Radiation risk estimates at low doses are based on plausible assumptions, but are estimates nevertheless.

They are not, and can never be, direct measurements!

Radiation and Cancer:
Relevant Human Cohorts

- ✓ A bomb survivors
- ✓ TB patients (multiple fluoroscopies)
- ✓ Tinea Capitis children
- ✓ Ankylosing Spondylitics
- ✓ RT patients

Radiation and Cancer
Emerging Human Cohorts

- ✓ Chernobyl
- ✓ Mayak
- ✓ Airline personnel

Radiation and Cancer

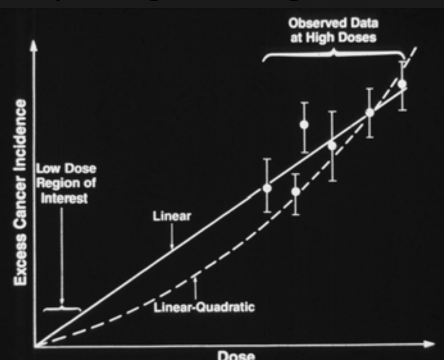
Most of our information comes from studies of A-bomb survivors

Radiation and Cancer:

A-bomb survivors

- 87,000 survivors followed
- 7,800 cancer deaths observed
- 7,400 expected
- Therefore 400 excess cancers

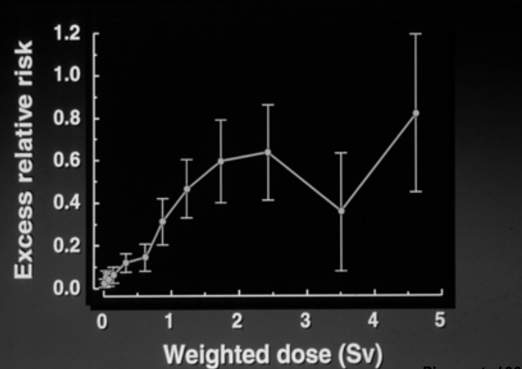
Extrapolating from High to Low Doses



A Linear Extrapolation from High to Low Doses?

- At low doses the Japanese dose-response relations are consistent with a linear relation between dose and cancer risk.
- Although controversial, a linear model (implying no low-dose threshold for risk) is most likely valid.

Solid Cancers – A-Bomb Survivors



Radiation and Cancer

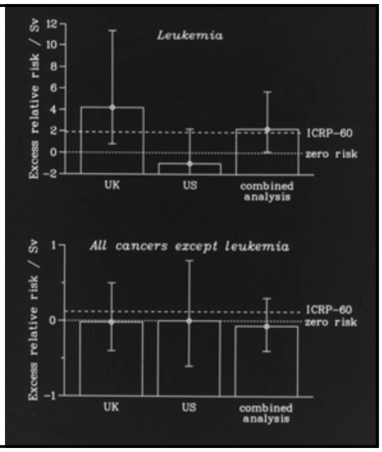
Can low-dose risks be estimated directly from groups exposed to low doses of radiation?

Recent study of 120,000 nuclear workers exposed to ~40 mSv consistent both with:

- Zero risk
- A risk appropriately extrapolated from A bomb survivor data.

The Nuclear Worker Study

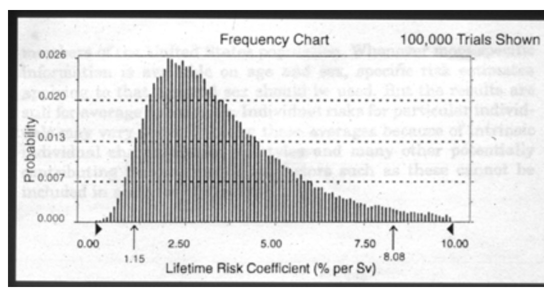
Cardis et al 1995



Estimated excess fatal cancers (ICRP) % / Sv

	High Dose / High Dose Rate	Low Dose / Low Dose Rate
General population	10%	5%
Working population	8%	4%

Distribution of uncertainties in radiation risk



Radiation and Cancer

Individual Susceptibility to Radiation Carcinogenesis

ATM: Ataxia Telangiectasia

Non-Cancer Radiation Risks

… are not quantified as well as the cancer risks

Radiation Risks

Teratogenic risks

Order of magnitude larger than

Carcinogenic risks

Order of magnitude larger than

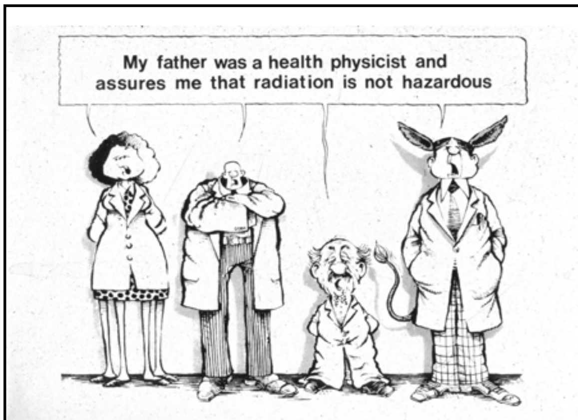
Hereditary risks

Gene Mutations

Single Dominant	✓ Polydactyly ✓ Huntindon's chorea ✓ Retinoblastoma
Recessive	✓ Sickle-cell anemia ✓ Tay-Sachs disease ✓ Cystic fibrosis
Sex linked	✓ Color blindness ✓ Hemophilia

Radiation-Induced Mutations

Radiation does not produce new, unique mutations, but simply increases the incidence of the same mutations that occur spontaneously



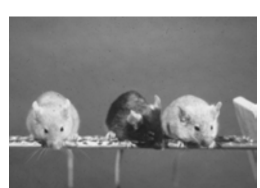
Heritable Effects

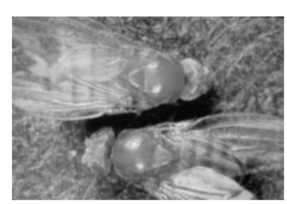
Children of the survivors of the A bomb attacks have been studied for:

- Untoward pregnancy outcomes
- Death of live-born children
- Sex chromosome abnormalities
- Electrophoretic variants of blood proteins

But no statistically significant effects have been observed

We are heavily reliant on animal data for hereditary risk estimates



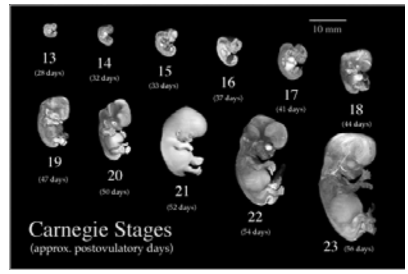


Hereditary Effects - ICRP

Probability / caput
of severe hereditary disorder
(working population)

0.6% / Sv

IN UTERO EFFECTS OF RADIATION



Teratogenic Risks

(i.e., to the embryo/fetus, if relevant)

Moderate doses of radiation can produce catastrophic effects on the developing embryo and fetus.

The principle effects of radiation on the developing embryo and fetus are:

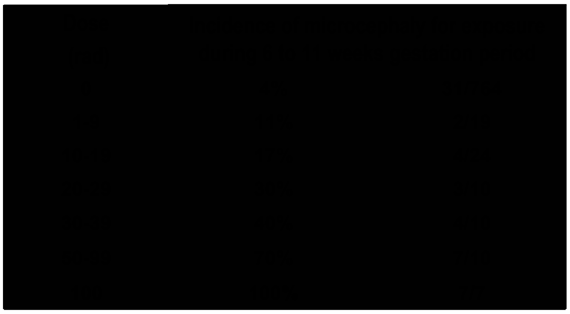
- Growth retardation
- Embryonic, neonatal, or fetal death
- Congenital malformations and functional impairment, such as mental retardation.

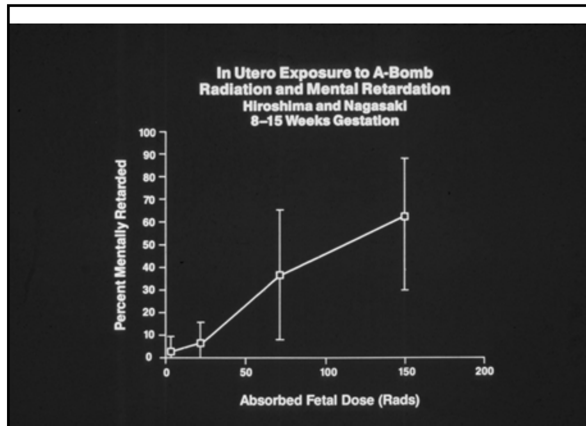
Factors Influencing Probability of Teratogenic Effects

- ✓ Dose to embryo/fetus
- ✓ Stage of gestation at time of exposure

A-bomb survivors irradiated *in-utero*, with microcephaly

Microcephaly at Hiroshima





In utero exposure & mental retardation

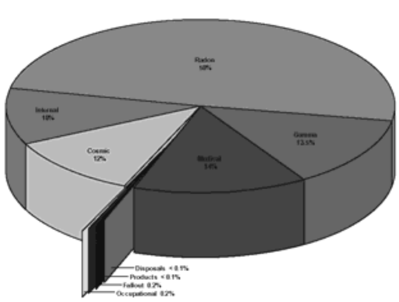
Severe mental retardation,
after in-utero exposure
(8-15 weeks gestation period)

Risk: 40% / Sv

Radiation Risks

Teratogenic risks
order of magnitude larger than
Carcinogenic risks
order of magnitude larger than
Hereditary risks

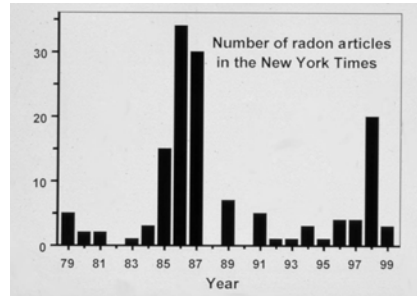
Typical sources of exposure to ionizing radiation



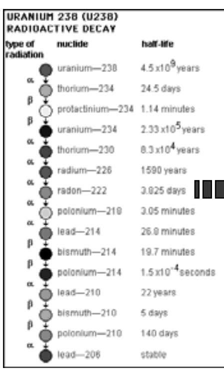
Stanley Watras at the Limerick nuclear power plant, 1984

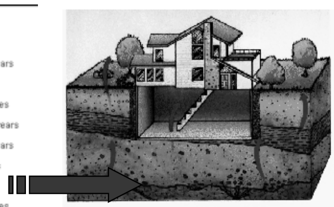
Stanley Watras and family, Boyertown, PA, 1985

Number of articles about radon in the New York Times



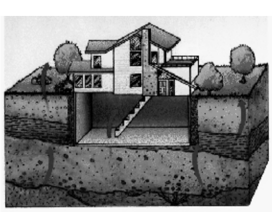
The uranium-238 decay chain

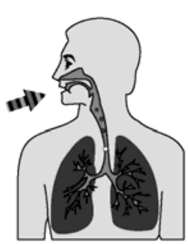




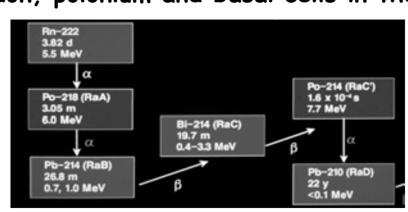
The Reading Prong: A granite formation

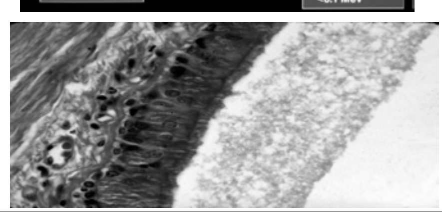
Radon: From Rocks to Lungs





Radon, polonium and basal cells in the lung





Radon risks are estimated by studying uranium miners

Estimated lung cancer risks from lifetime exposure to radon

	Percent risk of lung cancer in *smokers*	Percent risk of lung cancer in *non smokers*
1 pCi/l	0.7%	0.05%
4 pCi/l	3%	0.2%
20 pCi/l	14%	1%

Estimated lung cancer deaths per year in the US due to radon

In the range 15,000 to 22,000
(~1 in 8 of all lung cancer deaths)

About 85% of these deaths are attributable to radon + smoking

Testing houses for high radon levels

Radon remediation: Sub-slab ventilation

1-800-SOS RADON