

MEASURING
RADIATION
and its
EFFECTS

ACTIVITY units

ACTIVITY units

1 **Bequerel (Bq)** \equiv 1 radioactive decay per second.

1 **Curie (Ci)** \equiv 37 billion **Bq**

ACTIVITY units

1 **Bequerel (Bq)** \equiv 1 radioactive decay per second.

1 **Curie (Ci)** \equiv 37 billion **Bq**

An isotope with a *half-life* of $T_{1/2}$ has a *mean lifetime* of

$$\tau = T_{1/2} / \ln 2 \approx 1.44 T_{1/2}$$

and a *decay rate* of $\lambda = 1/\tau$

ACTIVITY units

1 **Bequerel (Bq)** \equiv 1 radioactive decay per second.

1 **Curie (Ci)** \equiv 37 billion **Bq**

An isotope with a *half-life* of $T_{1/2}$ has a *mean lifetime* of

$$\tau = T_{1/2} / \ln 2 \approx 1.44 T_{1/2}$$

and a *decay rate* of $\lambda = 1/\tau$

so a sample of N such nuclei will have an *activity* of

$$A = \lambda N = N \ln 2 / T_{1/2} \text{ Bq}$$

(if $T_{1/2}$ is measured in *seconds*)

ACTIVITY units

1 **Bequerel (Bq)** \equiv 1 radioactive decay per second.

1 **Curie (Ci)** \equiv 37 billion **Bq**

An isotope with a *half-life* of $T_{1/2}$ has a *mean lifetime* of

$$\tau = T_{1/2} / \ln 2 \approx 1.44 T_{1/2}$$

and a *decay rate* of $\lambda = 1/\tau$

so a sample of N such nuclei will have an *activity* of

$$A = \lambda N = N \ln 2 / T_{1/2} \text{ Bq}$$

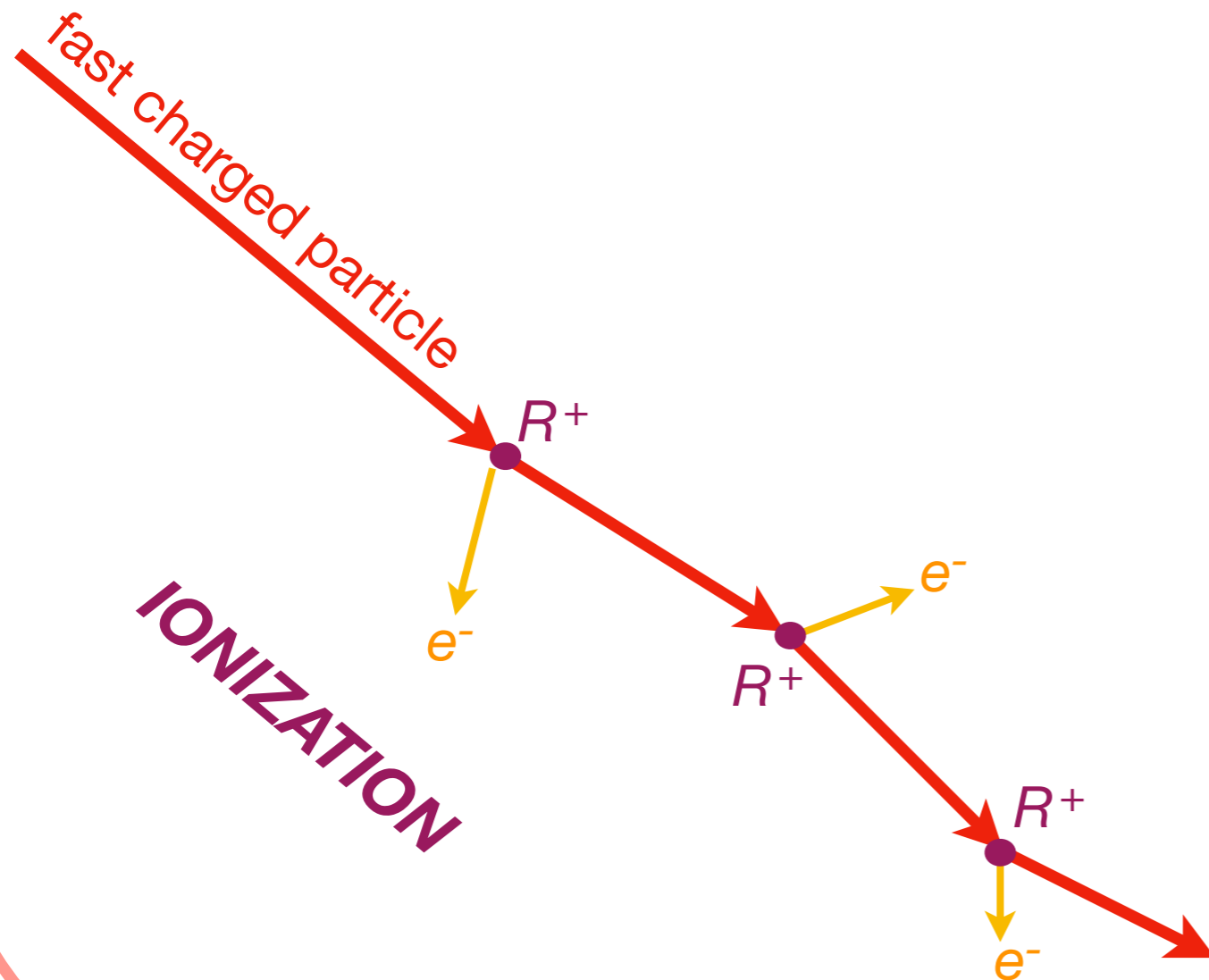
(if $T_{1/2}$ is measured in *seconds*)

Note: the *activity is higher* if the *lifetime is shorter*. (But not for long!)

*What does Radiation **DO** to us?*

What does Radiation **DO** to us?

CELL NUCLEUS

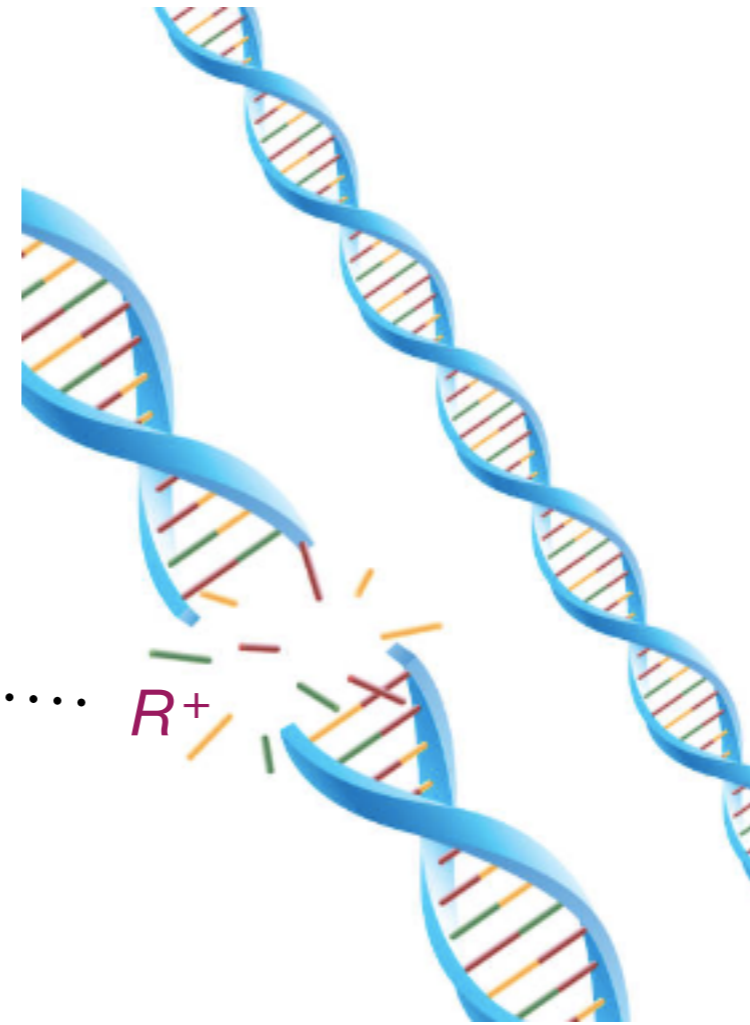
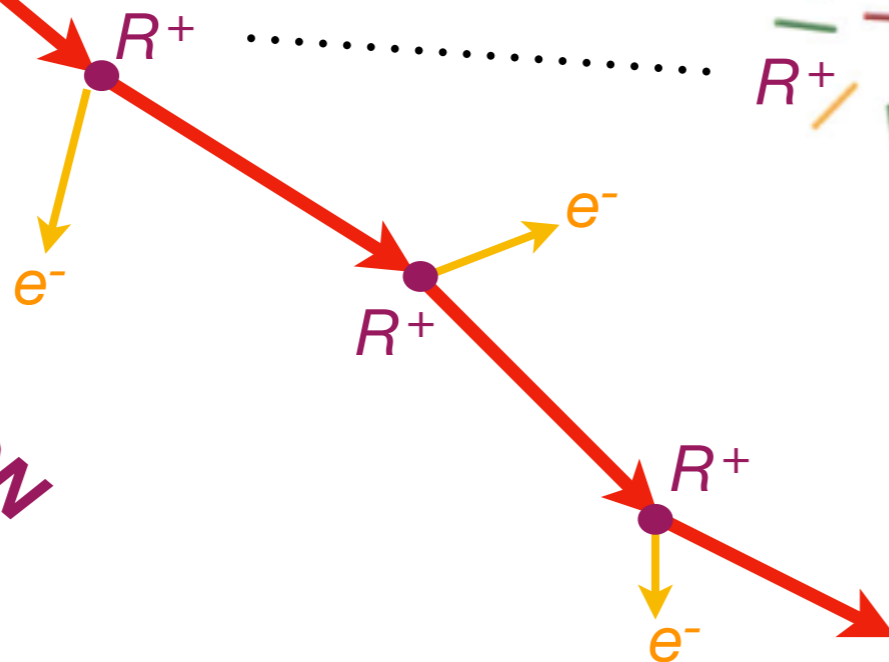


What does Radiation *DO* to us?

CELL NUCLEUS

fast charged particle

IONIZATION



**DNA Double
Strand Break
(DSB)**

What does Radiation *DO* to us?

CELL NUCLEUS

fast charged particle

R^+

e^-

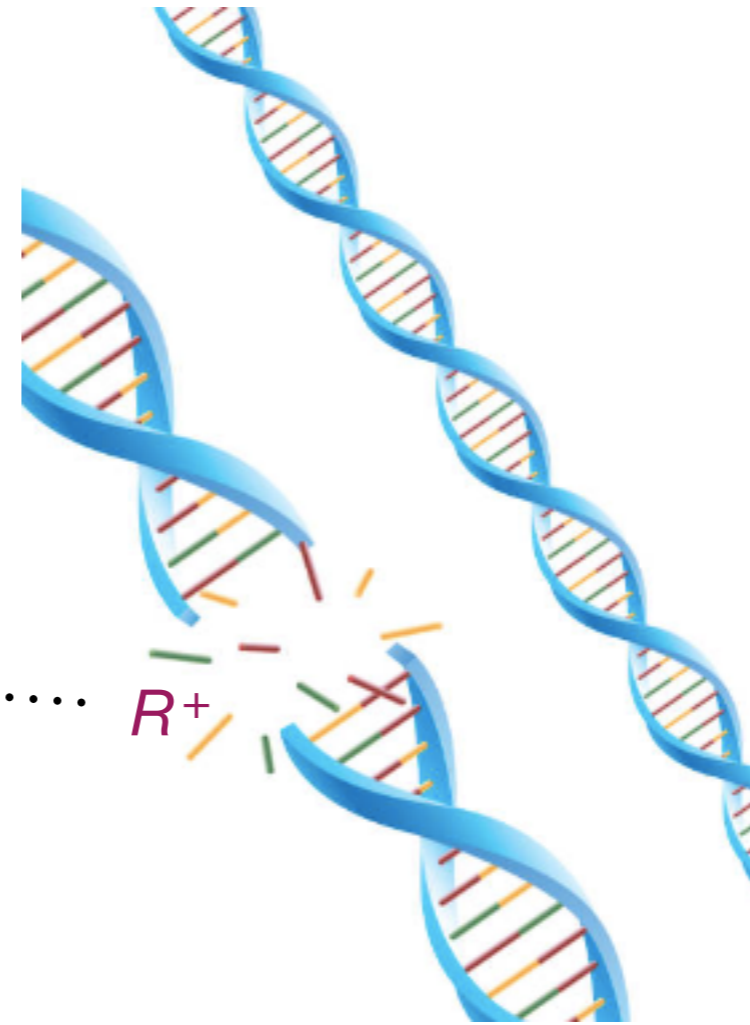
R^+

e^-

R^+

e^-

R^+



Usual
healing time:
hours to days

**DNA Double
Strand Break
(DSB)**

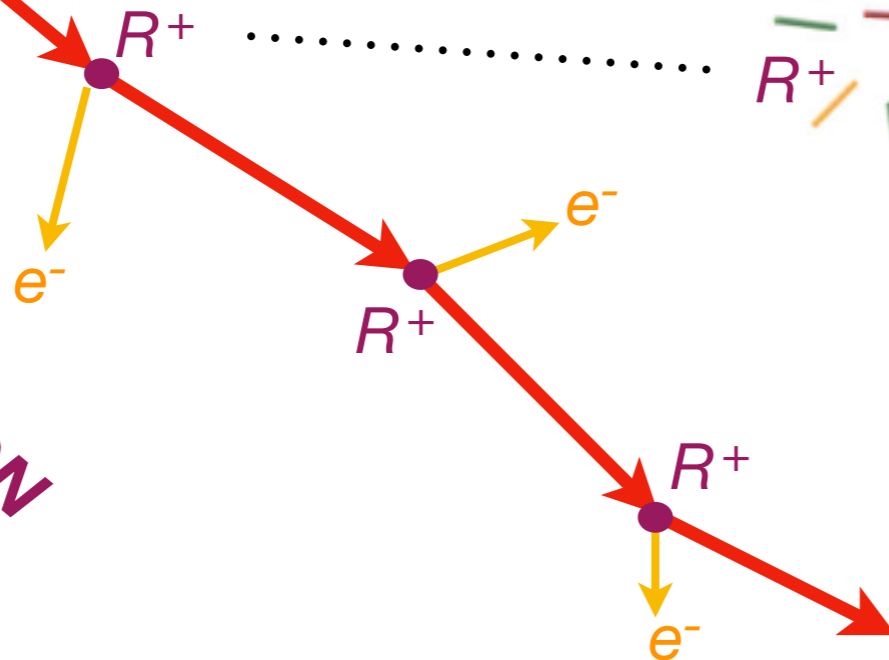
IONIZATION

What does Radiation *DO* to us?

CELL NUCLEUS

fast charged particle

IONIZATION



Daily Inventory for 1 cell:

Natural Background Radiation: 0.00005
Radiation Worker (Max.): 0.00137
Normal Cell Metabolism: 45

Usual
healing time:
hours to days

**DNA Double
Strand Break
(DSB)**

***Ionizing Radiation →
DNA Strand Breaks***

Ionizing Radiation → DNA Strand Breaks

Single strand breaks (SSBs) usually *heal* in *milliseconds*.

NIH: SSBs occur *naturally* more than 10,000 times a day in any single mammalian cell.

Ionizing Radiation → DNA Strand Breaks

Single strand breaks (SSBs) usually *heal* in *milliseconds*.

NIH: SSBs occur *naturally* more than 10,000 times a day in any single mammalian cell.

Double strand breaks (DSBs) can take longer to heal, and may even be *permanent*, causing...

Ionizing Radiation → DNA Strand Breaks

Single strand breaks (SSBs) usually *heal* in *milliseconds*.

NIH: SSBs occur *naturally* more than 10,000 times a day in any single mammalian cell.

Double strand breaks (DSBs) can take longer to heal, and may even be *permanent*, causing...

- **Cell Reproductive Death** [most common]

Cells usually survive for their natural lifetimes — a few days for hair follicles, skin and mucous membrane cells; “forever” for brain cells and some muscle cells.

Ionizing Radiation → DNA Strand Breaks

Single strand breaks (SSBs) usually *heal* in *milliseconds*.

NIH: SSBs occur *naturally* more than 10,000 times a day in any single mammalian cell.

Double strand breaks (DSBs) can take longer to heal, and may even be *permanent*, causing...

- **Cell Reproductive Death** [most common]

Cells usually survive for their natural lifetimes — a few days for hair follicles, skin and mucous membrane cells; “forever” for brain cells and some muscle cells.

- **Genetic Mutation** [most subtle]

Damaged *gamete* cells → *mutations* (usually fatal to foetus; almost always detrimental to the individual offspring...)

*****Ionizing Radiation → DNA Strand Breaks*****

Single strand breaks (SSBs) usually *heal* in *milliseconds*.

NIH: SSBs occur *naturally* more than 10,000 times a day in any single mammalian cell.

Double strand breaks (DSBs) can take longer to heal, and may even be *permanent*, causing...

- **Cell Reproductive Death** [most common]

Cells usually survive for their natural lifetimes — a few days for hair follicles, skin and mucous membrane cells; “forever” for brain cells and some muscle cells.

- **Genetic Mutation** [most subtle]

Damaged *gamete* cells → *mutations* (usually fatal to foetus; almost always detrimental to the individual offspring...)

- **Cancer** [most unpleasant]

Runaway replicative zeal of a misguided cell...

DOSE units

1 **rad** \equiv 100 erg/g (energy deposited per unit mass)

1 **gray (Gy)** \equiv 100 **rad** \equiv 1 J/kg. (standard international unit)

DOSE units

1 **rad** \equiv 100 erg/g (energy deposited per unit mass)

1 **gray (Gy)** \equiv 100 **rad** \equiv 1 J/kg. (standard international unit)

Relative *Biological Effectiveness* (***RBE***) “fudge factor”:

- X-rays, γ -rays & β -rays (fast electrons): $RBE = 1$ (by definition)
- Slow neutrons: average $RBE \approx 3$. (Variable!)
- Fast neutrons, protons & α -rays: $RBE = 10$.
- Fast heavy ions: $RBE = 20$.

DOSE units

1 **rad** \equiv 100 erg/g (energy deposited per unit mass)

1 **gray (Gy)** \equiv 100 **rad** \equiv 1 J/kg. (standard international unit)

Relative *Biological Effectiveness* (**RBE**) “fudge factor”:

- X-rays, γ -rays & β -rays (fast electrons): $RBE = 1$ (by definition)
- Slow neutrons: average $RBE \approx 3$. (Variable!)
- Fast neutrons, protons & α -rays: $RBE = 10$.
- Fast heavy ions: $RBE = 20$.

REM (R, *Roentgen Equivalent to Man*):

$$1 \text{ R} \equiv RBE \times \text{rad}.$$

$$(1 \text{ mR} \equiv \text{milliREM} \equiv 10^{-3} \text{ R.})$$

sievert (standard international unit):

$$1 \text{ sievert (Sv)} \equiv RBE \times \text{gray} = 100 \text{ REM}$$

Problems with DOSE UNITS:

Problems with DOSE UNITS:

No mention of *over what time* the dose is *delivered*.

∴ Implicitly *assumed* that DNA damage is *accumulative*.

Safety standards usually limit mSv *per year*.

But normal cell oxygen metabolism also causes DNA DSB...

...and most DNA DSB *heal* within *hours*.

Meanwhile, a healthy *immune* system is constantly eliminating lone cancer cells.

Still, the rare *permanent* DSB may occur, and under constant irradiation the number of such defects *does* accumulate.

Maximum Permissible *Occupational* Doses

USA & Canada

Maximum Permissible *Occupational* Doses

USA & Canada

- Non-Radiation Worker: **1 mSv/year** vs. **1 mSv/year**
- Radiation Workers: **50 mSv/year** vs. **50 mSv/year**

Maximum Permissible *Occupational* Doses

USA & Canada

- Non-Radiation Worker: **1 mSv/year** vs. **1 mSv/year**
- Radiation Workers: **50 mSv/year** vs. **50 mSv/year**
- Natural Background (at sea level): **1.8 mSv/year**
- Cosmic Ray Muons *alone*: **0.3 mSv/year** (at sea level)

Maximum Permissible *Occupational* Doses

USA & Canada

- Non-Radiation Worker: **1 mSv/year** vs. **1 mSv/year**
- Radiation Workers: **50 mSv/year** vs. **50 mSv/year**
- Natural Background (at sea level): **1.8 mSv/year**
- Cosmic Ray Muons *alone*: **0.3 mSv/year** (at sea level)
- Kerala Coast, India: **3.3 to 60 mSv/year**
- Guarapari beach, Brazil: **175 to 482 mSv/year**
- Ramsar region, Iran: up to **260 mSv/year**

Maximum Permissible *Occupational* Doses

USA & Canada

- Non-Radiation Worker: **1 mSv/year** vs. **1 mSv/year**
- Radiation Workers: **50 mSv/year** vs. **50 mSv/year**
- Natural Background (at sea level): **1.8 mSv/year**
- Cosmic Ray Muons *alone*: **0.3 mSv/year** (at sea level)
- Kerala Coast, India: **3.3 to 60 mSv/year**
- Guarapari beach, Brazil: **175 to 482 mSv/year**
- Ramsar region, Iran: up to **260 mSv/year**
- Abdominal/Pelvic CT scan: **20-30 mSv** (*all at once*)

Maximum Permissible Occupational Doses

USA & Canada converted to $\mu\text{Sv per day}$

Maximum Permissible Occupational Doses

USA & Canada converted to $\mu\text{Sv per day}$

- Non-Radiation Worker: **3 $\mu\text{Sv/day}$** vs. **3 $\mu\text{Sv/day}$**
- Radiation Workers: **137 $\mu\text{Sv/day}$** vs. **137 $\mu\text{Sv/day}$**

Maximum Permissible Occupational Doses

USA & Canada converted to $\mu\text{Sv per day}$

- Non-Radiation Worker: **3 $\mu\text{Sv/day}$** vs. **3 $\mu\text{Sv/day}$**
- Radiation Workers: **137 $\mu\text{Sv/day}$** vs. **137 $\mu\text{Sv/day}$**
- Natural Background (at sea level): **5 $\mu\text{Sv/day}$**
- Cosmic Ray Muons *alone*: **1 $\mu\text{Sv/day}$** (at sea level)

Maximum Permissible Occupational Doses

USA & Canada converted to $\mu\text{Sv per day}$

- Non-Radiation Worker: **3 $\mu\text{Sv/day}$** vs. **3 $\mu\text{Sv/day}$**
- Radiation Workers: **137 $\mu\text{Sv/day}$** vs. **137 $\mu\text{Sv/day}$**
- Natural Background (at sea level): **5 $\mu\text{Sv/day}$**
- Cosmic Ray Muons *alone*: **1 $\mu\text{Sv/day}$** (at sea level)
- Kerala Coast, India: **9 to 164 $\mu\text{Sv/day}$**
- Guarapari beach, Brazil: **480 to 1320 $\mu\text{Sv/day}$**
- Ramsar region, Iran: up to **712 $\mu\text{Sv/day}$**

Maximum Permissible Occupational Doses

USA & Canada converted to $\mu\text{Sv per day}$

- Non-Radiation Worker: **3 $\mu\text{Sv/day}$** vs. **3 $\mu\text{Sv/day}$**
- Radiation Workers: **137 $\mu\text{Sv/day}$** vs. **137 $\mu\text{Sv/day}$**
- Natural Background (at sea level): **5 $\mu\text{Sv/day}$**
- Cosmic Ray Muons *alone*: **1 $\mu\text{Sv/day}$** (at sea level)
- Kerala Coast, India: **9 to 164 $\mu\text{Sv/day}$**
- Guarapari beach, Brazil: **480 to 1320 $\mu\text{Sv/day}$**
- Ramsar region, Iran: up to **712 $\mu\text{Sv/day}$**
- Abdominal/Pelvic CT scan: **20,000-30,000 μSv** (*all at once*)

EFFECTS of Penetrating Radiation

EFFECTS of Penetrating Radiation

- **Instant Death:** ~ **50** Sieverts [Sv] “*whole-body*” can wipe out the central nervous system (CNS) *when delivered all at once*.

EFFECTS of Penetrating Radiation

- **Instant Death:** ~ **50** Sieverts [Sv] “*whole-body*” can wipe out the central nervous system (CNS) *when delivered all at once*.
- **Overnight Death:** ~ **9** Sv whole-body may accomplish the same thing in about a day.

EFFECTS of Penetrating Radiation

- **Instant Death:** ~ **50** Sieverts [Sv] “*whole-body*” can wipe out the central nervous system (CNS) *when delivered all at once*.
- **Overnight Death:** ~ **9** Sv whole-body may accomplish the same thing in about a day.
- **Ugly Death:** ~ **5** Sv → severe *radiation sickness* (nausea, hair loss, skin lesions, *etc.*) as short-lived cells fail to provide new generations to replace their normal mortality. Complications (infection) usually kill. Some recover completely but may develop leukemia years later; offspring (if any) may have genetic mutations.

EFFECTS of Penetrating Radiation

- **Instant Death:** ~ **50** Sieverts [Sv] “*whole-body*” can wipe out the central nervous system (CNS) *when delivered all at once*.
- **Overnight Death:** ~ **9** Sv whole-body may accomplish the same thing in about a day.
- **Ugly Death:** ~ **5** Sv → severe *radiation sickness* (nausea, hair loss, skin lesions, *etc.*) as short-lived cells fail to provide new generations to replace their normal mortality. Complications (infection) usually kill. Some recover completely but may develop leukemia years later; offspring (if any) may have genetic mutations.
- **Sub-Acute Exposures:** ~ **1** Sv whole-body delivered all at once → no immediate symptoms, but possible leukemia (rarely, years later).

Why there is so much disagreement

Why there is so much disagreement

It is hard to calculate how much harm is done by a given amount of radioactivity. We can fairly easily calculate the **activity** of a certain amount of a given radioisotope, and then we can fairly easily find how much *energy* its ionizing radiation deposits *per kg* of flesh; but the same energy deposited by one type of particles can be an order of magnitude worse for you than the same amount of energy deposited by another type of particles; and it makes a *huge* difference whether that energy is deposited *all at once* or spread out over time, because *the damage heals*. Moreover, many of these “fudge factors” are based on empirical observations that are not rigorously quantitative.

As a result, it's very tempting to make qualitative **comparisons**, especially with “natural background radiation”. But even then we have disagreements on how a *low* dose should be compared with a *high* dose....

Radiation Dose Chart

This is a chart of the ionizing radiation dose a person can absorb from various sources. The unit for absorbed dose is "sievert" (Sv), and measures the effect a dose of radiation will have on the cells of the body. One sievert (all at once) will make you sick, and too many more will kill you, but we safely absorb small amounts of natural radiation daily. Note: The same number of sieverts absorbed in a shorter time will generally cause more damage, but your cumulative long-term dose plays a big role in things like cancer risk.

■ Sleeping next to someone (0.05 μSv)

■ Living within 50 miles of a nuclear power plant for a year (0.09 μSv)

■ Eating one banana (0.1 μSv)

■ Living within 50 miles of a coal power plant for a year (0.3 μSv)

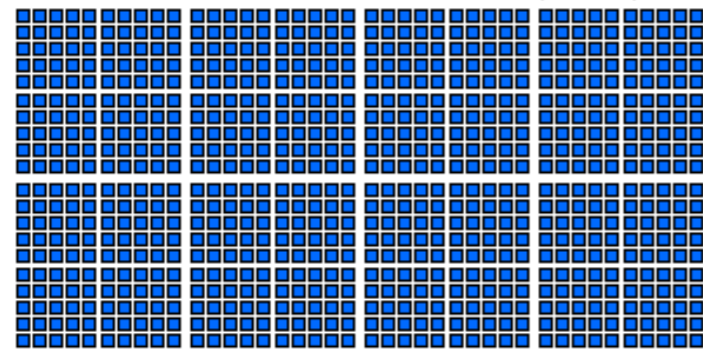
■ Arm x-ray (1 μSv) ■ Using a CRT monitor for a year (1 μSv)

■ Extra dose from spending one day in an area with higher-than-average natural background radiation, such as the Colorado plateau (1.2 μSv)

■ Dental x-ray (5 μSv)

■ Background dose received by an average person over one normal day (10 μSv)

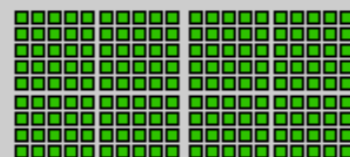
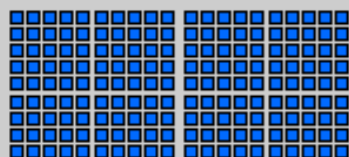
■ Airplane flight from New York to LA (40 μSv)



■ Using a cell phone (0 μSv)—a cell phone's transmitter does not produce ionizing radiation* and does not cause cancer.

* Unless it's a banana-ophone.

■ ■ (0.05 μSv)



■ Chest x-ray (20 μSv)

■ All the doses in the blue chart combined (~60 μSv)

■ Extra dose to Tokyo in weeks following Fukushima accident (40 μSv)

■ Living in a stone, brick, or concrete building for a year (70 μSv)

■ Average total dose from the Three Mile Island accident to someone living within 10 miles (80 μSv)

■ Approximate total dose received at Fukushima Town Hall over two weeks following accident (100 μSv)

■ EPA yearly release limit for a nuclear power plant (250 μSv)

■ Yearly dose from natural potassium in the body (390 μSv)

■ Mammogram (400 μSv)

■ EPA yearly limit on radiation exposure to a single member of the public (1 mSv=1,000 μSv)

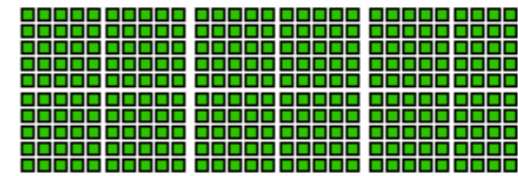
■ Maximum external dose from Three Mile Island accident (1 mSv)

■ Typical dose over two weeks in Fukushima Exclusion Zone (1 mSv, but areas northwest saw far higher doses)

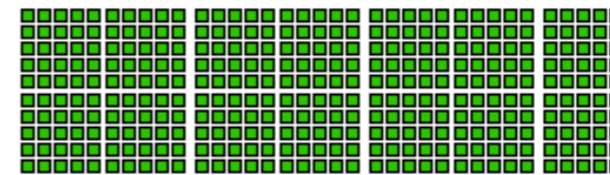
■ Head CT Scan (2 mSv)

■ Normal yearly background dose. About 85% is from natural sources. Nearly all of the rest is from medical scans (~4 mSv)

■ EPA yearly release target for a nuclear power plant (30 μSv)

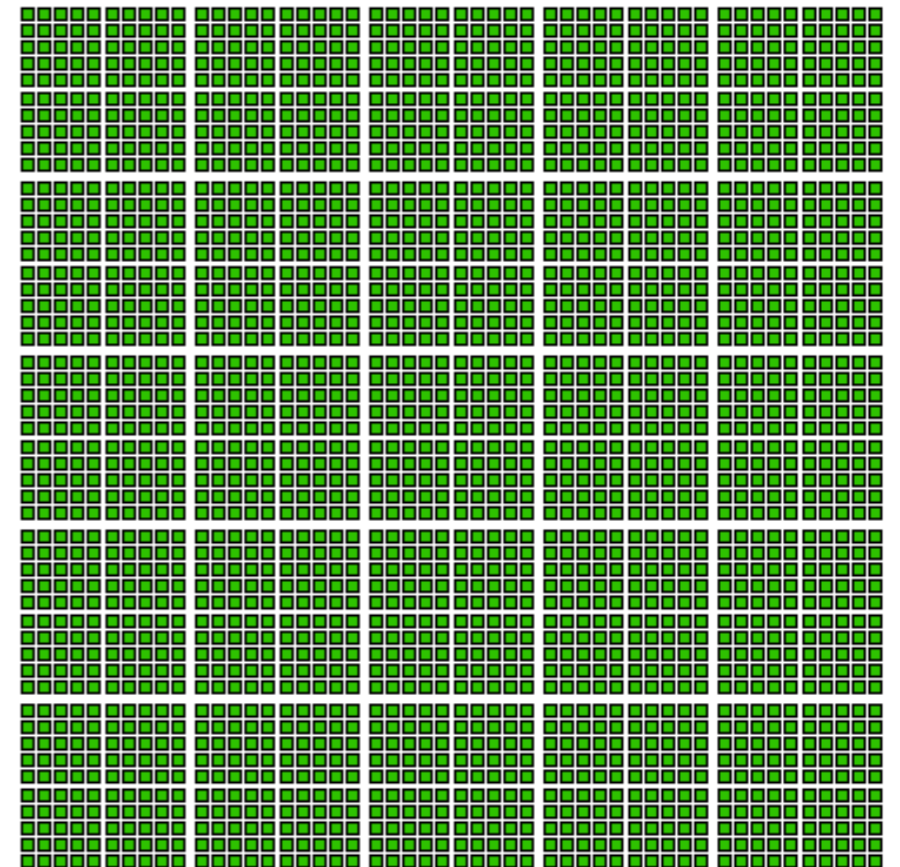


Dose from spending an hour on the grounds at the Chernobyl plant in 2010 (6 mSv in one spot, but varies wildly)



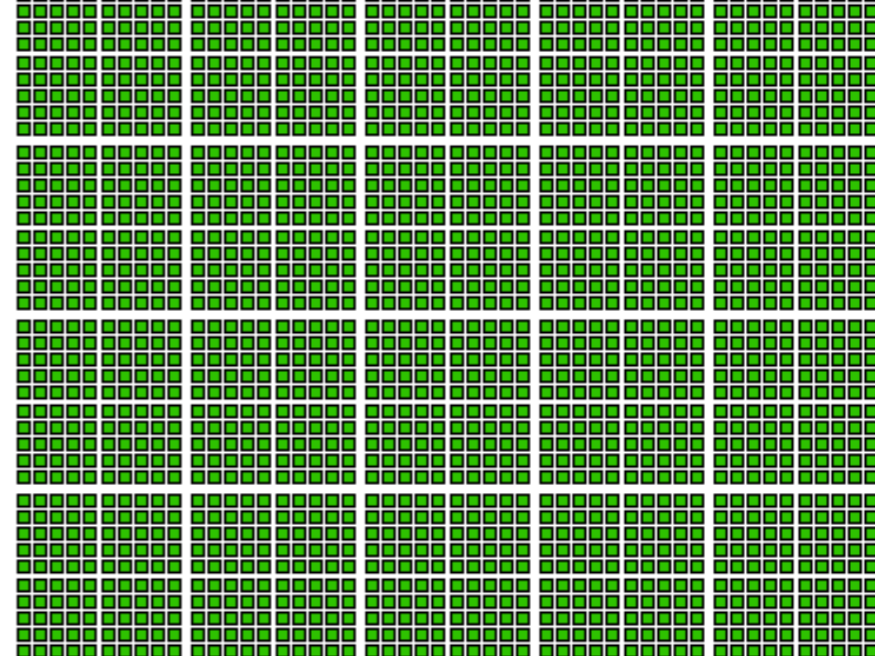
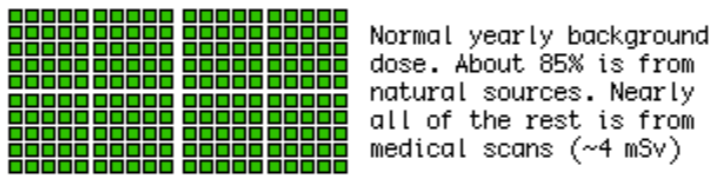
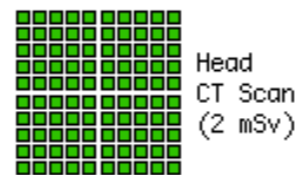
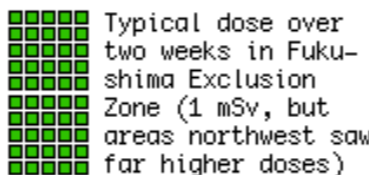
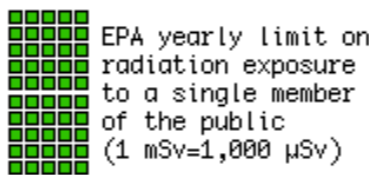
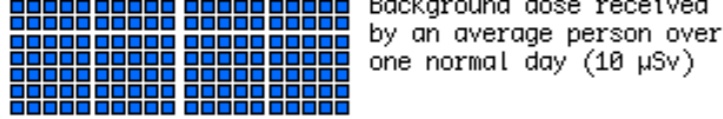
Chest CT scan (7 mSv)

Maximum yearly dose permitted for US radiation workers (50 mSv)



Radiation worker one-year dose limit (50 mSv)

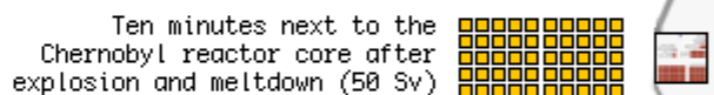
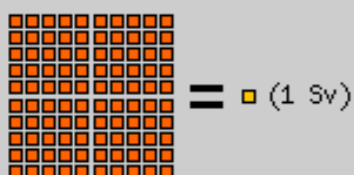
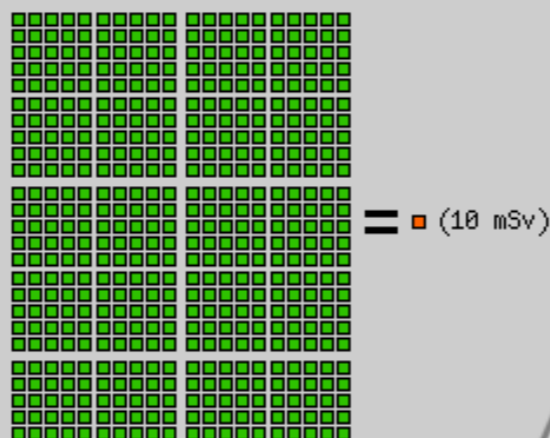
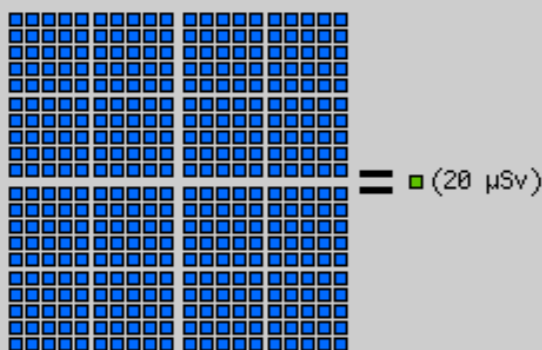




Using a cell phone (0 μ Sv)—a cell phone's transmitter does not produce ionizing radiation* and does not cause cancer.

* Unless it's a bananaphone.

■ = (0.05 μ Sv)



Sources:

- <http://www.nrc.gov/reading-rm/doc-collections/cfr/part020/>
- www.nema.ne.gov/technological/dose-limits.html
- http://www.deq.idaho.gov/inl_oversight/radiation/dose_calculator.cfm
- http://www.deq.idaho.gov/inl_oversight/radiation/radiation_guide.cfm
- <http://mitnse.com/>
- http://www.bnl.gov/bnlweb/PDF/03SER/Chapter_8.pdf
- http://dels-old.nas.edu/dels/rpt_briefs/rerf_final.pdf
- <http://people.reed.edu/~emcmanis/radiation.html>
- <http://en.wikipedia.org/wiki/Sievert>
- <http://blog.vornaskotti.com/2010/07/15/into-the-zone-chernobyl-pripyat/>
- <http://www.nrc.gov/reading-rm/doc-collections/fzact-sheets/tritium-radiation-fs.html>
- http://www.mext.go.jp/component/a_menu/other/detail/_icsFiles/afieldfile/2011/03/18/1303727_1716.pdf
- <http://radiology.rsna.org/content/248/1/254>

Approximate total dose at one station at the north-west edge of the Fukushima exclusion zone (40 mSv)



All doses in green chart combined (~75 mSv)

Radiation worker one-year dose limit (50 mSv)

Lowest one-year dose clearly linked to increased cancer risk (100 mSv)

Dose received by two Fukushima plant workers (~180 mSv)



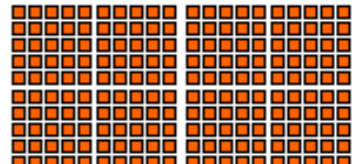
Dose causing symptoms of radiation poisoning if received in a short time (400 mSv, but varies)

EPA guidelines for emergency situations, provided to ensure quick decision-making:

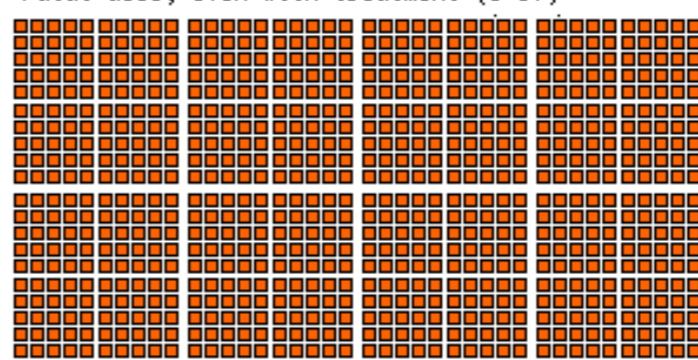
Dose limit for emergency workers protecting valuable property (100 mSv)

Dose limit for emergency workers in lifesaving operations (250 mSv)

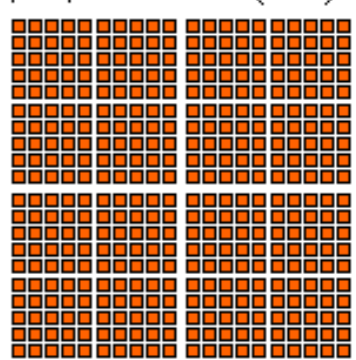
Severe radiation poisoning, in some cases fatal (2000 mSv, 2 Sv)



Fatal dose, even with treatment (8 Sv)



Usually fatal radiation poisoning. Survival occasionally possible with prompt treatment (4 Sv)



Thresholds and Linearity

Thresholds and Linearity

We have data on the survivors of *Hiroshima* and *Nagasaki*. We also have data on the people exposed to high radiation levels at *Chernobyl*. We know roughly how much their probability of (e.g.) thyroid cancer was heightened over time by exposure to Iodine-131, and we know how many suffered immediate effects of “radiation sickness”. What we *don't* know so well is how people are affected by much *lower* levels of radiation exposure. One reason for this is that we don't have a “**control group**” of people who are not exposed to *any* radiation. There are no such people! Your *bones* are radioactive.

Thresholds and Linearity

We have data on the survivors of *Hiroshima* and *Nagasaki*. We also have data on the people exposed to high radiation levels at *Chernobyl*. We know roughly how much their probability of (e.g.) thyroid cancer was heightened over time by exposure to Iodine-131, and we know how many suffered immediate effects of “radiation sickness”. What we *don't* know so well is how people are affected by much *lower* levels of radiation exposure. One reason for this is that we don't have a “**control group**” of people who are not exposed to *any* radiation. There are no such people! Your *bones* are radioactive.

One model is “**LNT**” — a simple *Linear* model with **No Threshold**: that is, we assume there is no such thing as a “harmless” amount of radiation, that radiation damage *never heals*, and that the probability of harm is *proportional* to the radiation dose. This model has the sole advantage of simplicity. And yet it is the *basis for all regulations*.

Thresholds and Linearity

We have data on the survivors of *Hiroshima* and *Nagasaki*. We also have data on the people exposed to high radiation levels at *Chernobyl*. We know roughly how much their probability of (e.g.) thyroid cancer was heightened over time by exposure to Iodine-131, and we know how many suffered immediate effects of “radiation sickness”. What we *don't* know so well is how people are affected by much *lower* levels of radiation exposure. One reason for this is that we don't have a “**control group**” of people who are not exposed to *any* radiation. There are no such people! Your *bones* are radioactive.

One model is “**LNT**” — a simple *Linear* model with **No Threshold**: that is, we assume there is no such thing as a “harmless” amount of radiation, that radiation damage *never heals*, and that the probability of harm is *proportional* to the radiation dose. This model has the sole advantage of simplicity. And yet it is the *basis for all regulations*.

The “**Threshold**” model assumes that the “normal background” radiation level is *harmless*, and may even be *beneficial* up to a point (“**hormesis**”). There is plentiful evidence for the latter.

Maximum Permissible Occupational Doses

USA & Canada converted to $\mu\text{Sv per day}$

- Non-Radiation Worker: **3 $\mu\text{Sv/day}$** vs. **3 $\mu\text{Sv/day}$**
- Radiation Workers: **137 $\mu\text{Sv/day}$** vs. **137 $\mu\text{Sv/day}$**
- Natural Background (at sea level): **5 $\mu\text{Sv/day}$**
- Cosmic Ray Muons *alone*: **1 $\mu\text{Sv/day}$** (at sea level)
- Kerala Coast, India: **9 to 164 $\mu\text{Sv/day}$**
- Guarapari beach, Brazil: **480 to 1320 $\mu\text{Sv/day}$**
- Ramsar region, Iran: up to **712 $\mu\text{Sv/day}$**
- Abdominal/Pelvic CT scan: **20,000-30,000 μSv** (*all at once*)

Maximum Permissible Occupational Doses

USA & Canada converted to μSv per day

- Non-Radiation Worker: **3 $\mu\text{Sv}/\text{day}$** vs. **3 $\mu\text{Sv}/\text{day}$**
- Radiation Workers: **137 $\mu\text{Sv}/\text{day}$** vs. **137 $\mu\text{Sv}/\text{day}$**
- Natural Background (at sea level): **5 $\mu\text{Sv}/\text{day}$**
- Cosmic Ray Muons *alone*: **1 $\mu\text{Sv}/\text{day}$** (at sea level)

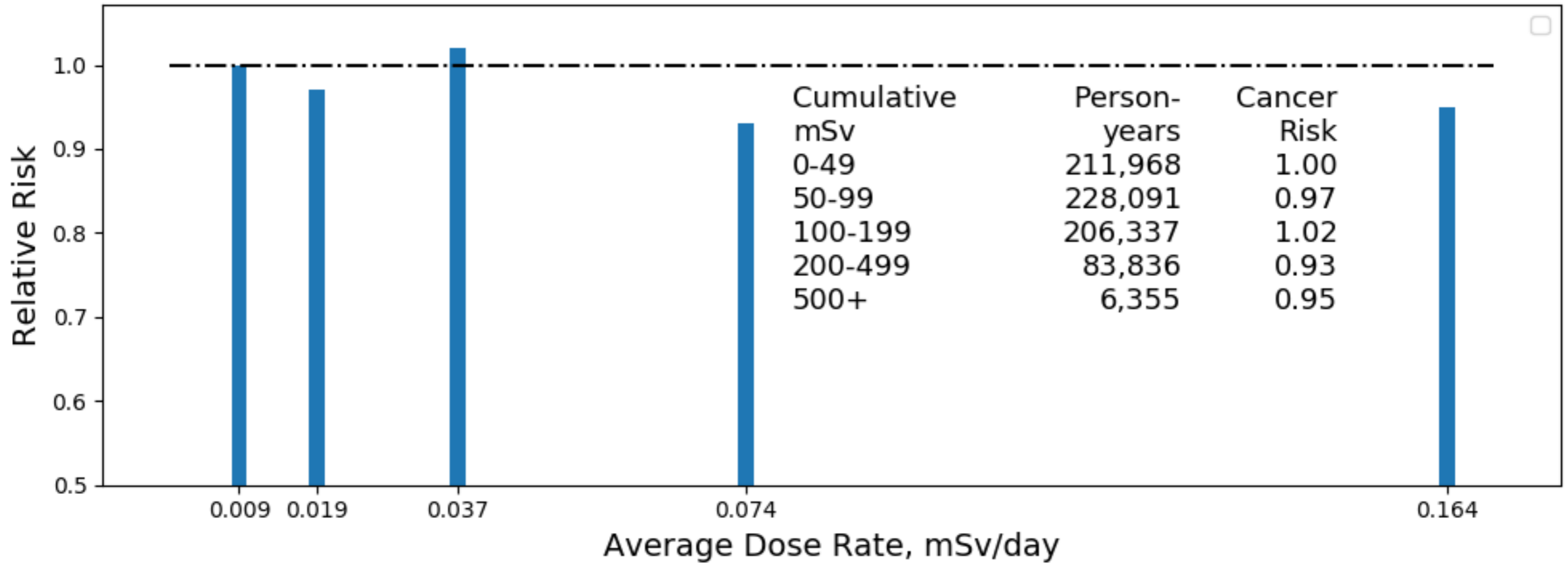
- Kerala Coast, India: **9 to 164 $\mu\text{Sv}/\text{day}$**
- Guarapari beach, Brazil: **480 to 1320 $\mu\text{Sv}/\text{day}$**
- Ramsar region, Iran: up to **712 $\mu\text{Sv}/\text{day}$**

**LOWER
than
average
incidence
of cancer**

- Abdominal/Pelvic CT scan: **20,000-30,000 μSv** (*all at once*)

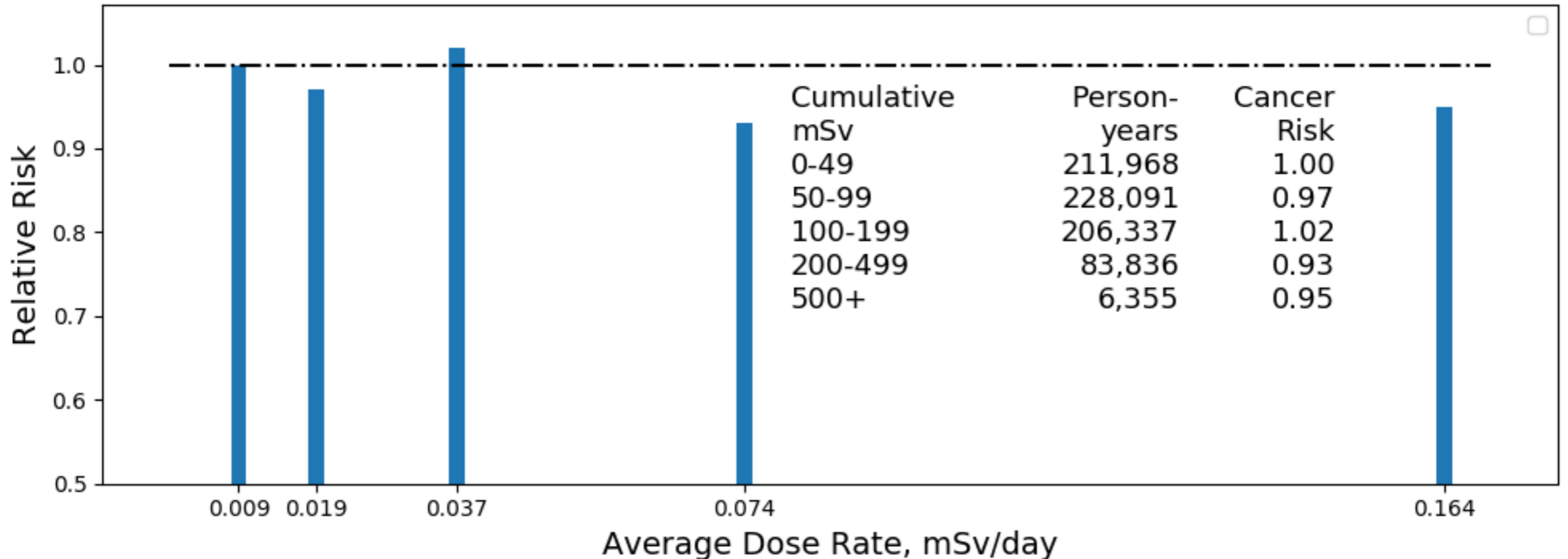
Kerala data

Kerala 1990-2005 All Solid Cancer, Ave 10.5 years.



Kerala data

Kerala 1990-2005 All Solid Cancer, Ave 10.5 years.



The Kerala coast is one of the ***wealthiest*** regions of India.

Health is strongly influenced by **wealth**.

But *wealth* is **not** correlated with *radiation dose*.