

**MEASURING**  
**RADIATION**  
and its  
**EFFECTS**

# ***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*)

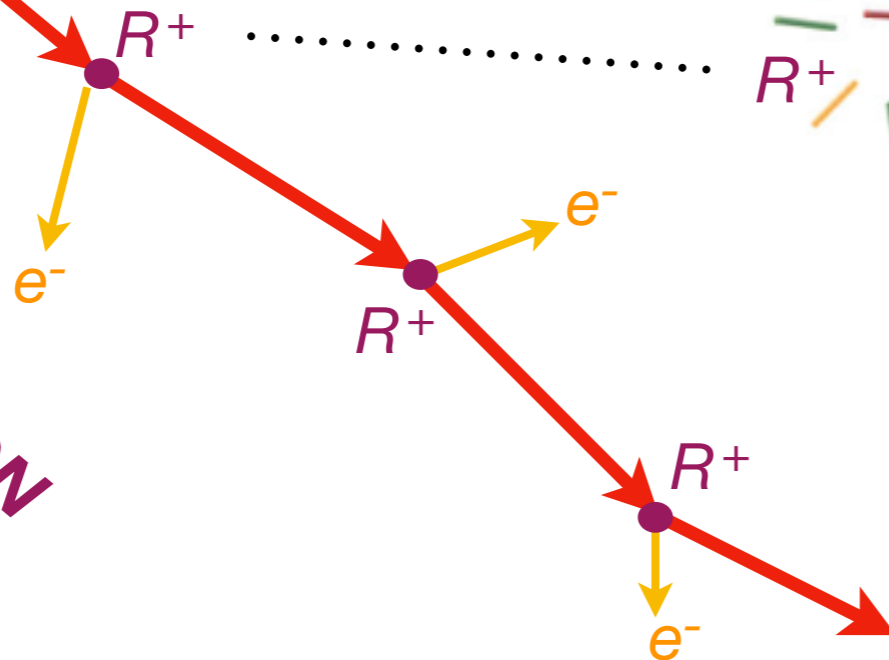
**Note:** the *activity is higher* if the *lifetime is shorter*. (But not for long!)

# What does Radiation *DO* to us?

## 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*****

**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)

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

- X-rays,  $\gamma$ -rays &  $\beta$ -rays (fast electrons):  $RBE = 1$  (by definition)
- Slow neutrons: average  $RBE \approx 3$ . (Variable!)
- Fast neutrons, protons &  $\alpha$ -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:*

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

- 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 $\mu\text{Sv per day}$

- 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  $\mu\text{Sv}$**  (*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.
- **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***

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)

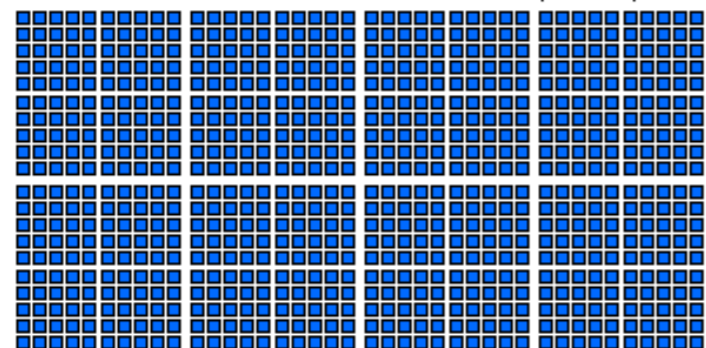
■ Arm x-ray (1 μSv)      ■ Using a CRT monitor for a year (1 μSv)

■ 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)

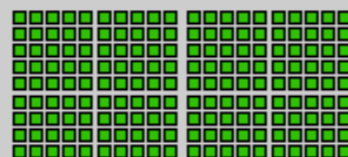
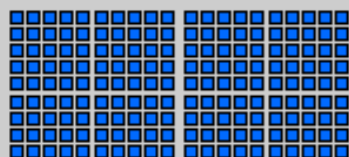
■ Airplane flight from New York to LA (40 μSv)



■ 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)

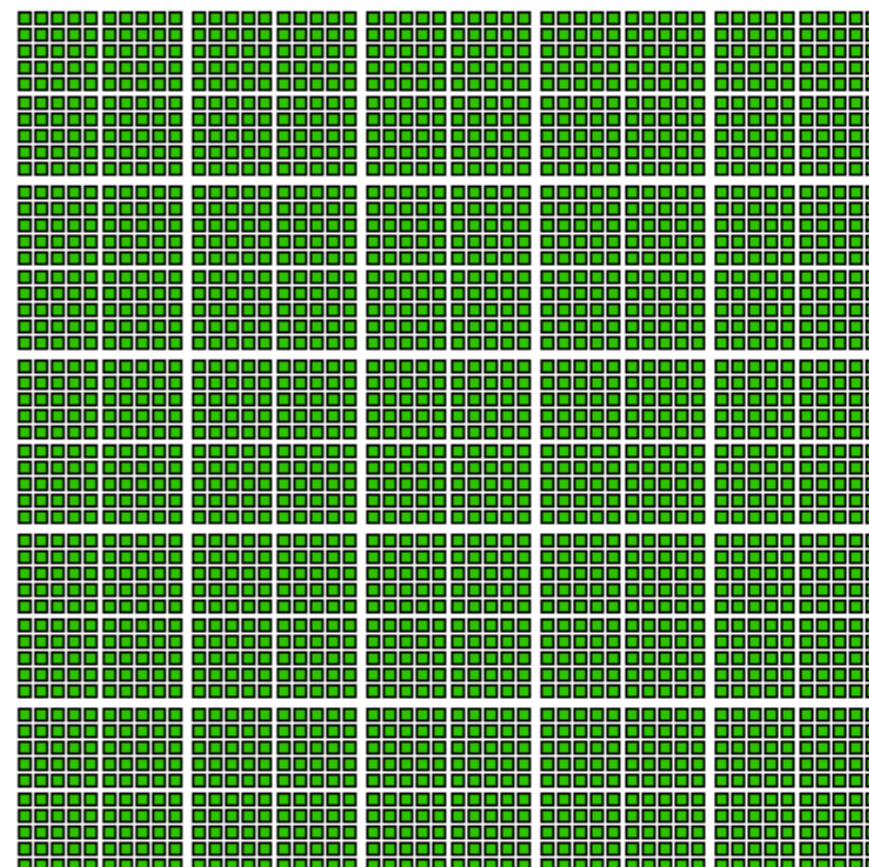
■ Normal yearly background dose. About 85% is from natural sources. Nearly all of the rest is from medical scans (~4 mSv)

■ 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)

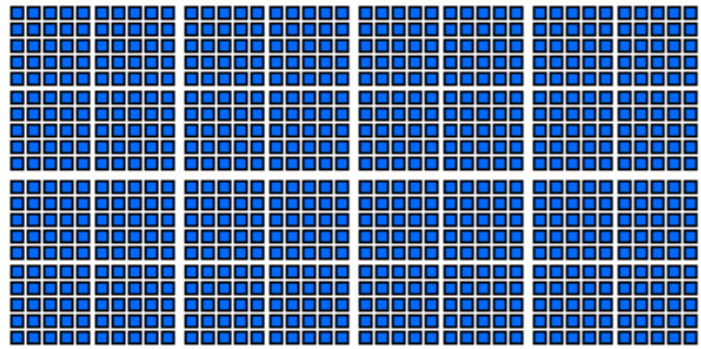


■ Radiation worker one-year dose limit (50 mSv)



Background dose received by an average person over one normal day (10  $\mu$ Sv)

Airplane flight from New York to LA (40  $\mu$ Sv)



EPA yearly limit on radiation exposure to a single member of the public (1 mSv=1,000  $\mu$ Sv)

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)

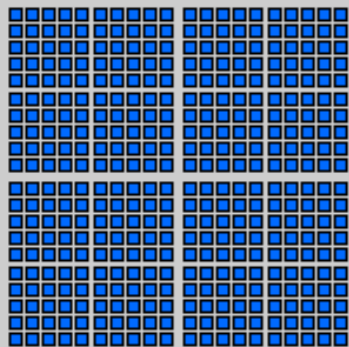
Head CT Scan (2 mSv)

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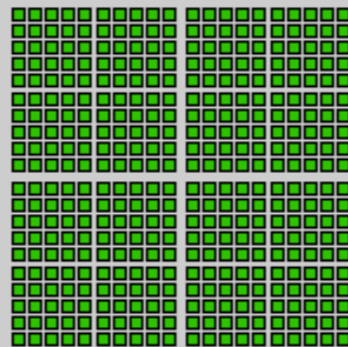
Using a cell phone (0  $\mu$ Sv)—a cell phone's transmitter does not produce ionizing radiation\* and does not cause cancer.

\* Unless it's a bananaphone.

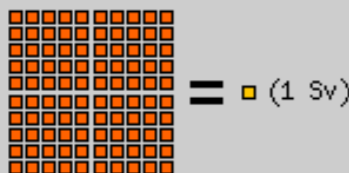
■ = (0.05  $\mu$ Sv)



■ = (20  $\mu$ Sv)



■ = (10 mSv)



■ = (1 Sv)

Ten minutes next to the Chernobyl reactor core after explosion and meltdown (50 Sv)



Sources:

- <http://www.nrc.gov/reading-rm/doc-collections/cfr/part020/>
- [www.nema.ne.gov/technological/dose-limits.html](http://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/dose_calculator.cfm)
- [http://www.deq.idaho.gov/inl\\_oversight/radiation/radiation\\_guide.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://www.bnl.gov/bnlweb/PDF/03SER/Chapter_8.pdf)
- [http://dels-old.nas.edu/dels/rpt\\_briefs/rerf\\_final.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://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)

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

Fatal dose, even with treatment (8 Sv)

Chart by Randall Munroe, with help from Ellen, Senior Reactor Operator at the Reed Research Reactor, who suggested the idea and provided a lot of the sources. I'm sure I've added in lots of mistakes; it's for general education only. If you're basing radiation safety procedures on an internet PNG image and things go wrong, you have no one to blame but yourself.

# ***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

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- Cosmic Ray Muons *alone*: **1  $\mu\text{Sv/day}$**  (at sea level)

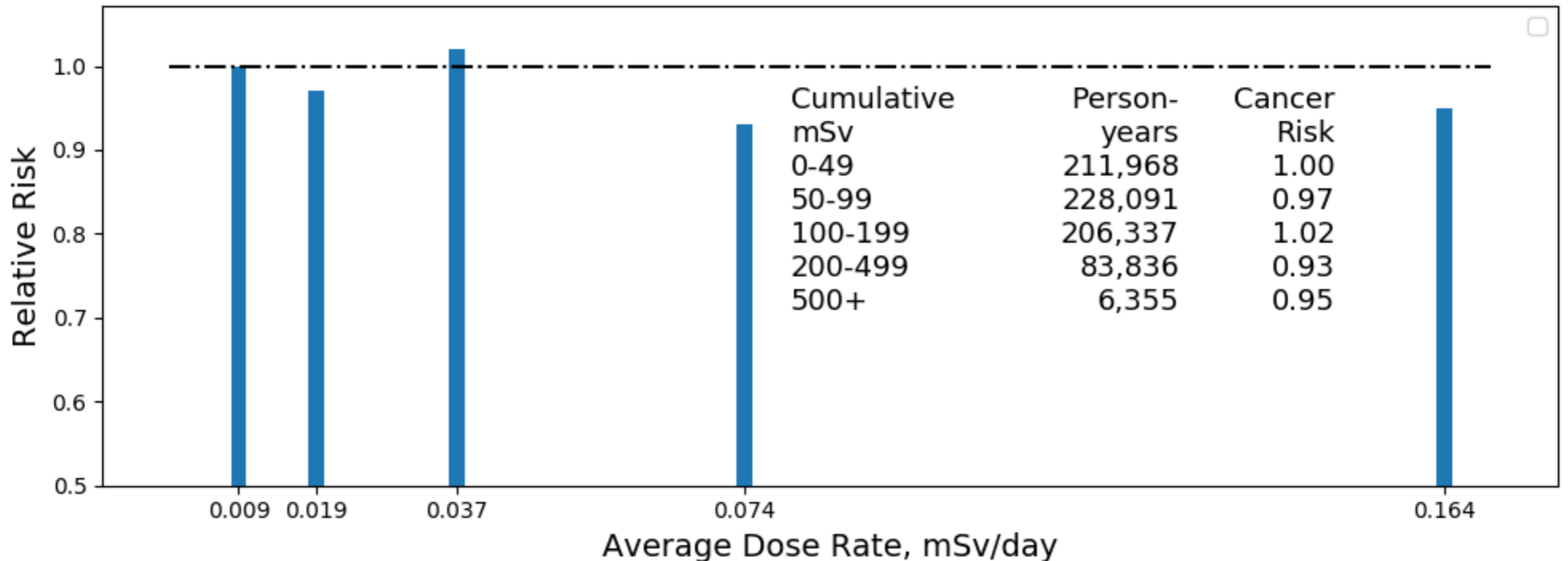
- Kerala Coast, India: **9 to 164  $\mu\text{Sv/day}$**
- Guarapari beach, Brazil: **480 to 1320  $\mu\text{Sv/day}$**
- Ramsar region, Iran: up to **712  $\mu\text{Sv/day}$**

**LOWER  
than  
average  
incidence  
of cancer**

- Abdominal/Pelvic CT scan: **20,000-30,000  $\mu\text{Sv}$**  (*all at once*)

# 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*.