

Nuclear Medicine and Radiation Safety

How are radioisotopes used in medicine, and how is radiation dose measured and kept safe?

●● Intermediate

Nuclear Chemistry

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Before you start: it helps to understand [Radioactive Decay and Half-Life](#).

What is it?

Radiation from radioactive nuclei is **ionizing**: it has enough energy to knock electrons out of atoms and molecules in the body. This can break bonds in DNA directly, or split water into reactive **free radicals** that damage cells. The same property makes radiation **dangerous** and **useful**: it can harm healthy tissue, but it can also be aimed at cancer cells, and the gamma rays that escape the body can be detected to make images.

Three quantities describe radiation and its effects:

Quantity	Unit	Meaning
Activity	becquerel, Bq	1 Bq = 1 decay per second
Absorbed dose	gray, Gy	1 Gy = 1 J of energy absorbed per kg of tissue
Equivalent dose	sievert, Sv	absorbed dose × radiation weighting factor

The **radiation weighting factor** is 1 for gamma rays, X-rays and beta particles, but **20 for alpha particles**, which deposit their energy in a very short track and do much more damage per joule.

KEY IDEA

Medicine uses the **right radiation for the job**. **Imaging** needs gamma rays that escape the body, from an isotope with a short half-life. **Therapy** needs radiation that deposits its energy locally (beta or alpha particles), or a carefully aimed external beam.

Why does it matter?

- **Diagnosis.** Millions of scans a year use technetium-99m to image bones, the heart and other organs, and fluorine-18 PET scans find cancers and study the brain.
- **Treatment.** Iodine-131 treats overactive and cancerous thyroid glands; external gamma and X-ray beams and implanted sources treat many cancers.

- **Safety.** Patients, staff and the public must be protected, so doses are measured, limited and kept as **low as reasonably achievable** (ALARA).

How does it work?

1. Choosing a tracer for imaging

A good imaging isotope:

- emits **gamma rays** (they pass out of the body to the camera; alpha and beta would be absorbed and only cause damage);
- has a **short half-life** (hours), long enough for the scan but short enough to limit the dose;
- can be attached to a molecule that collects in the organ of interest.

Technetium-99m ($t_{1/2} = 6.01$ h, 140 keV gamma rays) fits all three. **Iodine-123** ($t_{1/2} = 13.2$ h) is taken up by the thyroid, which uses iodine.

2. PET scans

In positron emission tomography, a glucose-like molecule labelled with **fluorine-18** ($t_{1/2} = 110$ min) collects in very active tissue such as tumours. Each fluorine-18 nucleus emits a **positron**, which meets an electron within a millimetre or so. The two **annihilate**, and their mass becomes two **511 keV gamma rays** that fly apart in opposite directions. Detectors around the patient record both, and a computer traces back where they came from.

3. Radiotherapy

- **Iodine-131** (beta and gamma emitter, $t_{1/2} = 8.02$ d) concentrates in the thyroid, where its beta particles destroy the tissue.
- **External beams** of high-energy X-rays or gamma rays are aimed at a tumour from several directions, so the tumour gets a high dose while surrounding tissue gets less.
- **Brachytherapy** places small sealed sources inside or next to the tumour. Some newer treatments use **alpha emitters**, such as radium-223 ($t_{1/2} = 11.4$ d) for cancer that has spread to bone.

4. Protection: time, distance, shielding

- **Time:** dose = dose rate $\times$ time, so spend as little time near a source as possible.
- **Distance:** the dose rate from a small source falls with the **square of the distance** (inverse-square law): $\frac{\text{rate}_2}{\text{rate}_1} = \left(\frac{d_1}{d_2}\right)^2$.
- **Shielding:** lead, concrete or water absorbs radiation. Each **half-value thickness** of a shield halves the intensity.

Workers wear **dosimeters** that record their dose, and dose limits are set well below the levels known to cause harm.

Dose (equivalent)	Example
about 2.4 mSv per year	worldwide average natural background (radon, rocks, cosmic rays, food)
1 mSv per year	limit for the public from artificial sources (excluding medical)
20 mSv per year	limit for radiation workers (averaged over 5 years)

∞ THINK OF IT LIKE THIS

Standing near a radioactive source is like standing near a campfire. You warm up less if you stay a shorter time (**time**), step back (**distance**: much cooler two steps away), or stand behind a wall (**shielding**). The fire itself (the activity) stays the same; what changes is how much reaches you.

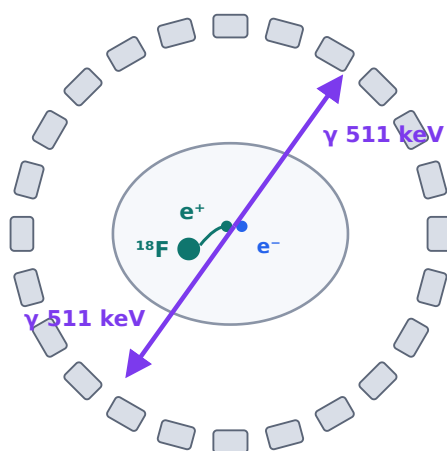
Q MORE PRECISELY

The **effective dose** (also in sieverts) goes one step further: it weights each organ by its sensitivity to radiation, so that doses to different parts of the body can be compared and added. In a patient, the activity of a tracer falls both by radioactive decay and by the body excreting it; the combined rate is described by an **effective half-life**, which is shorter than the physical half-life. Radiation effects are of two kinds: high doses cause predictable tissue damage (such as burns or radiation sickness), while low doses slightly raise the long-term **probability** of cancer, which is why every unnecessary dose is avoided.

Visualise it

How a PET scan works

Two gamma rays fly apart at 180° and hit the detector ring.

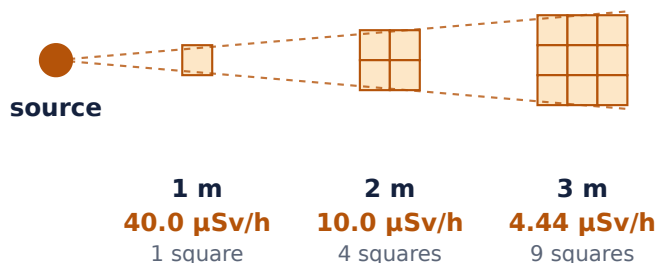


Positron + electron annihilate: their mass becomes two gamma

Two gamma rays at 180° let the scanner trace each decay back to its source.

Distance: the inverse-square law

Double the distance: the radiation spreads over 4× the area.



Dose rate $\propto 1 \div \text{distance}^2$: at 3 m it is 1/9 of that at 1 m.
Also: less time near the source, and more shielding.

Doubling the distance cuts the dose rate to a quarter.

Worked example

WORKED EXAMPLE: Absorbed dose and equivalent dose

Question: A 70.0 kg person absorbs 0.0150 J from gamma rays. Find the absorbed dose and the equivalent dose. What would the equivalent dose be if the same energy came from alpha particles?

Step 1 Absorbed dose = $\frac{0.0150 \text{ J}}{70.0 \text{ kg}} = 2.14 \times 10^{-4} \text{ J/kg} = 2.14 \times 10^{-4} \text{ Gy}$

Step 2 Gamma (weighting factor 1): $2.14 \times 10^{-4} \text{ Gy} \times 1 = 2.14 \times 10^{-4} \text{ Sv} = \mathbf{0.214 \text{ mSv}}$

Step 3 Alpha (weighting factor 20): $2.14 \times 10^{-4} \text{ Gy} \times 20 = 4.29 \times 10^{-3} \text{ Sv} = \mathbf{4.29 \text{ mSv}}$, twenty times more harmful for the same energy.

WORKED EXAMPLE: Distance and the inverse-square law

Question: The dose rate 1.00 m from a source is 40.0 μSv/h. What is it at 2.00 m and at 3.00 m?

Step 1 $\text{rate}_2 = \text{rate}_1 \times \left(\frac{d_1}{d_2}\right)^2$

Step 2 At 2.00 m: $40.0 \text{ μSv/h} \times \left(\frac{1.00 \text{ m}}{2.00 \text{ m}}\right)^2 = \mathbf{10.0 \text{ μSv/h}}$

Step 3 At 3.00 m: $40.0 \text{ μSv/h} \times \left(\frac{1.00 \text{ m}}{3.00 \text{ m}}\right)^2 = \mathbf{4.44 \text{ μSv/h}}$

 WORKED EXAMPLE: How much tracer is left?

Question: A patient receives 740 MBq of technetium-99m ($t_{1/2} = 6.01$ h). What activity remains 18.0 h later (ignoring excretion)?

Step 1 $n = \frac{18.0 \text{ h}}{6.01 \text{ h}} = 2.995$ half-lives

Step 2 $A = 740 \text{ MBq} \times \left(\frac{1}{2}\right)^{2.995} = \mathbf{92.8 \text{ MBq}}$, about one-eighth of the starting activity.

Common mistake

 COMMON MISTAKE: Confusing activity with dose

A source with a high activity (Bq) does not necessarily give a high dose: the dose depends on the type and energy of the radiation, how much is absorbed, the distance and the time. Activity describes the source; dose describes what the body receives.

 COMMON MISTAKE: Halving the dose rate when the distance doubles

The inverse-square law means doubling the distance divides the dose rate by **4**, not 2; tripling it divides by **9**.

 COMMON MISTAKE: Thinking an imaged patient becomes permanently radioactive

Tracers have short half-lives and are also excreted, so the activity falls quickly. After a technetium-99m scan, the activity is about one-sixteenth of the starting value within a day. External X-ray and gamma beams leave **no** radioactivity in the body at all.

 NOTATION NOTE

- Prefixes: $1 \text{ mSv} = 10^{-3} \text{ Sv}$; $1 \mu\text{Sv} = 10^{-6} \text{ Sv}$; $1 \text{ MBq} = 10^6 \text{ Bq}$.
- Older units: $1 \text{ curie (Ci)} = 3.7 \times 10^{10} \text{ Bq}$; $1 \text{ rad} = 0.01 \text{ Gy}$; $1 \text{ rem} = 0.01 \text{ Sv}$.
- keV and MeV are units of energy for single photons or particles ($1 \text{ keV} = 1.602 \times 10^{-16} \text{ J}$).

Remember this

REMEMBER THIS

- Activity in Bq (decays per second); absorbed dose in Gy (J/kg); equivalent dose in Sv = Gy $\times$ weighting factor (1 for γ , X, β ; 20 for α).
- Imaging: gamma emitters with short half-lives (Tc-99m, 6.01 h). PET: F-18 positrons give two 511 keV gamma rays.
- Therapy: beta or alpha emitters placed in the tumour (I-131, Ra-223), or aimed external beams.
- Protection: less time, more distance (rate $\propto 1/d^2$), more shielding; keep doses as low as reasonably achievable.

References

1. Brown, T. L.; LeMay, H. E., Jr.; Bursten, B. E.; Murphy, C. J.; Woodward, P. M.; Stoltzfus, M. W. Chemistry: The Central Science, 15th ed.; Pearson, 2022.

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