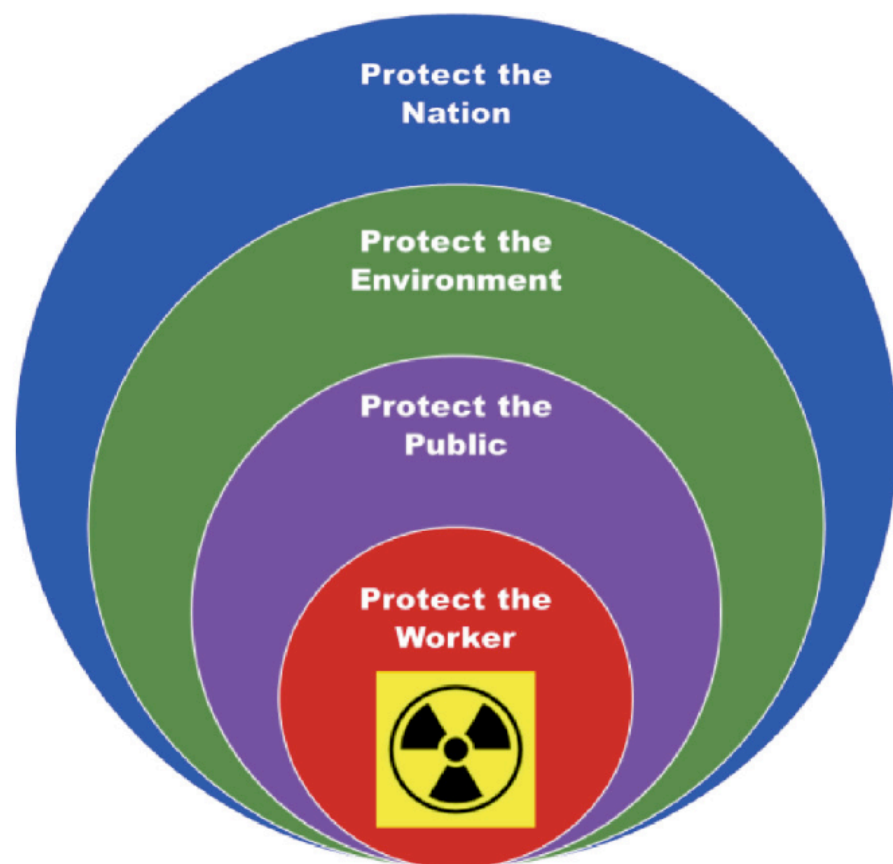




Evolving Radiation Safety in the AI Era: Smart Monitoring, Advanced Shielding, and Future Technologies



**RADIATION
SAFETY**

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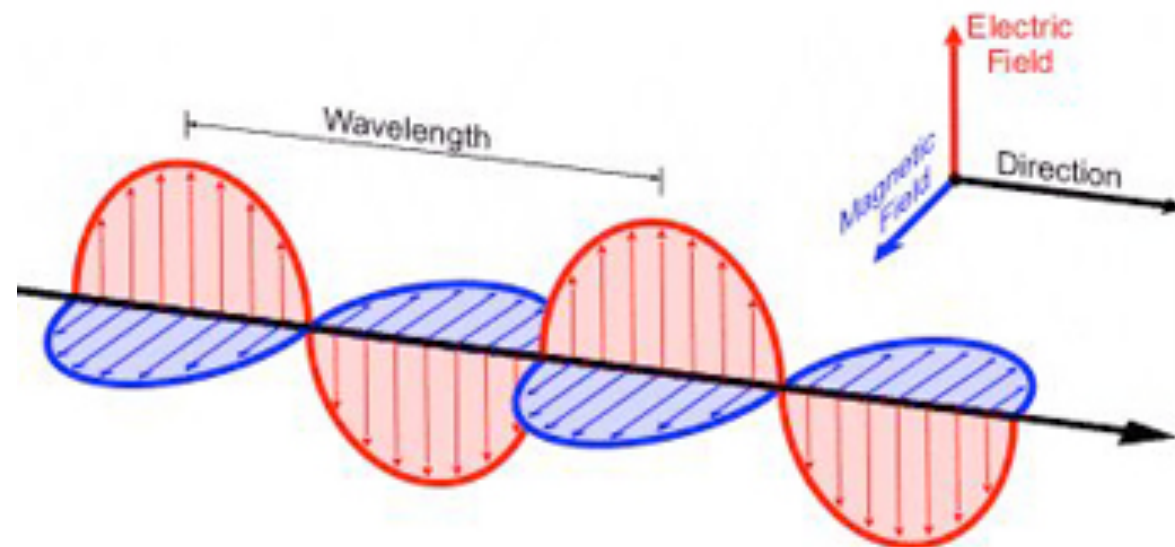
What Is Radiation?

Radiation is energy transmitted as waves or particles through space or matter.

Two main categories:

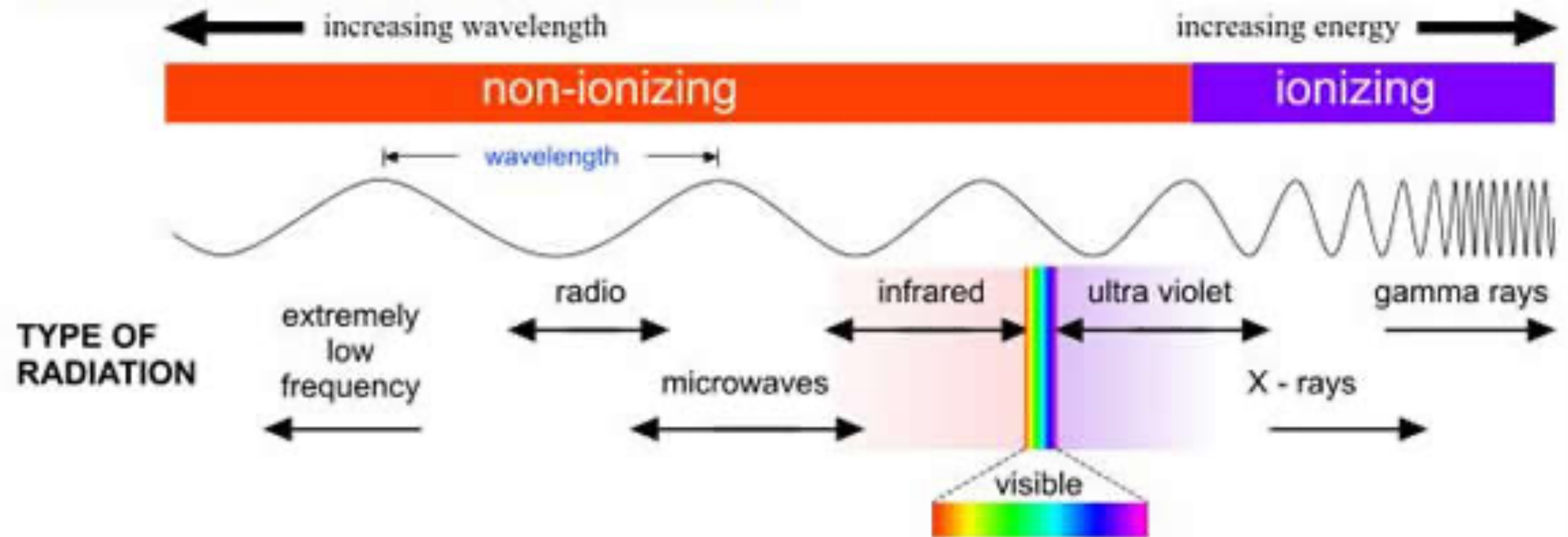
- ✓ Electromagnetic radiation
- ✓ Particle radiation

Ionising radiation has sufficient energy to ionise atoms and molecules.





THE ELECTROMAGNETIC SPECTRUM



SOURCES





Radiation exposure effects depends on

✓ **Type of radiation:** Ionising or Non Ionising

✓ **Dose received :** It is typically measured in units such as gray (Gy) or sievert (Sv).

Absorbed dose (Gy) measures the physical energy deposited in tissue, while effective dose (Sv) accounts for radiation type and tissue sensitivity to estimate the overall biological risk to the whole body.

✓ **Exposure :** Acute Exposure, Chronic Exposure , Brief Intermittent Exposure; Prolonged Exposure

✓ **Individual sensitivity:** Age, Genetics, Health Factor, Life Style

Absorbed dose = How much rain falls

Effective dose = How much damage the rain causes



Why Radiation Safety Is Essential ?

Radiation is indispensable in modern society:

- ✓ Medical imaging and radiotherapy
- ✓ Nuclear power generation
- ✓ Industrial radiography
- ✓ Scientific research

Without proper controls, exposure can cause:

- ✓ Acute radiation syndrome
- ✓ Cancer
- ✓ Genetic damage

Therefore, protection of workers, patients, and public is critical.

Time Distance Shielding

To reduce radiation exposure:



Mechanism of Radiation Associated Damage

Ionizing radiation affects the human body by causing damage at the atomic or molecular level leading to cellular damage.

✓ Direct effects

Ionization of DNA molecules

Single- and double-strand breaks

Chromosomal aberrations

**High Linear Energy Transfer (LET) radiation:
alpha particle, heavy ion, neutron**

✓ Indirect effects

Body is ~70% water

Radiation interacts mostly with water molecules

Produces free radicals (especially •OH)

Radicals diffuse and damage DNA and other molecules

Low-LET radiation (most medical exposures)

Advances in Medical Imaging: X-ray → CT → Spectral CT → MARS → Future

1901 Nobel Prize in Physics
Wilhelm Conrad Röntgen



MARS scanners
Medipix All Resolution System
Developed using CERN Medipix technology

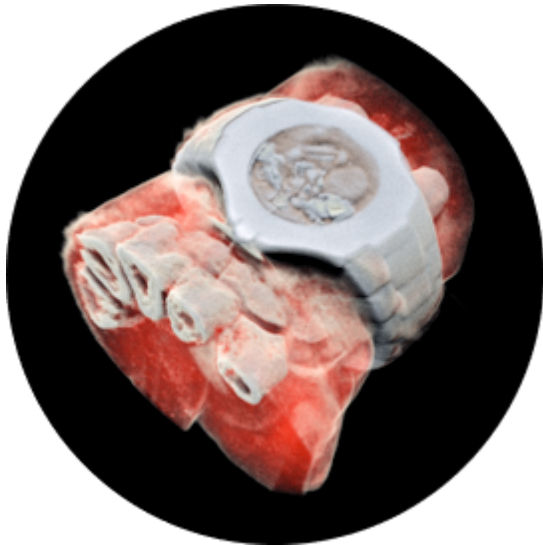


Figure: The first 3D image of a living human image captured by Medipix-incorporated MARS technology in 2018. Of course, the cuts are not real, but just virtual, by the computer.

Feature	MARS Scanner	X-ray
Image type	Color, material-specific	Black & White
Technology	Photon-counting CT	Conventional
Soft tissue detail	Excellent	Limited
Quantitative info	Yes	No
Radiation dose	Low–moderate (efficient)	Low (X-ray) to high (CT)
Diagnostic power	Very high	Moderate
Availability	Experimental / limited	Widely available

Conventional Scanner:

All incoming photons — regardless of energy — are combined into one signal:

$$\text{Signal} \propto \sum E_{\text{photons}}$$

Different gray shades occur because tissues attenuate X-rays by different amounts, so the total energy reaching the detector varies along each path even though individual photon energies are not measured.

MARS (Medipix All Resolution System) is a photon-counting spectral CT (Computed Tomography) technology that uses Medipix detectors to produce high-resolution, material-specific 3D images. Each pixel contains amplifier, discriminator counter.

Feature	Conventional	MARS Detector
Detector type	Scintillator +Photodiode	Semiconductor(CdTe/CZT))
Conversion	Indirect (light to charge)	Direct
Photon counting	✗ No	✓ Yes
Energy measurement	✗ No	✓ Yes
Spectral imaging	✗ No	✓ Yes

Conventional X-ray scanners use energy-integrating detectors that measure total deposited energy, whereas advanced systems like MARS scanners count individual photons and their energies.



AI/ML and Smart Monitoring

Instead of using fixed “one-size-fits-all” scan settings, AI determines the **best settings for each individual patient and situation**.

Traditional imaging uses preset protocols.

AI-driven imaging is **personalised, adaptive, and predictive** to ensure that patients receive the **lowest possible radiation dose** without compromising the diagnostic quality of the images.

How it works:

- ✓ AI analyses large datasets of imaging studies, patient parameters (age, weight, anatomy), and outcomes.
- ✓ Based on this, it predicts the **optimal settings** (tube voltage, current, scan length, contrast) tailored for each patient.
- ✓ AI can even adjust settings **in real time** during a scan to maintain image quality while lowering dose.

Impact: This reduces unnecessary exposure, supports **personalised imaging protocols**, and helps meet regulatory “as low as reasonably achievable” (ALARA) standards.



Advances in Shielding Technologies

Material Type	Density(g/cm ³)	Shielding Efficiency	Toxicity	Weight	Applications
Lead	11.3	Excellent	High	Heavy	Aprons, walls, containers
Tungsten/Bismuth Alloys	9 - 19	Excellent	Low	Very heavy	Nuclear, industrial shielding
Polymer + Heavy Metal Fillers	2 - 4	Good to Very good	Medium	Moderate	Aprons, Curtains
Concrete/Heavy Concrete	2.3–3.6	Moderate	Low	Bulky	Facilities, reactors
Nano-Composites	1.5–3.5	Excellent (at thin layers)	Low	Lightweight	Wearables, portable shields

Polymers with Heavy Metal Fillers: Flexible polymers (PVC, rubber, polyethylene) embedded with lead, tungsten, or bismuth powders. Slightly less shielding efficiency per unit thickness. Still heavy if high shielding levels required.

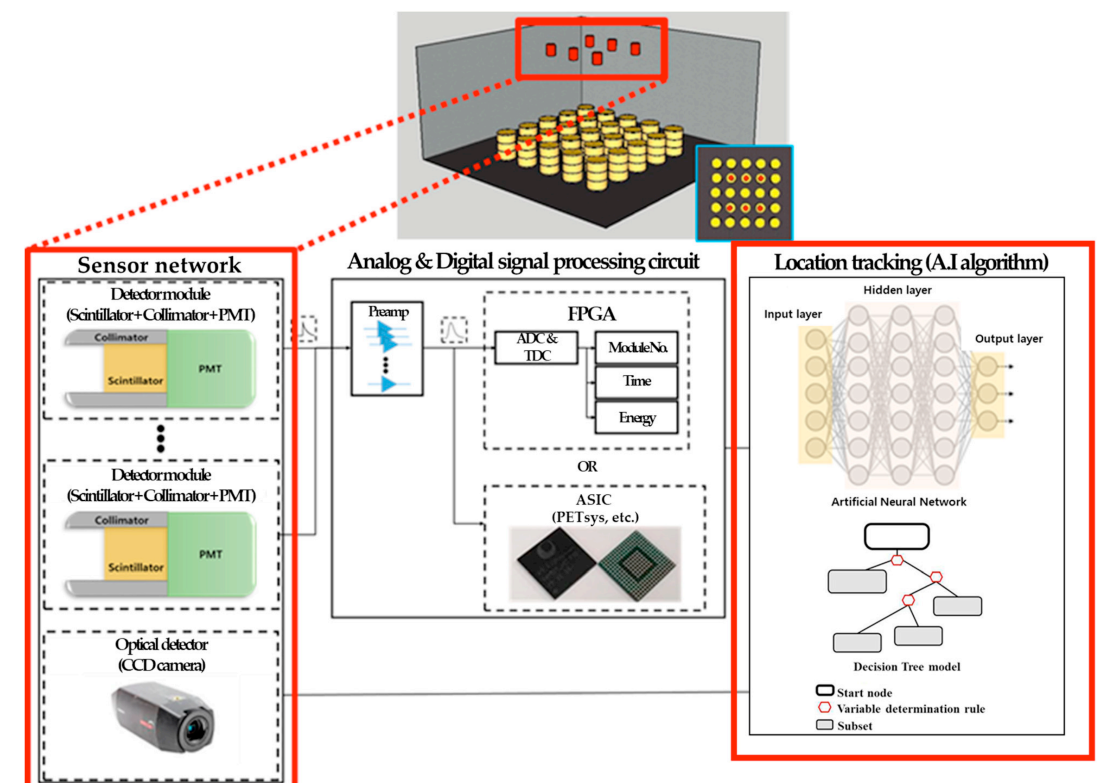
Nano composite Materials (Next-Gen Shielding): Polymers or lightweight matrices reinforced with nanoparticles of heavy metals (bismuth oxide, tungsten oxide, lead oxide, or even carbon-based nano structures). Expensive and still in research/scale-up stage. Long-term durability and performance data are still limited.

Goal: Maximum attenuation with minimum weight and toxicity.



Innovations in Detection & Monitoring

- ✓ **Wearable Dosimeters:** Compact electronic dosimeters allow continuous monitoring and data logging for individuals.
- ✓ **AI-based Real-time Monitoring:** Algorithms predict potential overexposure by analysing dose patterns. AI integrates with sensors and detectors to continuously track radiation levels across facilities. Machine learning algorithms analyse patterns, detect anomalies, and predict potential leaks or unsafe exposures. Alerts and automated responses are generated instantly, ensuring faster safety actions and improved radiation protection.





Digital Twins For Radiation Safety

A **Digital Twin** is a virtual replica of a real-world system — in this case, a radiation facility, imaging machine, or treatment room.

How it works:

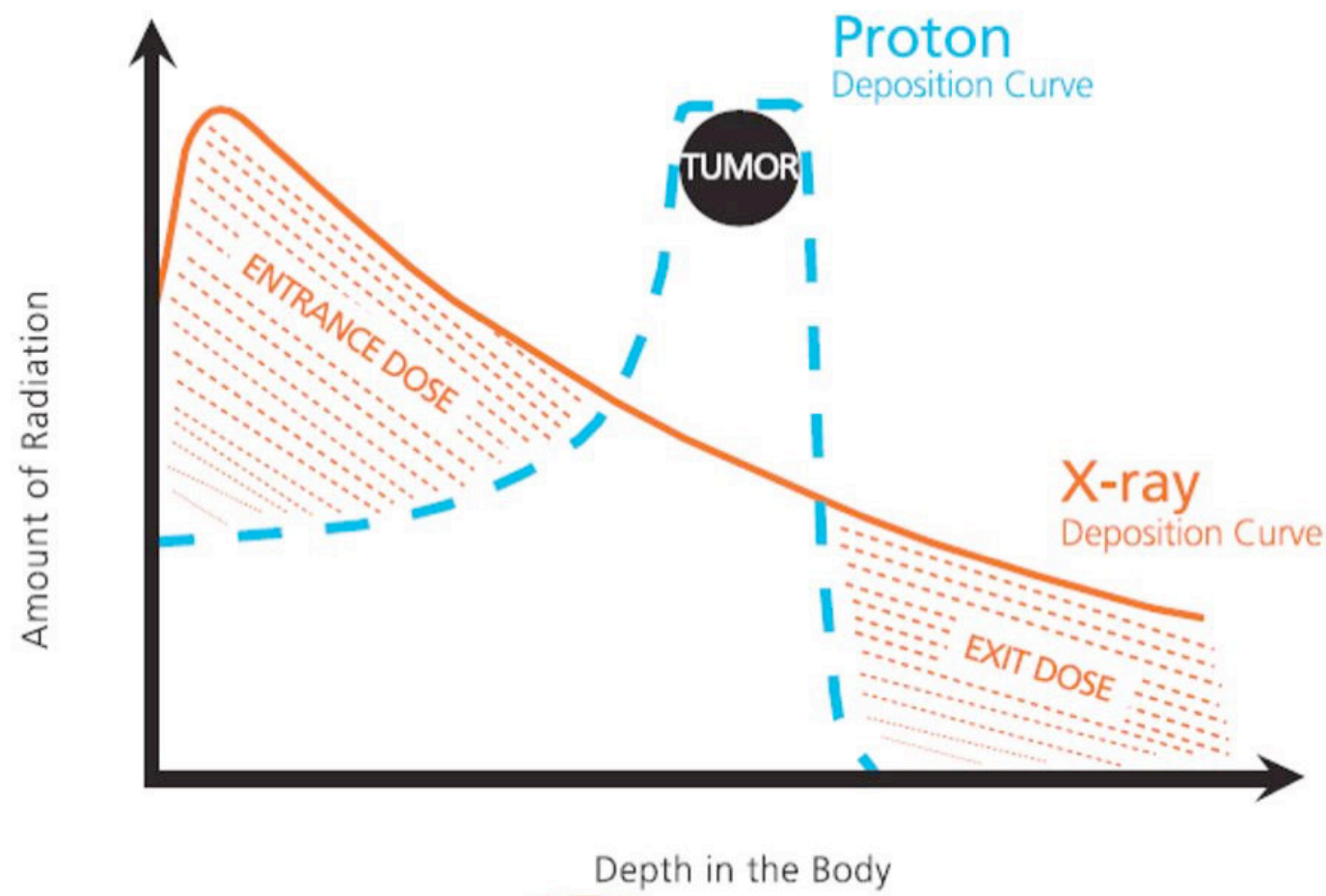
- ✓ Engineers and radiation safety officers create a digital model of the facility, incorporating equipment layout, shielding, radiation sources, and personnel movement.
- ✓ This twin can simulate **radiation exposure scenarios** such as accidental leaks, equipment malfunctions, or patient overload conditions.
- ✓ Staff can use the model for **training, planning, and emergency drills** without actual risk.

Impact: Improves preparedness, enhances **safety culture**, and allows **optimisation** of workflows and **shielding design** before implementation in the real world.

Proton Therapy

Provides precise dose delivery, minimising collateral damage.

Proton therapy works by directing proton particles towards the tumour. Unlike X-rays, which continue to release radiation beyond the tumour site, **protons release their energy only at a specific depth**, directly within the tumour. This targeted approach allows the radiation to be precisely delivered to the cancer cells, minimising damage to the healthy surrounding tissues.



Key Feature: Bragg Peak



Emerging Technologies

✓ **Space Radiation Protection:** Astronauts exposed to cosmic rays require new shielding methods.

The space radiation environment: variety of charged particles, including protons and electrons with an mean energy of around 10 MeV, as well as high-energy heavy ions and high-energy protons (GeV).

The main sources of particles : Galactic cosmic radiation (GCR), Solar particle events, Earth's trapped radiation belt.

Space radiation shielding: **passive materials** (like polyethylene, aluminium, and hydrogen-rich composites) to absorb or deflect charged particles, while **active shielding** using magnetic or electric fields is still experimental and not yet operational on spacecraft.

✓ **Robotics & Automation:** Robots handle radioactive materials in hazardous environments.

Radiation-resistant robot: radiation will cause irreversible damage to both electronic devices and rubber components of the robot, so designing a corresponding radiation-resistant layer is the foundation in the whole design process



Current Challenges in Radiation Safety

- ✓ **Occupational Exposure:** Healthcare workers, nuclear plant operators, and researchers face risks of cumulative exposure. Example: interventional radiologists often exceed typical dose thresholds.
- ✓ **Public Perception:** Fear of radiation accidents (Chernobyl, Fukushima) has led to mistrust despite strong regulatory systems.

Chernobyl (1986, Ukraine): A reactor explosion during a flawed safety test released massive radioactive material, causing widespread contamination and long-term health effects.

Fukushima (2011, Japan): A tsunami disabled cooling systems at the nuclear plant, leading to core meltdowns, hydrogen explosions, and radiation release.
- ✓ **Regulatory Limitations:** Variability in national implementation of International Atomic Energy Agency (IAEA) / International Commission on Radiological Protection (ICRP) guidelines, lack of enforcement in some regions. In India we follow **Atomic Energy Regulatory Board**.



Education and Capacity Building

- ✓ **Continuous Training:** Regular refreshers for radiology staff improve compliance.
- ✓ **E-learning & Simulations:** Virtual reality enables safe training in radiation environments.
- ✓ **Interdisciplinary Education:** Collaboration between physics, engineering, and medicine is essential.

📖 *Reference:* IAEA, “Radiation Protection of Patients – Training Resources,” 2022.



Policy & Global Perspective

Radiation safety requires coordinated international regulations. **IAEA Guidelines:**
Framework for radiation protection globally.

✓ **National Regulations:** AERB (India)

✓ **Global Initiatives:** WHO-IAEA Radiological Health projects.

 *Reference:* IAEA, “Radiation Safety Standards and Guides,” 2021.



Regulatory Limitations in India

☑ Framework & Authority:

- ✓ India's primary regulator for radiation safety is the **Atomic Energy Regulatory Board (AERB)**, established under the **Atomic Energy Act, 1962**.
- ✓ AERB aligns its safety codes with IAEA standards and ICRP recommendations, but adaptation depends on local context and priorities.

☑ Variability in Implementation:

- ✓ While India follows IAEA/ICRP guidelines in principle, there can be **delays in updating national regulations** when international standards are revised.

[The Safety Code on Management of Nuclear and Radiological Emergencies (July 2022) is among the most recent significant ones. Also, the Deterministic Safety Analysis guide (Dec 2024) is very recent for reactor safety regulations.]

- ✓ Enforcement is stronger in the **nuclear power sector** (heavily regulated by AERB) but less consistent in **medical and industrial uses of radiation** (e.g., diagnostic imaging centers, radiotherapy clinics, industrial radiography). *Radiation Protection Rules or Dose Limits were ever formally updated after 2004 .*



☑ Challenges in Enforcement:

- ✓ **Uneven compliance:** Smaller medical facilities, especially in rural areas, may lack the infrastructure, trained Radiation Safety Officers (RSOs), or resources to fully comply with AERB regulations.
- ✓ **Manpower limitations:** AERB has limited inspectors relative to the vast number of X-ray units, nuclear medicine facilities, and industrial users across the country.
- ✓ **Informal sector practices:** In some cases, equipment may be operated without proper licensing or monitoring, creating risks for workers and the public.

☑ Implications:

- ✓ Regulatory gaps can lead to **overexposure risks in diagnostic radiology, improper disposal of radioactive sources, and occupational safety concerns.**
- ✓ Disparities in enforcement reduce overall harmonization with international best practices and make India vulnerable to safety and security risks if not systematically addressed.

Maintaining radiation doses as low as reasonably achievable (ALARA) is a fundamental principle of radiation safety.

Atomic Energy Regulatory Board (AERB), is the primary regulatory body responsible for nuclear and radiation safety.

The AERB sets guidelines and regulations to ensure the safe use of radiation sources in various applications, including medical, industrial, and research settings.

September 2021, the annual effective dose limit for radiation workers in India is 20 millisieverts (mSv) averaged over five consecutive years, with no single year exceeding 50 mSv.

Dosimeter



China's stunning breakthrough: scientists create a battery that lasts over a century without charging

The secret lies in using Carbon-14 instead of Nickel-63. The slow radioactive decay is harnessed for energy and fully contained in a silicon carbide shell, which also serves as the energy conversion layer. The result: no radiation leakage and an energy density 10 times higher than a [lithium-ion](#) battery. Tests show it can operate between -100°C and $+200^{\circ}\text{C}$, with less than 5% degradation over 50 years. And with a half-life of 5,730 years, its theoretical lifespan stretches into the **millennia**, leaving harmless material at the end.



Carbon-14 has a half-life of about 5,730 years, meaning that half of any given sample will have decayed after this period.

