Radiation Units, Weighting Factors & X-Ray Math Reference

Comprehensive guide to ionizing radiation quantities, ICRP weighting factors, radiographic exposure formulas, and patient dosimetry

1. General & X-Ray Units of Measure

Ionizing radiation is measured across four stages: source activity, air ionization, energy absorbed by matter, and biological risk. Both International System (SI) and conventional units are summarized below.

Quantity	What It Measures	SI Unit	Conventional Unit	Conversion & X-Ray Notes
Radioactivity	Rate of unstable atomic nuclei decaying per second	Becquerel (Bq)	Curie (Ci)	1 Ci = 3.7×10^{10} Bq *(Not used for X-ray tubes)*
Exposure / Air Kerma	Ionization produced in air by X-rays or gamma rays	Coulomb/kg (C/kg) milligray (mGy)	Roentgen (R) or milliroentgen (mR)	1 R = 2.58×10^{-4} C/kg Modern systems display **mGy**
Absorbed Dose (D)	Energy deposited per unit mass of tissue or matter	Gray (Gy) or milligray (mGy)	rad	1 Gy = 100 rad 1 mGy = 0.1 rad
Equivalent Dose (H_T)	Biological damage adjusted for radiation type	Sievert (Sv) or millisievert (mSv)	rem	1 Sv = 100 rem For X-rays: **1 mGy = 1 mSv**
Effective Dose (E)	Whole-body stochastic health & cancer risk	Sievert (Sv) or millisievert (mSv)	rem	Weighted sum of all exposed organs
Dose Area Product (DAP)	Total radiation energy exiting the X-ray collimator	$Gy \cdot cm^2$	$R \cdot cm^2$	Combines air kerma & field area (fluoroscopy/radiography)
CT Dose Index ($CTDI_{vol}$)	Standardized radiation output per slice in a CT scan	milligray (mGy)	rad	Measured in 16 cm (head) or 32 cm (body) phantoms

Common Metric Prefixes: 1 Sv = 1,000 mSv (millisieverts) = 1,000,000 µSv (microsieverts). Dose rates add a time unit, such as µSv/h or mGy/min.

2. ICRP Weighting Factors (Publication 103)

Weighting factors translate physical absorbed energy (Gy) into biological risk (Sv) based on radiation type and organ sensitivity.

A. Radiation Weighting Factors (W_R)

Radiation Type	Energy Range	Factor (W_R)	Radiobiological Basis
X-rays	All energies	**1**	Sparsely ionizing photons; baseline reference
Gamma (γ) rays	All energies	**1**	Identical tissue interaction to X-rays
Beta (β) particles / Electrons	All energies	**1**	Low mass and charge; sparse ionization track
Protons & Charged Pions	> 2 MeV	**2**	Higher mass creates denser ionization tracks
Neutrons	Varies by energy	**2.5 to 20**	Continuous curve peaking near 1 MeV
Alpha (α) particles & Heavy Ions	All energies	**20**	High linear energy transfer; severe clustered DNA damage

B. Tissue Weighting Factors (W_T)

Organ or Tissue	W_T Value	Clinical & X-Ray Relevance
Red Bone Marrow	**0.12**	High leukemia risk; exposed in pelvis, spine, and chest imaging
Colon	**0.12**	Major contributor in abdominal, pelvic, and barium enema exams
Lung	**0.12**	Primary concern in chest radiography and thoracic CT
Stomach	**0.12**	High sensitivity during upper GI and abdominal scans
Breast	**0.12**	Highly radiosensitive; tracked closely in mammography and chest CT
Remainder Tissues*	**0.12**	Averages dose across 14 secondary organs (total group weight = 0.12)
Gonads (Testes / Ovaries)	**0.08**	Reflects hereditary risk (updated from 0.20 in ICRP 60)
Bladder	**0.04**	Moderate sensitivity during pelvic radiography and CT
Esophagus	**0.04**	Exposed in cervical/thoracic spine and swallowing studies
Liver	**0.04**	Moderate sensitivity during abdominal imaging
Thyroid	**0.04**	Especially sensitive in pediatric patients; shielded in dental/neck exams
Bone Surface	**0.01**	Low stochastic cancer risk despite high photoelectric absorption
Brain	**0.01**	Low sensitivity; keeps head CT effective dose relatively low
Salivary Glands	**0.01**	Relevant in dental panoramic, CBCT, and head/neck exams
Skin	**0.01**	Lowest stochastic weight (high doses still risk deterministic erythema)
Total Whole Body	**1.00**	Sum of all tissue weighting factors

**Remainder Tissues (0.12 total): Adrenals, extrathoracic region, gall bladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate (male), small intestine, spleen, thymus, and uterus/cervix (female).*

3. Core Radiation & Patient Dosimetry Calculations

1. Equivalent Dose (H_T)

$$H_T = D \times W_R$$

D = absorbed dose in Gy (or mGy); $\mathbf{W_R}$ = radiation weighting factor (1 for X-rays). Result is in Sv (or mSv).

2. Effective Dose (E)

$$E = \Sigma\ (H_T \times W_T) = \Sigma\ (D_T \times W_R \times W_T)$$

Multiplies each exposed organ's equivalent dose by its tissue weighting factor (W_T) and sums all exposed organs.

3. CT Dose Length Product (DLP) & Estimated Effective Dose

$$DLP = CTDI_{vol} \times \text{Scan Length (cm)} \quad | \quad E \approx DLP \times k$$

DLP is measured in mGy·cm. Multiplying DLP by an anatomical conversion coefficient (**k**, e.g., ~0.0021 for head, ~0.014 for chest, ~0.015 for abdomen/pelvis) estimates effective dose in mSv.

4. Cumulative Occupational / Area Dose

$$\text{Total Dose} = \text{Dose Rate} \times \text{Time}$$

Calculates total exposure over a shift or procedure (e.g., mGy/min × minutes, or µSv/h × hours).

5. Radioactive Decay (General Reference for Isotopes)

$$A = A_0 \times (0.5)^{(t\ /\ t_{1/2})}$$

$\mathbf{A_0}$ = initial activity; **t** = elapsed time; $\mathbf{t_{1/2}}$ = isotope half-life. (Applies to nuclear medicine/isotopes rather than X-ray tubes).

4. Essential X-Ray Tube & Radiographic Physics Math

6. Tube Current-Time Product (mAs) & Output Proportionality

$$mAs = mA \times \text{Exposure Time (s)} \quad | \quad I_1\ /\ I_2 = mAs_1\ /\ mAs_2$$

mAs governs the total number of X-ray photons produced. Beam intensity (I) and patient dose are directly proportional to mAs when kVp and distance remain constant.

7. Inverse Square Law (Distance vs. Beam Intensity)

$$I_1 \times d_1^2 = I_2 \times d_2^2 \quad \rightarrow \quad I_2 = I_1 \times (d_1 / d_2)^2$$

I_1, I_2 = radiation intensities at distances d_1, d_2 from the focal spot. Doubling distance reduces intensity to 1/4 (25%).

8. Direct Square Law (Density Maintenance Formula)

$$mAs_1 / mAs_2 = d_1^2 / d_2^2 \quad \rightarrow \quad mAs_2 = mAs_1 \times (d_2 / d_1)^2$$

Calculates the new **mAs** needed to keep detector exposure (image brightness/density) constant when changing the Source-to-Image Distance (SID).

9. The 15% Rule (kVp vs. mAs Relationship)

$$\text{Increasing kVp by 15\% } \approx \text{ Doubling mAs (2× detector exposure)}$$

To maintain constant image receptor exposure when increasing **kVp by 15%**, divide the original **mAs by 2** (reduces patient entrance dose). Decreasing kVp by 15% requires multiplying mAs by 2.

10. Half-Value Layer (HVL) & Shielding Attenuation

$$I = I_0 \times (0.5)^n \quad \text{where} \quad n = \text{Thickness} / \text{HVL}$$

I_0 = initial intensity; **I** = transmitted intensity; **n** = number of Half-Value Layers (thickness of aluminum or lead required to cut beam intensity by 50%).

11. Image Magnification, Object Size & Unsharpness

$$MF = SID / SOD \quad | \quad \text{Object Size} = \text{Image Size} / MF \quad | \quad U_g = \text{Focal Spot Size} \times (OID / SOD)$$

MF = Magnification Factor; **SID** = Source-to-Image Distance; **SOD** = Source-to-Object Distance (SID − OID); **OID** = Object-to-Image Distance; U_g = Geometric Unsharpness (penumbra).

12. Grid Conversion Formula (Bucky Factor)

$$mAs_2 = mAs_1 \times (\text{Bucky Factor}_2 / \text{Bucky Factor}_1)$$

Adjusts mAs when adding, removing, or changing radiographic grids. Typical Bucky Factors (G): No grid = 1; 5:1 grid = 2; 8:1 grid = 4; 12:1 grid = 5; 16:1 grid = 6.

13. Heat Units (HU) for X-Ray Tube Rating

$$\text{Single-Phase: } HU = kVp \times mAs \quad | \quad \text{3-Phase (12-pulse) / High-Frequency: } HU = kVp \times mAs \times 1.4$$

Calculates thermal energy deposited in the X-ray tube anode to prevent overheating (3-phase 6-pulse uses a factor of 1.35).

14. Minimum Wavelength (λ_{min}) & Maximum Photon Energy

$$\lambda_{min}\ (\text{Å}) = 12.4 / kVp \quad | \quad E_{max}\ (\text{keV}) = kVp$$

Determines the shortest X-ray wavelength (in Angstroms) and peak photon energy (in keV) generated at a given peak kilovoltage (**kVp**).

5. Worked Practice Examples

Example A — Effective Dose from Partial-Body X-Ray: A chest CT delivers an absorbed dose of **8 mGy** to the lungs (W_T = 0.12) and **6 mGy** to the esophagus (W_T = 0.04), with negligible dose elsewhere.

• Equivalent Dose (W_R = 1): Lung = 8 mSv; Esophagus = 6 mSv.

• Effective Dose: E = (8 mSv × 0.12) + (6 mSv × 0.04) = 0.96 + 0.24 = **1.20 mSv**.

Example B — Inverse Square Law (Radiation Safety): A radiographer stands **1 meter** from a fluoroscopy source where the dose rate is **120 µSv/h**. What is the dose rate if they step back to **2 meters**?

• $I_2 = 120 \times (1 / 2)^2 = 120 \times 0.25 =$ **30 µSv/h**.

Example C — Direct Square Law (SID Change): A technique uses **10 mAs** at **40 inches SID**. What mAs maintains image density at **72 inches SID**?

• $mAs_2 = 10 \times (72 / 40)^2 = 10 \times (1.8)^2 = 10 \times 3.24 =$ **32.4 mAs**.

Example D — Half-Value Layer Shielding: An X-ray beam has an intensity of **80 mGy/min**. A lead barrier has a thickness of **3 HVLs**. What is the transmitted intensity?

• $I = 80 \times (0.5)^3 = 80 \times 0.125 =$ **10 mGy/min**.

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