Radiation Dosimeters

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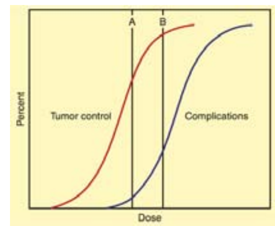
Why dose measurement ?



- International Commission on Radiation Units and Measurements (ICRU) has recommended: an overall dosimetric uncertainties of **±5%** and an overall spatial uncertainty of **±5mm**.

ICRU Report No. 24

Radiation Absorbed Dose

- Absorbed dose is the mean energy dE imparted by ionizing radiation to material of mass dm

$$D = \frac{d\bar{\varepsilon}}{dm} \quad [\mathrm{Gy}]$$

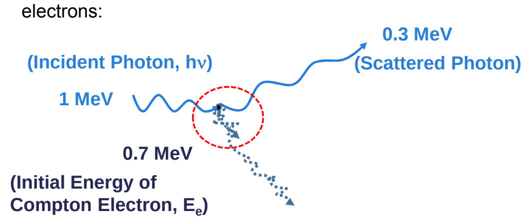
- A measure of the biologically significant effects produced by ionizing radiation

1Gy = 1 J/kg

- Ionizing radiation:
  - Uncharged particle: indirect ionizing (two-step process)
  - Charged particle: direct ionizing

Energy transferred to charged particle

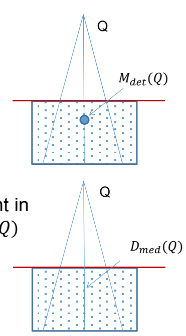
When a photon interacts with the electrons in the material, a part or all of its energy is converted into kinetic energy of electrons:



Basic quantities

- Detector reading: $M_{det}(Q)$
  - Meter reading
  - Charge reading
  - Current reading
  - Light output ….
- Average dose at point of measurement in medium in absence of detector $D_{med}(Q)$
- Absorbed dose calibration coefficient:

$$N_{D,w} = \frac{D_{water}(Q)}{M_{det}(Q)}$$



Dosimeter characteristics

- Environmental and measurement corrections
  - Dose rate dependency
  - Dose dependency
  - Background correction
  - Temperature, pressure
  - Polarity, recombination
- Linearity / Range
- Energy dependence
- Directional (angular) dependence
- Spatial resolution/size effects
- Read-out convenience

Common dosimeters

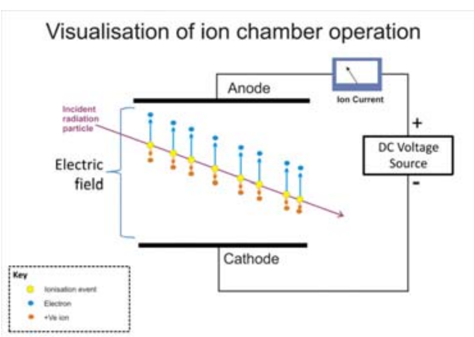
Clinical dosimeters:
- Ionization chamber
- Semiconductor Diode
- Metal-oxide-silicon-semiconductor field effect transistor (MOSFET)
- Thermoluminescent Dosimeters (TLD)
- Film (radiographic and radiochromic)

Other dosimeters:
- Gel Dosimeter
- Calorimetry:
- Alanine
- Plastic scintillate system
- Diamond dosimeter

Ionization chamber

- Basic instrument for radiation therapy physicist
- Gas-filled radiation detector
- High precision with small uncertainties
- Require calibration

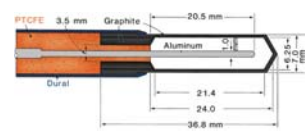
Major types of clinical ionization chambers
- Cylindrical
- Parallel plate
- Extrapolation chambers



- Energy to produce an ion pair (*W/e*): 33.97 eV/ion or J/C

Cylindrical ionization chamber

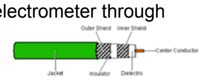
- Three electrodes
  - Chamber wall
    - low Z materials: acrylic, PMMA, graphite, <1mm
  - Collector
    - Al ~1mm diameter
  - Guard

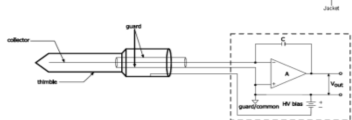


- Chamber volume ranges from 0.015 cc to 0.6 cc
  - Volume of chamber determines the size of the signal
  - Larger volume -> higher sensitivity -> Lower spatial resolution and larger gradient effect

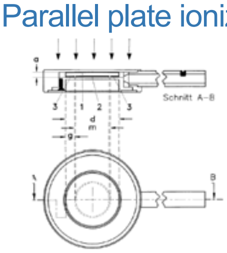
Cylindrical ionization chamber

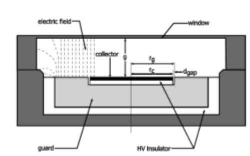
- High voltage applied across wall and collector. The guard ring remains the same potential as the collector.
  - prevent leakage current
  - define the collecting volume
- Three electrodes connect to the electrometer through trial-axial cable





Parallel plate ionization chamber





- Guard ring reduces leakage current and improves electric field uniformity and defines collection volume
- Rule of thumb: guard should be > 3 times the gap
- recommended for low energy e- beam dosimetry. Also used for surface dose and depth dose measurement in the build-up region of photon beams.

Electrometers

- A device for measuring charges
- Rate (current) or integrated mode (charge)
- Input current is very low; special sensitive devices are necessary to measure it
- Example: Current from 0.6 cc Farmer chamber in 100 R/min field at 760 mm Hg and 22 ºC is:

100 R/min × 1/60 s/min × 2.58×10⁻⁴ C/kg·R x 0.6cc × 10⁻⁶m³/cc × 1.29 kg/m³ = 3.33 ×10⁻¹⁰A = 0.333 nA

$100\ R/min \times 1/60\ s/min \times 2.58\times10^{-4}\ C/kg\cdot R \times 0.6cc \times 10^{-6} m^3/cc \times 1.29\ kg/m^3 = 3.33\times10^{-10} A = 0.333\ nA$

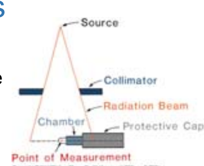
where 1.29 kg/m^3 is the density of air at 760 mm Hg and 0 °C.

Considerations in Ionization Chamber Measurement

- Ion collection:
  - Stem effect
  - Leakage
  - Collection efficiency
  - Polarity effect
- Calibration and Energy response
- Environmental conditions
  - Temperature
  - Pressure

Stem effect of chambers

- Measurable ionization in the body of the stem instead of collection volume
- Depends on guarding, in particular the length of the unguarded stem



Type of chamber	Length of unguarded stem (cm)	Stem Effect in %
Unguarded	7.0 to 8.5	0.3 to 0.6%
Guarded	1.0 to 1.5	0.1 to 0.3%
Well Guarded	< 1.0	< 0.1%

Chamber Leakage

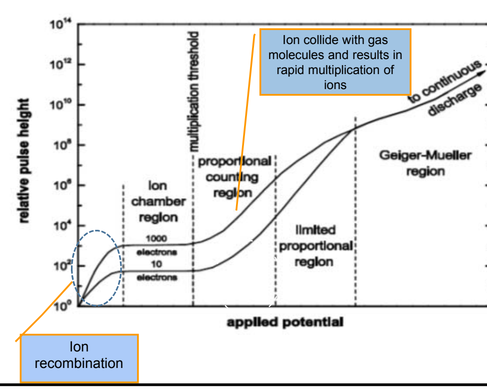
- Background signal collected before charge collected and with charge or reading
- Leakage comes from:
  - Chamber
  - Electrometer
  - Cable
- Leakage in the chamber is generally 1-10 fA for a good chamber

Ion collection efficiency

- A certain amount of ionization loss by recombination, especially at very high ionization intensity, such as pulsed beams
- Collection efficiency:

$$\text{Efficiency} = \frac{\text{The number of ions collected}}{\text{The number of ions produced}}$$

- It is recommended that the collection efficiency should be better than 99%
- The operation of the chamber changes as the voltage increases
- When V< 50volts, recombination occurs. It is desired to operate the chamber in the saturation range (300-400V)



Recombination correction (P_{ion})

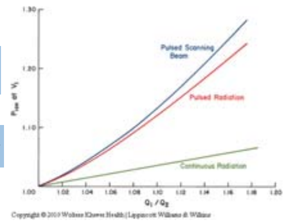
Two-voltage testing technique: one given working voltage and the other much lower voltage--theoretical formula by Boag and Currant

for continues radiation

$$P_{ion}(V_H) = \frac{1-(V_H/V_L)^2}{M_{raw}^H / M_{raw}^L - (V_H/V_L)^2}$$

for pulsed radiation

$$P_{ion}(V_H) = \frac{1-(V_H/V_L)}{M_{raw}^H / M_{raw}^L - (V_H/V_L)}$$



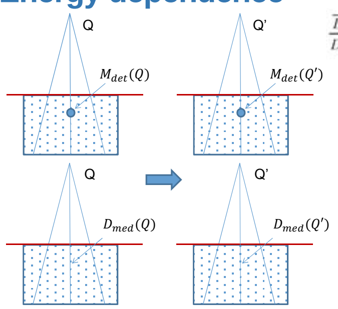
Chamber polarity effects

- For a given exposure, the ionic charge collected changes in magnitude as the polarity of the collecting voltage is reversed
- Polarity effects relatively more severe for measurements in electron beams than photon beams; the effect increases with decreasing electron energy
- Should be less than 0.5 % for any radiation beam quality

Energy dependence

General Cavity Theory:

$$\frac{D_{det}}{D_{med}} = d\left(\frac{L_\Delta}{\rho}\right)_{med}^{det} + (1-d)\left(\frac{\mu_{en}}{\rho}\right)_{med}^{det}$$

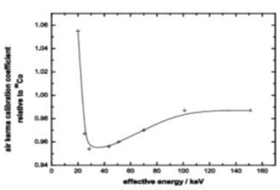


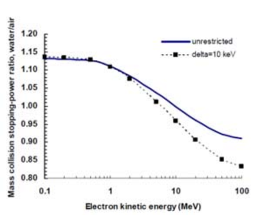
$D_{water}(Q) = N_{D,w} \cdot M_{det}(Q)$ $\quad D_{water}(Q') \overset{?}{=} N_{D,w} \cdot M_{det}(Q')$

Energy dependence

- It is desired to have a uniform energy response for all the energies
- The chamber wall or window is very important for the energy response
- Depends on the effective atomic number, stopping power ratio of air to water
- In general chamber calibration is done at a reference energy such as Cobalt-60.
- Energy correction is applied when using the chamber for other energies

Energy dependency





For a typical farmer chamber:
Co-60 K_Q =1
6MV K_Q = 0.992
15MV K_Q = 0.972

K_Q – beam quality factor in TG-51 calibration

Angular Dependence

- Ion chambers generally show a negligible angular dependence
- Directional response:
  - ≤ ± 0.5 % for rotation water around the chamber axis
  - ≤ ± 1 % for tilting of the axis up to
    ± 20° (radial incidence)
    ± 15° (axial incidence)

Environmental conditions

- Most Ion chambers are not sealed. Air density changes with temperature and pressure.
- Temperature ↓ or Pressure ↑ → the density or the mass of air ↑
- The chamber reading for a given exposure will increase as the temperature decreases or as the pressure increases
- The correction $C_{T,P} = \frac{760}{P} \times \frac{273.2 + T}{295.2}$

Commercial ionization chambers

Specifications

$N_{gas}/(N_x A_{ion})$ (cGy/R): 0.849
K_{ecal} : 0.897
Volume: .... 0.6 cc (nominal)
Sensitivity: .... 0.2 nC/cGy (nominal)
Wall material: .... acrylic (PMMA) + graphite C)
Wall thickness: .... 0.425 mm, (0.335 mm PMMA, 0.09 mm C)
Wall density: .... 56 mg/cm²
Sensitive volume: .... 6.1 mm diameter, 23.6 mm long
Electrode: .... aluminum, 1.1 mm diameter, 21.2 mm long
Thimble O.D.: .... 6.95 mm
Leakage: .... ± 4 x 10 - 15 A
Bias voltage: .... 500 V maximum
Rate limit for 99.5% ion collection efficiency:
.... 300 V; 280 R/s, 500 V; 780 R/s
Rate limit for 99.5% ion collection efficiency, pulsed:
.... 100 V; 34 mR/pulse, 400 V; 57 mR/pulse
Buildup cap: .... acrylic, 4.55 mm wall, 16.4 mm o.d.
Cap machine thread: .... M 11 x 1
Cable: .... low-noise triaxial, 1 m
Connector: .... triaxial BNC with cap and chain (TNC optional)

Features:
- Waterproof
- Fully guarded
- Redesigned for long term stability
- Characterized for TG-51

Commercial ionization chambers

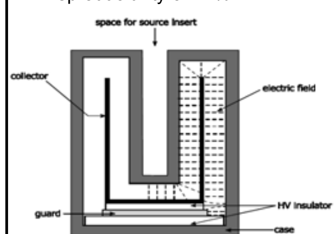
Specifications

$N_{gas}/(N_x A_{ion})$ (cGy/R): 0.8564
Kecal : 0.896
Volume: .... 0.02 cc, nominal, vented to the atmosphere
Sensitivity: .... 0.0067 nC/cGy, nominal
Leakage current: .... < 4 x 10 - 15 A
Entrance window: .... 0.03 mm polyethylene 2.5mg/cm²
Ion collector: .... 5 mm diameter, acrylic, graphite coated
Guard Ring Width: .... 2 mm
Electrode separation: .... 1 mm
Bias voltage: .... ±300 V typical, 400 V maximum
External dimensions: .... 30 mm diameter x 14 mm
Protective cap: .... acrylic, 0.87 mm thick, 102.6 mg/cm²
Cable: .... 1 meter, low-noise triaxial, BNC male connector (TNC optional)

- Waterproof
- Wide guard ring designed for negligible polarity and perturbation effects
- 5 mm diameter collector
- Characterized for TG-51

Brachytherapy Ionization Chambers

- Specialized well chamber used in brachytherapy
- Repeating measurements of same source give reproducibility of <1%



Characteristics of Ion chamber

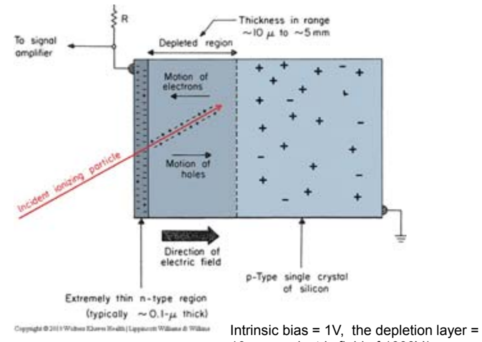
	Ion Chamber
Dose rate dependency	Pion, usually very small <1%
Dose dependency	No
Background correction	Leakage <10 fA
Temperature, pressure	Need correction
Polarity	Small
Linearity	Linear
Directional dependence	Small
Spatial resolution/size effects	Wide range (0.015 cc to 0.6 cc)
Readout convenience	Instantaneous
Energy dependence	Relatively small for therapeutic beams

Diode

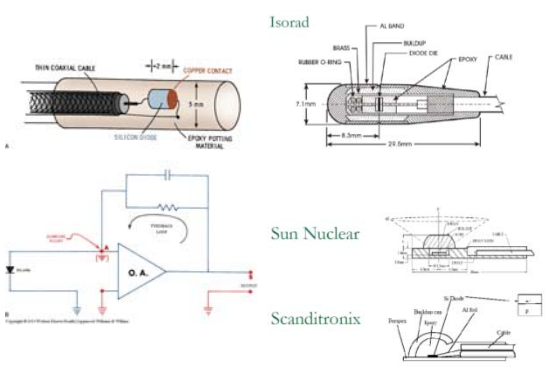
- Silicon p–n junction diodes are often used for relative dosimetry
- Intrinsic semiconductor (Si) is material with a narrow energy band width (1.1 eV).
- Temperature gives enough energy to produce a small amount of electron and hole (pair); both are conductive
- Doping "do<u>n</u>or" impurity (e.g. phosphorous or arsenic) produces additional electrons (n-type)
- Doping "acce<u>p</u>tor" impurity (e.g. boron or aluminum) produces additional holes (p-type)

n-type and p-type Diodes

- A diode is a p-n junction made by doping the semiconductor with donors and acceptors at adjacent junctions.
- n-type diodes have the high doping level of n-type semiconductors and the low doping level of p-type semiconductors. The reverse is true for p-type diodes



Intrinsic bias = 1V, the depletion layer = 10μm => electric field of 1000V/cm



Sensitivity

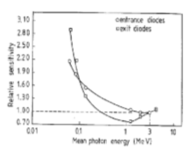
- The energy required to produce an electron-hole pair in Si is 3.5 eV compared to 34 eV required to produce an ion pair in air.
- The density of Si is 1,800 times that of air
- The current produced per unit volume is about 18,000 times larger in a diode than in an ion chamber

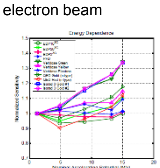
=> highly sensitive

=> high spatial resolution

Energy Dependence

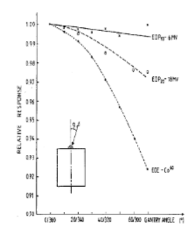
- High atomic number of silicon (Z = 14) compared to that of water or air
  - Diodes exhibit severe energy dependence in photon beams
  - Energy dependency depends on build-up material and structure design
- The stopping power ratio of silicon to water does not vary significantly with electron energy or depth
  - Less energy dependency in electron beam



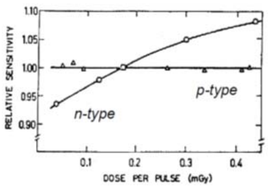


Angular dependence

- Diodes exhibit angular dependence
- Depends on structure design and build-up
  - Cylindrical detector has less angular dependence



Dose rate dependence

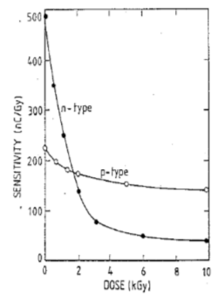


- Dose rate decreases as treatment source-surface distance (SSD) increases.
- Diodes also exhibit SSD dependence.

SSD Dependence (Ratio at 200 cm)

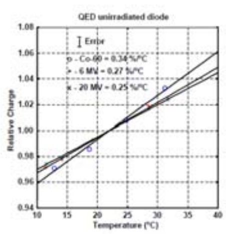
Diode	6 MV	20 MV	Co-60
Isorad 1 Gold	0.950	0.957	0.988
Isorad 2 Gold	0.965	0.973	---
Isorad Red	0.974	0.994	0.987
SPD	1.002	0.995	---
EDP30	0.995	0.998	0.994

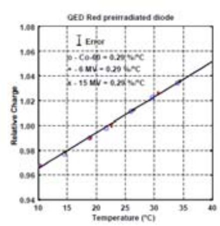
Accumulated Dose Dependence



- Diode usually pre-irradiated by vendor to remove accumulated dose dependence
- Periodic cross-calibration of diodes for absolute dose measurement

Temperature dependence





Commercial Diodes

Specifications

Photon and Electron Diode Detectors
Nominal Sensitivity: 1.5nC/cGy
Sensitivity Volume: 0.25 mm^3
Output Polarity: Positive/Negative
Linearity: <.1% for dose ranges from 0.01 Gy to 10 Gy
<.1% for dose rates 3 to 5 Gy/min
Reproducibility: 0.2%
Angular Dependence: <2% ± 60° for lower energy diodes (Item 322-913). <2% ± 10°; <5% ± 60° for higher energy photon diodes and electron diodes.
Sensitivity Loss at 10 kGy: <15%
Cable Length: 3 meters
Connector: Coaxial BNC-M
Dimensions: 8 mm ∅
Weight: 42 gm

Characteristics of Diode

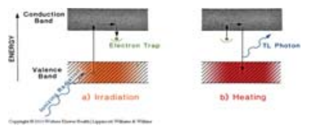
	Diode
Dose rate dependency	Strong dose rate (dose per pulse) depend
Dose dependency	Yes
Background correction	Leakage primarily contributed by electrometer
Temperature, pressure	0.3%/ °C
Polarity	NA
Linearity	Linear
Directional dependence	Large, depends on construction
Spatial resolution/size effects	High spatial resolution
Readout convenience	Instantaneous
Energy dependence	Large

Thermoluminescence dosimeter (TLD)

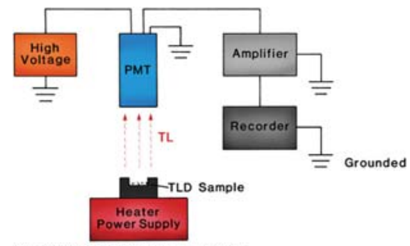
- Thermoluminescence is the emission of light by heat
- Uses the band theory of solids
- Defect centers in the crystal lattice are responsible for the TL process
- Defects (impurities) are responsible for both the traps and for the recombination centers.
- The basic process is the storage of energy from radiation in “traps”.
- Release of the this energy by the application of heat.
- Most common TLD: lithium fluoride (LiF), lithium borate ($Li_2B_4O_7$), and calcium fluoride (CaF_2).

TLD basis

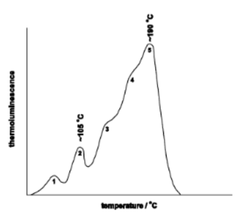
- When irradiated, electrons in the valence band (ground state) receive sufficient energy to be raised to the conduction band.
- The vacancy thus created in the valence band is called a positive hole.
- The electron and the hole move independently through their respective bands until they recombine (electron returning to the ground state) or until they fall into a trap (metastable state).
- Electrons can be released by heat and recombine with holes.
- Recombination produces light with a wavelength characteristic of center



TLD reader



Glow curve

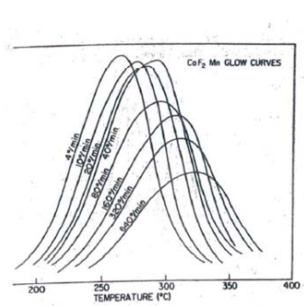


- A plot of thermoluminescence against temperature is called a glow curve
- As the temperature increases, the probability of releasing trapped electrons increases
- Because most phosphors contain a number of traps at various energy levels in the forbidden band, the glow curve may consist of a number of glow peaks
- The different peaks correspond to different "trapped" energy levels.

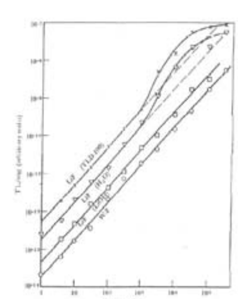
Annealing

- Low temperature traps fade away with time at room temperature
- Pre-heat period without light integration: rapidly get through the unstable-trap region
- Annealing at 400C for 1 hour resets the trap structure and eliminates any electrons in residual traps

Effect of readout temperature rate



Linearity and sensitivity



- For LiF:Mg, Ti:
  - Linear up to the range of 5Gy to 10Gy
  - Supralinear 10Gy to 1kGy
  - Damage after 1kGy
- TLD sensitivity affected by impurities

TLD readout can be affected by

- TLD handling – vacuum tweezers
- Stable high voltage on reader
- Dark current of PMT
- Infrared from heating pan
- Hot gas used to eliminate pan
- Nitrogen flow for reduction of surface effects
- The wavelength sensitivity of the photomultiplier tube

Energy Response

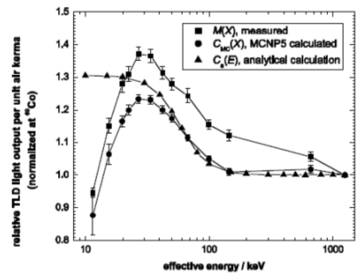


Table 8.10 Characteristics of Various Phosphors

Characteristic	LiF	Li_2B_{4O7}:Mn	CaF_2:Mn	CaF_2:nat	$CaSo_4$:Mn
Density (g/cc)	2.64	2.3	3.18	3.18	2.61
Effective atomic no.	8.2	7.4	16.3	16.3	15.3
TL emission spectra (A)					
Range	3,500–6,000	5,300–6,300	4,400–6,000	3,500–5,000	4,500–6,000
Maximum	4,000	6,050	5,000	3,800	5,000
Temperature of main TL glow peak	195°C	200°C	260°C	260°C	110°C
Efficiency at cobalt-60 (relative to LiF)	1.0	0.3	3	23	70
Energy response without added filter (30 keV/cobalt-60)	1.25	0.9	13	13	10
Useful range	Small, <5%/12 wk	mR–10^6 R	mR–3×10^5 R	mR–10^4 R	R–10^4 R
Fading	mR–10^5 R	10% in first mo	10% in first mo	No detectable fading	50%–60% in the first 24 hr
Light sensitivity	Essentially none	Essentially none	Essentially none	Yes	Yes
Physical form	Powder, extruded, Teflon embedded, silicon embedded, glass capillaries	Powder, Teflon embedded	Powder, Teflon embedded, hotpressed chips, glass capillaries	Special dosimeters	Powder, Teflon embedded

From Cameron JR, Suntharalingam N, Kenney GN. *Thermoluminescent Dosimetry.* Madison: University of Wisconsin Press; 1968, with permission.

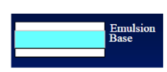
Summary of TLDs

- Advantages
  - Small size
  - Wide linear range
  - Reusable
- Disadvantage
  - Slight instabilities in sensitivities
  - Susceptible to surface contamination
  - Structural damage – scratches

Characteristics of Ion chamber

	TLD
Dose rate dependency	No
Dose dependency	No
Background correction	Primarily from reader
Temperature, pressure	Readout temperature
Polarity	No
Linearity	Linear up to 5~10Gy
Directional dependence	Small
Spatial resolution/size effects	Small size
Readout convenience	Passive
Energy dependence	Relatively small for therapeutic beams

Radiographic film



- A radiographic film consists of a transparent film base (cellulose acetate or polyester resin) coated with an emulsion containing very small crystals of silver bromide.
- When exposed to ionizing radiation or visible light, a chemical change takes place within the exposed crystals to form what is referred to as a latent image.
- When developed, the affected crystals are reduced to small grains of metallic silver.
- The degree of blackening of an area of the film depends on the amount of free silver deposited and, consequently, on the radiation energy absorbed.

Optical density

- The degree of blackening of the film is measured by determining optical density with a densitometer
- The optical density, OD, is defined as:

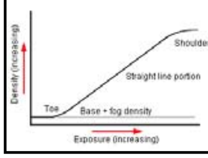
$OD = \log_{10}(Io/I)$

$OD = \log_{10}(T)$ where T is transmittance

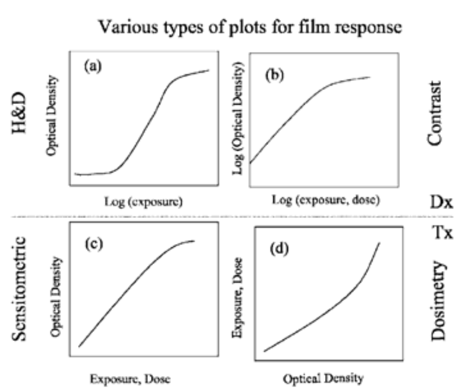
where I_0 is the amount of light collected without film and I_t is the amount of light transmitted through the film.

Characteristic curves of Film

- H&D curve is the film response curve where the log exposure is plotted on the *X* axis and the OD on the *Y* axis.
- important for quantifying contrast and dynamic range of a radiographic film
- typically has three sections: toe, gradient, and shoulder



Gradient, gamma, slope = $(D_2-D_1)/Log(E_2/E_1)$
Speed (sensitivity)= 1/Roentgens for OD equal to unity
Latitude (Contrast): range of log exposure to give an acceptable density range



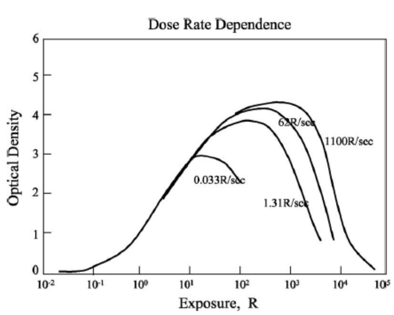
Characteristics of Optical Density

$OD = f(D, D_r, E, \gamma, d, FS, \theta, \tau)$,

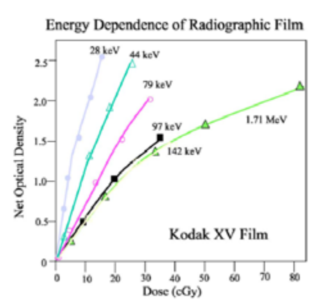
Where

- D = Dose
- D_r = Dose rage
- E = Energy
- T = type of radiation (x-ray, electron etc)
- d = depth of measurement
- FS = field size
- θ = directional (parallel or perpendicular)
- τ = processor condition (development time and developer concentration)

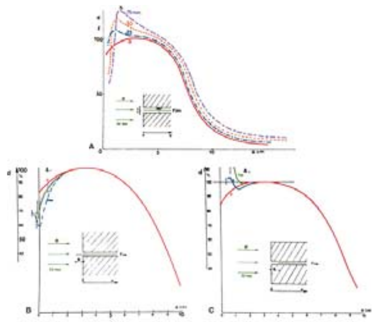
Dose rate dependence



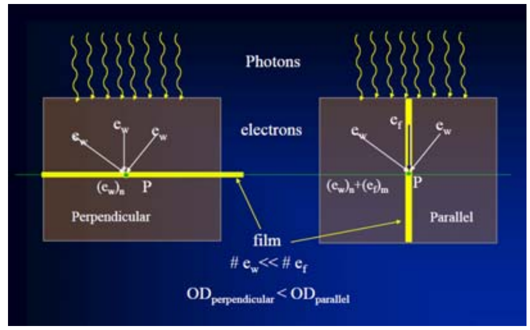
Energy dependence



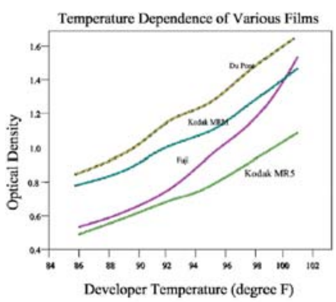
Film Placement



Directional dependence



Processor condition



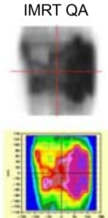
Commercial radiographic film

TABLE I. Physical properties of Kodak films.

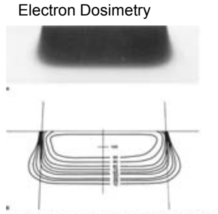
Description	XV2	EDR2
Grain crystal	AgBr and AgI	AgBr
Total silver density (g/cm²) (both sides of the film)	4.2	2.3
Effective thickness (μm)	0.4	0.2
Grain size distribution	Variation in size and shape	Monodisperse
Base thickness (μm)	180	180
Gelatin coating thickness (g/cm²) (per side)	3	5
Double sided	Yes	Yes
Dynamic range	0.05–0.80 Gy	0.1–5.0 Gy
Dynamic OD range	0–4	0–4
Approximate Dose (Gy) for OD 1	0.4	2.0
Maximum recommended dose (Gy)	0.8	5.0

Clinical Application of Film

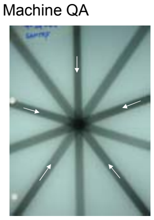
IMRT QA



Electron Dosimetry



Machine QA



Characteristics of Film

	Film
Dose rate dependency	Yes
Dose dependency	No
Background correction	Fog
Temperature, pressure	Processor developer
Polarity	NA
Linearity	Limited range
Directional dependence	Large
Spatial resolution/size effects	High spatial resolution
Readout convenience	Passive
Energy dependence	Large

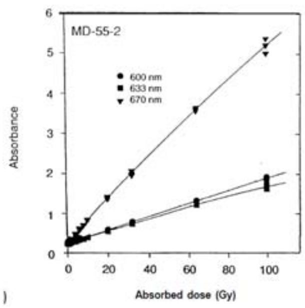
Radiochromic film

- Radiochromic film consists of a single or double layer of radiation-sensitive organic microcrystal monomers, on a thin polyester base with a transparent coating
- Color of the radiochromic films turns to a shade of blue upon irradiation
- Darkness of the film increases with increasing absorbed dose
- No processing is required to develop or fix the image.

Energy dependence

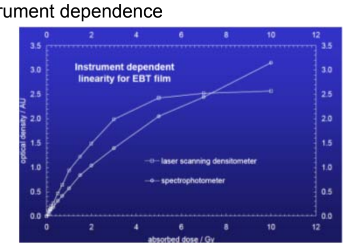
- Effective Z: 6.0 - 6.5
- Sensor material has similar electron stopping power as water & muscle
- Sensor material has similar mass-energy absorption coefficients as water and muscle for energy > 100 keV
- For secondary electron 0.1 to 1.0 MeV and photon energy 0.1 to 1.33 MeV : ~2% of water and muscle

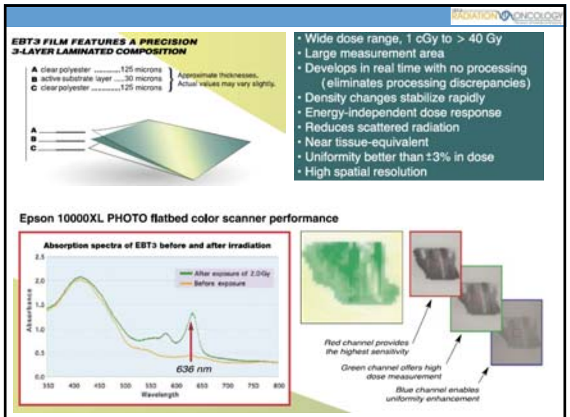
Linearity



Issues of Radiochromic film

- Film non-uniformity
- Variation in film sensitivity during manufacture process
- Instrument dependence





Calorimetry

- A basic method of determining absorbed dose in a medium.
- Absorbed dose = change in temperature of water
- 4.18 Joule = 1 calorie of heat
- Specific heat of water = 1 cal / g / ºC
- The increase in temperature (ΔT) produced by 1 Gy is:

  $\Delta T = 2.39 \times 10^{-4}$ °C

- Small changes in temperature are measured by "thermistors", semiconductors which show large change in resistance with small changes in temp.
- Clinically impractical to be implemented

Ferrous Sulfate (Fricke) Dosimeter

- The energy absorbed from ionizing radiation may produce a chemical change
- When irradiated, the ferrous ions, Fe^{2+}, are oxidized by radiation to ferric ions, Fe^{3+}.
- G-value = number of molecules per 100 eV absorbed

$$D = \frac{\Delta m}{\rho G} \cdot 9.64 \times 10^6 (Gy)$$

- G-value = 15.7$\pm$0.6 / 100eV for electrons 1-30 MeV, photon values similar
- Nearly tissue equivalent

Other dosimeters

- Alanine (Chemical based)
- Plastic scintillate system (Radiation induce light in scintillator)
- Diamond dosimeter (solid sate dosimeter)
- Metal-oxide-silicon-semiconductor field effect transistor (MOSFET)

Summary

- Absolute dosimetry means that the dose is determined from the first principles—without reference to another dosimeter.
  - The free-air ionization chamber, specially designed spherical chambers of known volume (e.g., at NIST), the calorimeter, and the ferrous sulfate (Fricke) dosimeter are examples of absolute dosimeters. They are also called primary standards
- Secondary dosimeters require calibration against a primary standard.
  - Ion chambers.
  - TLD, diodes, and film are also secondary dosimeters but are used primarily for relative dosimetry. They require calibration against a calibrated ion chamber as well as appropriate corrections for energy dependence (e.g., with depth) and other conditions that may affect their dose response characteristics.

References

- Khan, The Physics of Radiation Therapy, Chapter 8
- AAPM Task Group No. 69 Report (Radiographic Film)
- AAPM Task Group No. 55 Report (Radiochromic Film)
- AAPM Task Group No. 62 Report (Diode)
- AAPM Task Group No. 106 Report (Commissioning equipment and procedures)