Radiation Dosimeters and Detectors

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Slides from E. Podgorsak. PhD

Exposure

- Exposure is the quotient of ΔQ by Δm where
  - ΔQ is the sum of the electrical charges on all the ions of one sign produced in air, liberated by photons in a volume element of air and completely stopped in air.
  - Δm is the mass of the volume element of air.
- The special unit of exposure is the roentgen (R). It is applicable only for:
  - Photon energies below 3 MeV
  - Interaction between photons and air.
- 1 R corresponds to a charge of either sign of 2.58×10^{-4} C produced in 1 kg of air.

General Requirements for Dosimeters

- A dosimeter is a device that measures directly or indirectly
  - Exposure
  - Kerma
  - Absorbed dose
  - Equivalent dose
  - Or other related quantities.
- The dosimeter along with its reader is referred to as a dosimetry system.

Properties of Dosimeters

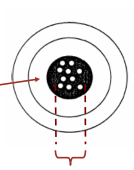
A useful dosimeter exhibits the following properties:

- High accuracy and precision
- Linearity of signal with dose over a wide range
- Small dose and dose rate dependence
- Flat Energy response
- Small directional dependence
- High spatial resolution
- Large dynamic range
- Convenience of use
- Sensitivity

Accuracy and precision

Accuracy specifies the proximity of the mean value of a measurement to the true value.

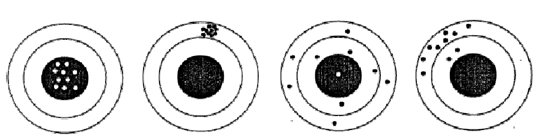
Precision specifies the degree of reproducibility of a measurement.



Note:
High precision
is equivalent to
small standard deviation.

Accuracy and precision

Examples for use of precision and accuracy:



High precision and High accuracy	High precision and Low accuracy	Low precision and High accuracy	Low precision and Low accuracy

Note: The accuracy and precision associated with a measurement is often expressed in terms of its uncertainty.

Linearity

- The dosimeter reading should be linearly proportional to the dosimetric quantity.
- Beyond a certain range, usually a non-linearity sets in.
- This effect depends on the type of dosimeter.

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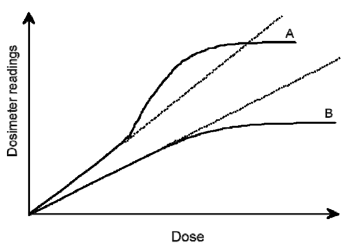
Linearity

Two possible cases



Case A:
- linearity
- supralinearity
- saturation

Case B:
- linearity
- saturation

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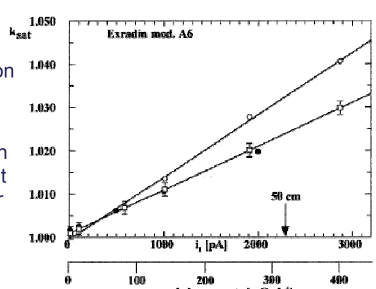
Dose rate dependence

Example:

The ion recombination effect is dose rate dependent.

This dependence can be taken into account by a correction factor that is a function of dose rate.



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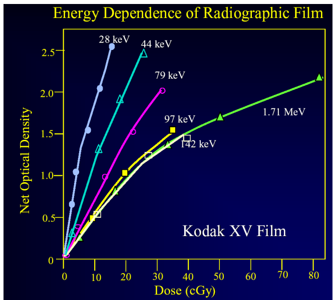
Energy dependence

The response of a dosimetric system is generally a function of the radiation energy.

Example 1:
Energy dependence of film dosimetry

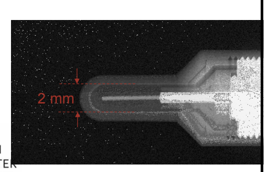


Directional dependence

- The variation in response as a function of the angle of the incidence of the radiation is called the directional dependence of a dosimeter.
- Due to construction details and physical size, dosimeters usually exhibit a certain directional dependence.
  - Diodes
  - Plane parallel chambers
  - TLDs

Spatial resolution and physical size

- The quantity absorbed dose is a point quantity.
- Ideal measurement requires a point-like detector.
- Examples that approximate a 'point' measurement are:
  - TLD
  - Diode
  - Film, gel, where the 'point' is defined by the resolution of the read-out system).
  - Pin-point micro-chamber.



Spatial resolution and physical size

- Ionization chamber-type dosimeters normally have a larger finite size.
  - Measurement result corresponds to the integral over the sensitive volume.
  - Measurement result can be attributed to a point within the volume referred to as the effective point of measurement.
  - Measurement at a specific point requires positioning of the effective point of measurement at this point.

Convenience of use

- Ionization chambers are **re-usable** with no or little change in sensitivity.
- Semiconductor dosimeters are **re-usable** but with gradual loss of sensitivity.
- Some dosimeters are not re-usable at all:
  - Film
  - Gel

Convenience of use

- Ionization chambers are re-usable dosimeters that are **rugged** and **handling** does not influence their sensitivity
  - (exception: ionization chambers with graphite wall)
- TL dosimeters are re-usable but are sensitive to handling and they lose sensitivity with repeated use.
- Some dosimeters measure **dose distribution** in a single exposure:
  - Films
  - Gels

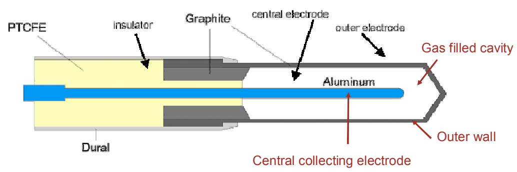
Sensitivity

- A high sensitivity is required to monitor low levels of radiation.
  - Scintillators
  - GM counters
- Scintillation-based systems are even more sensitive than GM counters because of higher gamma conversion efficiency and the dynode amplification.

Chambers and electrometers

Basic design of a cylindrical Farmer-type ionization chamber.

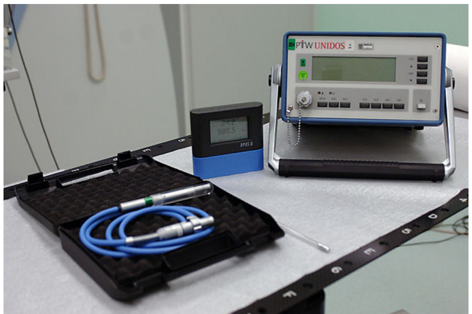
- An ionization chamber is basically a gas filled cavity surrounded by a conductive outer wall and having a central collecting electrode.



Chambers and electrometers

- Measure current or charge
- The wall and the collecting electrode are separated with a high quality insulator to reduce the leakage current when a polarizing voltage is applied to the chamber.
- A guard electrode is usually provided in the chamber to further reduce chamber leakage.
  - The guard electrode intercepts the leakage current and allows it to flow to ground directly, bypassing the collecting electrode.
  - The guard electrode ensures improved field uniformity in the active or sensitive volume of the chamber (for better charge collection).

Chambers and electrometers

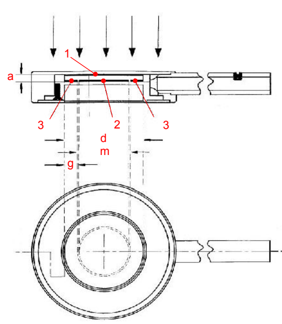


Cylindrical (thimble type) ionization chamber

- Cylindrical (thimble) ionization chamber
  - Most popular design
  - Independent of radial beam direction
  - Typical volume between 0.05 -1.00 cm^3
  - Typical radius ~2-7 mm
  - Length~ 4-25 mm
  - Thin walls: ~0.1 g/cm^2
  - **Used for**: electron, photon, proton, or ion beams.

Parallel-plate (plane-parallel) ionization chamber

(1) Polarizing electrode
(2) Measuring electrode
(3) Guard ring
- (a) height (electrode separation) of the air cavity
- (d) diameter of the polarizing electrode
- (m) diameter of the collecting electrode
- (g) width of the guard ring.



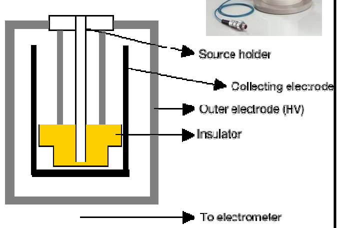
Parallel-plate (plane-parallel) ionization chamber

- Parallel-plate chamber is recommended for:
  - Dosimetry of electron beams with energies below 10 MeV.
  - Depth dose measurements in photon and electron beams.
  - Surface dose measurements of photon beams.
  - Depth dose measurements in the build-up region of mega-voltage photon beams.

Well chamber

- High sensitivity (useful for low rate sources as used in brachytherapy)
- Large volumes (about 250 cm^3)
- Can be designed to accommodate various sources sizes
- Usually calibrated in terms of the reference air kerma rate

Well type chamber



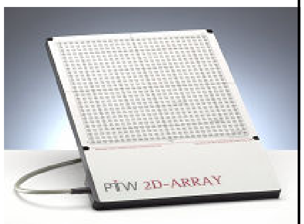
Extrapolation chambers

- Extrapolation chambers are parallel-plate chambers with a variable electrode separation.
- They can be used in **absolute radiation dosimetry** (when embedded into a tissue equivalent phantom).
- Cavity perturbation for electrons can be eliminated by:
  - Making measurements as a function of the cavity thickness
  - Extrapolating electrode separation to zero.
- Using this chamber, the cavity perturbation for parallel-plate chambers of finite thickness can be estimated.

Segmented chamber

Segmented chamber (example)

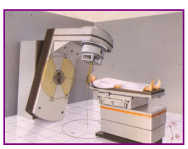
- 729 ionization chambers
- Volume of each: 5 mm x 5 mm x 4 mm
- Calibrated in terms of absorbed dose
- Commercialized software available



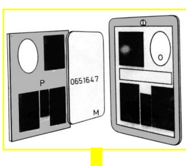
Radiographic film

Radiographic X-ray film performs important functions, e.g. in:

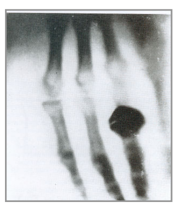
Radiotherapy



Radiation Protection



Diagnostic radiology



Radiographic film

Typical applications of a radiographic film in radiotherapy:

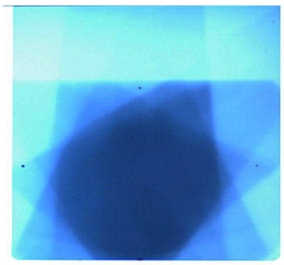
- Qualitative and quantitative dose measurements (including electron beam dosimetry)
- Quality control of radiotherapy machines:
  - Congruence of light and radiation fields
  - Determination of the position of a collimator axis
  - Dose profile at depth in phantom
  - Star-test
- Verification of treatment techniques in various phantoms
- Portal imaging.

Important aspect:
Film has also an archival property

Radiographic film

Typical applications of a radiographic film in radiotherapy:

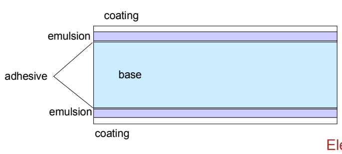
Verification of treatment techniques in various phantoms.

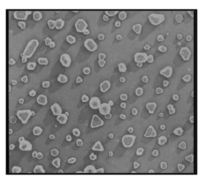


Radiographic film

Principle:

A thin plastic base layer (200 μm) is covered with a sensitive emulsion of AgBr crystals in gelatine (10-20 μm).





Electron micrograph of AgBr grains in gelatine with size of 0.1-3 μm

Radiographic film

- During irradiation:
  - Ag Br is ionized
  - Ag^+ ions are reduced to Ag: $Ag^+ + e^- \rightarrow Ag$
  - The elemental silver is black and produces a so-called latent image.
- During the development, other silver ions (yet not reduced) are now also reduced in the presence of silver atoms.
  - This means: If one silver atom in a silver bromide crystal is reduced, all silver atoms in this crystal will be reduced during development.
  - The rest of the silver bromide (in undeveloped grains) is washed away from the film during the fixation process.

Radiographic film

- Light transmission is a function of the film opacity and can be measured in terms of optical density (OD) with devices called densitometers.
- The OD is defined as $OD = \log_{10}\left(\frac{I_0}{I}\right)$ and is a function of dose, where

  I_0 is the initial light intensity, and
  I is the intensity transmitted through the film.

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Radiographic film

- Film gives excellent 2-D spatial resolution and, in a single exposure, provides information about the spatial distribution of radiation in the area of interest or the attenuation of radiation by intervening objects.

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Radiographic film

- The response of film depends on several parameters, which are difficult to control.
  - Consistent processing of the film is a particular challenge.
  - The useful dose range of film is limited and the energy dependence is pronounced for lower energy photons.
- Typically, film is used for qualitative dosimetry, but with proper calibration, careful use and analysis film can also be used for dose evaluation.
- Various types of film are available for radiotherapy work
  - for field size verification: direct exposure non-screen films
  - with simulators: phosphor screen films
  - in portal imaging: metallic screen films

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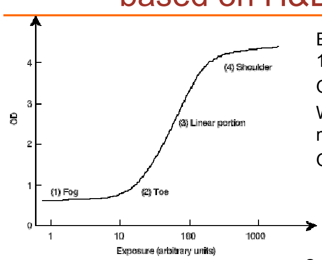
Radiographic film
The dose – OD relationship

- Ideally, the relationship between the dose and OD should be linear.
- Some emulsions are linear, some are linear over a limited dose range and others are non-linear.
- For each film, the dose versus OD curve (known as the sensitometric curve or as the characteristic or **H&D curve**, in honour of Hurter and Driffield) must therefore be established before using it for dosimetry work.

Parameters of Radiographic films based on H&D curve



Example:
1000 photons impinge on film.
Only 60% are absorbed.
What optical density would be measured?
OD = log (1000/40)=1.4

- *Gamma*: slope of the linear part
- *Latitude*: Range of exposures that fall in the linear part
- *Speed*: exposure required to produce an OD >1 over the fog
- *Fog*: OD of unexposed film

Radiochromic film

- Radiochromic film is a new type of film well suited for radiotherapy dosimetry.
- This film type is self-developing, requiring
  - neither developer
  - nor fixer.
- Principle: Radiochromic film contains a special dye that is polymerized and develops a blue color upon exposure to radiation.
- Similarly to the radiographic film, the radiochromic film dose response is determined with a suitable densitometer.

Radiochromic film

Advantages

- No quality control on film processing needed
- Radiochromic film is grainless ⇒ very high resolution
- Dose rate independence
- Better energy characteristics except for low energy x-rays (25 kV)
- Useful in high dose gradient regions for dosimetry:
  - stereotactic fields
  - the vicinity of brachytherapy sources

Disadvantage

- GafChromic films are generally less sensitive than radiographic films

LUMINESCENCE DOSIMETRY

- Upon absorption of radiation, some materials retain part of the absorbed energy in metastable states.
- When this energy is subsequently released in the form of ultraviolet, visible or infrared light, this phenomenon is called

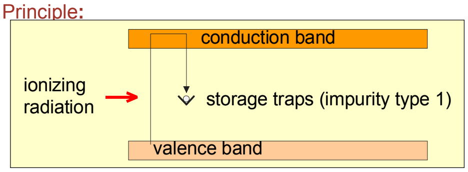
  Luminescence

LUMINESCENCE DOSIMETRY

- There are two types of luminescence:
  - Fluorescence
  - Phosphorescence
- The difference depends on the time delay between the stimulation and the emission of light:
  - Fluorescence has a time delay between 10^{-10} to 10^{-8} s.
  - Phosphorescence has a time delay exceeding 10^{-8} s.

LUMINESCENCE DOSIMETRY

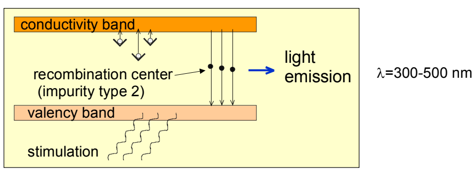
Principle:



- Upon radiation, free electrons and holes are produced
- In a luminescence material, there are so-called storage traps
- Free electrons and holes will either recombine immediately or become trapped (at any energy between valence and conduction band)

LUMINESCENCE DOSIMETRY

Principle (cont.):



- Upon stimulation, the probability increases for the electrons to be raised to the conduction band ….
- and to release energy (light) when they combine with a positive hole (needs an impurity of type 2)

LUMINESCENCE DOSIMETRY

- The process of luminescence can be accelerated with a suitable excitation in the form of heat or light.
- If the exciting agent is heat, the phenomenon is known as thermoluminescence
- When used for purposes of dosimetry, the material is called
  - Thermoluminescent (TL) material

    or
  - Thermoluminescent dosimeter (TLD).

LUMINESCENCE DOSIMETRY

- The process of luminescence can be accelerated with a suitable excitation in the form of heat or light.
- If the exciting agent is light, the phenomenon is referred to as **optically stimulated luminescence (OSL)**
- **Thermoluminescence (TL)** is thermally activated phosphorescence

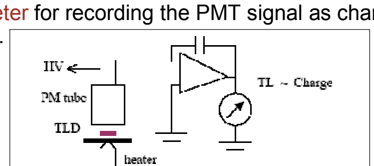
Thermoluminescent dosimeter systems

- TL dosimeters most commonly used in medical applications are (because of their tissue equivalence):
  - **LiF**:Mg,Ti
  - LiF:Mg,Cu,P
  - $Li_2B_4O_7$:Mn
- Other TLDs are (because of their high sensitivity):
  - $CaSO_4$:Dy
  - Al_2O_3:C
  - CaF_2:Mn
- TLDs are available in various forms (e.g., powder, chip, rod, ribbon, etc.).
- Before use TLDs have to be annealed to erase any residual signal.

TLD Reader

A basic TLD reader system consists of:

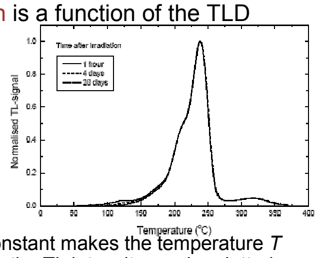
- Planchet for placing and heating the TLD dosimeter
- Photomultiplier tube (PMT) to detect the TL light emission, convert it into an electrical signal, and amplify it
- Electrometer for recording the PMT signal as charge or current.



TLD systems

The TL intensity emission is a function of the TLD temperature *T*

TLD glow curve or thermogram →



Keeping the heating rate constant makes the temperature *T* proportional to time *t* and so the TL intensity can be plotted as a function of *t*.

TLD Systems

- The main dosimetric peak of the LiF:Mg,Ti glow curve is between 180° and 260°C; this peak is used for dosimetry.
- TL dose response is linear over a wide range of doses used in radiotherapy, however:
  - In higher dose region it increases exhibiting supralinear behavior
  - at even higher doses it saturates
- To derive the absorbed dose from the TL-reading after calibration, correction factors have to be applied:
  - Energy correction
  - Fading
  - Dose-response non-linearity corrections

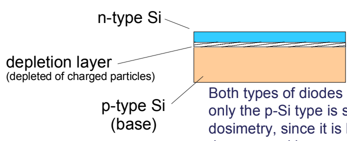
Optically stimulated luminescence

- Optically-stimulated luminescence (OSL) is based on a principle similar to that of the TLD. Instead of heat, light (from a laser) is used to release the trapped energy in the form of luminescence.
  - OSL is a novel technique offering a potential for *in vivo* dosimetry in radiotherapy.
  - A further novel development is based on the excitation by a pulsed laser (POSL)
  - The most promising material is Al_2O_3:C
  - To produce OSL, the chip is excited with a laser light through an optical fiber and the resulting luminescence (blue light) is carried back in the same fiber, reflected through a 90° by a beam-splitter and measured in a photomultiplier tube.

Semiconductors: Silicon diode dosimetry

- A silicon diode dosimeter is a positive-negative junction diode.
- The diodes are produced by taking n-type or p-type silicon and counter-doping the surface to produce the opposite type material.

These diodes are referred to as n-Si or p-Si dosimeters, depending upon the base material.



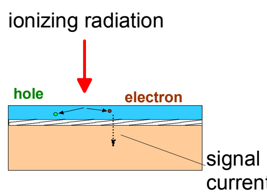
Both types of diodes are commercially available, but only the p-Si type is suitable for radiotherapy dosimetry, since it is less affected by radiation damage and has a much smaller dark current.

Silicon diode dosimetry

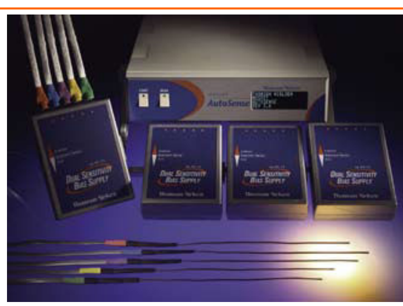
Principle

The depletion layer is typically several μm thick. When the dosimeter is irradiated, charged particles are set free which allows a signal current to flow.

Diodes can be operated with and without bias. In the photovoltaic mode (without bias), the generated voltage is proportional to the dose rate.

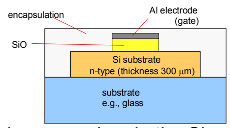


Silicon diode dosimetry systems



MOSFET dosimetry systems

- A MOSFET dosimeter is a Metal-Oxide Semiconductor Field Effect Transistor.



Physical Principle:

- Ionizing radiation generates charge carriers in the Si oxide.
- The charge carries moves towards the silicon substrate where they are trapped.
- This leads to a charge buildup causing a change in threshold voltage between the gate and the silicon substrate.

MOSFETs

Measuring Principle:

- MOSFET dosimeters are based on the measurement of the threshold voltage, which is a linear function of absorbed dose.
- The integrated dose may be measured during or after irradiation.

Characteristics:

- MOSFETs require a connection to a bias voltage during irradiation.
- They have a limited lifespan.
- The measured signal depends on the history of the MOSFET dosimeter.

MOSFETs

Advantages

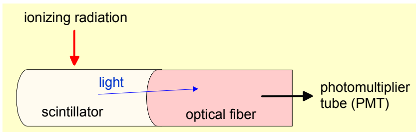
- MOSFETs are small
- Although they have a response dependent on radiation quality, they do not require an energy correction for mega-voltage beams.
- During their specified lifespan they retain adequate linearity.
- MOSFETs exhibit only small axial anisotropy (±2% for 360º).

Disadvantages

- MOSFETs are sensitive to changes in the bias voltage during irradiation (it must be stable).
- Similarly to diodes, they exhibit a temperature dependence.

Plastic scintillator dosimetry system

- Plastic scintillators are also a new development in radio-therapy dosimetry.



- The light generated in the scintillator is carried away by an optical fiber to a PMT (outside the irradiation room).
- Requires two sets of optical fibers, which are coupled to two different PMTs, allowing subtraction of the back-ground Cerenkov radiation from the measured signal.

Plastic scintillator dosimetry system

Advantages

- The response is **linear** in the therapeutic dose range.
- Plastic scintillators are almost **water equivalent**.
- They can be made very **small** (about 1 mm^3 or less)
- They can be used in cases where **high spatial resolution** is required:
  - High dose gradient regions
  - Buildup regions
  - Interface regions
  - Small field dosimetry
  - Regions very close to brachytherapy sources.

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Plastic scintillator dosimetry system

Advantages (cont.)

- Due to **flat energy dependence** and small size, they are ideal dosimeters for brachytherapy applications.
- Dosimetry based on plastic scintillators is characterized by **good reproducibility** and **long-term stability**.
  - They are independent of dose rate and can be used from 10 mGy/min (ophthalmic plaque dosimetry) to about 10 Gy/min (external beam dosimetry).
  - They have no significant directional dependence and need no ambient temperature or pressure corrections.

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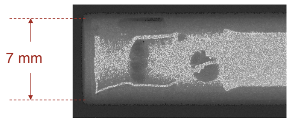
Diamond dosimeters

- Diamonds change their resistance upon radiation exposure. Under a biasing potential, the resulting current is proportional to the dose rate of radiation.
- The dosimeter is based on a natural diamond crystal sealed in a polystyrene housing with a bias applied through thin golden contacts.



Diamond dosimeters

Advantages

- Diamond dosimeters are **waterproof** and can be used for measurements in a water phantom.
- They are **tissue equivalent** and require nearly **no energy correction**.
- They are well suited for use in **high dose gradient regions**, (e.g., stereotactic radiosurgery).

Diamond dosimeters

Disadvantages

- In order to stabilize their dose response (to reduce the polarization effect) diamonds should **(must) be irradiated prior to each use.**
- They exhibit a small **dependence on dose rate**, which has to be corrected for when measuring:
  - Depth dose
  - Absolute dose
- Applying a higher voltage than specified can immediately destroy the diamond detector.

Gel dosimetry systems

Gel dosimetry systems are true 3-D dosimeters.

- The gel dosimeter is a phantom that can measure absorbed dose distribution in a full 3-D geometry.
- Gels are nearly tissue equivalent and can be molded to any desired shape or form.

Gel dosimetry systems

- Gel dosimetry is divided into two categories:
  Fricke gels and polymer gels
  Fricke gels are based on Fricke dosimetry
  - Fe^{2+} ions in ferrous sulfate solutions are dispersed throughout gelatin, agarose or PVA matrix.
  - Radiation induced changes are either due to direct absorption of radiation or via intermediate water free radicals.
  - Upon radiation, Fe^{2+} ions are converted into Fe^{3+} ions with a corresponding change in paramagnetic properties (measured by NMR relaxation rates, or optical techniques).

Polymer Gels

- In polymer gel, monomers such as acrylamid are dispersed in a gelatin or agarose matrix.
- Upon radiation, monomers undergo a polymerization reaction, resulting in a 3-D polymer gel matrix. This reaction is a function of absorbed dose.
- The dose signal can be evaluated using MR imaging, X-ray computed tomography (CT), **optical tomography**, vibrational spectroscopy or ultrasound.

Gel dosimeters

Advantages

- A number of polymer gel formulations are commercially available.
- There is a semilinear relationship between the NMR relaxation rate and the absorbed dose at a point in the gel dosimeter.
- Due to the large proportion of water, polymer gels are **nearly water equivalent and no energy corrections** are required for photon and electron beams used in radiotherapy.
- Polymer gels are well suited for use in **high dose gradient** regions, (e.g., stereotactic radiosurgery).

Gel dosimeters

Disadvantages

- Method usually needs access to an MRI machine.
- A major limitation of Fricke gel systems is the continual post-irradiation diffusion of ions, resulting in a blurred dose distribution.
- Post-irradiation effects can lead to image distortion.
- Possible post-irradiation effects:
  - Continual polymerization.
  - Gelation and strengthening of the gel matrix.

PRIMARY STANDARDS

- Primary standards are instruments of the highest metrological quality that permit determination of the unit of a quantity from its definition, the accuracy of which has been verified by comparison with standards of other institutions of the same level.
  - Primary standards are supported by Accredited Dose Calibration Labs (ADCL).

PRIMARY STANDARDS

- Ionization chambers used for calibration of radiotherapy beams must have a calibration coefficient traceable (directly or indirectly) to a primary standard.
- Primary standards are not used for routine calibrations, since they represent the unit for the quantity at all times.

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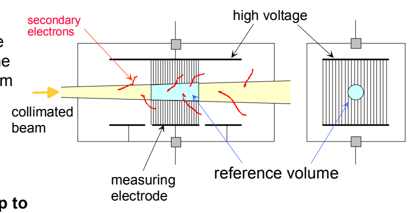
Primary standard for air kerma in air

- Free-air ionization chambers are the primary standard for air kerma in air for superficial and orthovoltage X rays (up to 300 kV).

Principle:
The reference volume (blue) is defined by the collimation of the beam and by the size of the measuring electrode. Secondary electron equilibrium in air is fulfilled.

Used for energies up to 3 MeV



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Primary standard for air kerma in air

- Free air ionization chambers cannot function as primary standard for ^{60}Co beams, since the air column surrounding the sensitive volume (for establishing the electronic equilibrium condition in air) would become very long.
- Therefore at ^{60}Co energy :
  - Graphite cavity ionization chambers with an accurately known chamber volume are used as the primary standard.
  - The use of the graphite cavity chamber is based on the Bragg–Gray cavity theory.

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Primary standard for absorbed dose to water

- Standards for absorbed dose to water enable therapy level ionization chambers to be calibrated directly in terms of absorbed dose to water instead of air kerma in air.
  - This simplifies the dose determination procedure at the hospital level and improves the accuracy compared with the air kerma based formalism.
  - Standards for absorbed dose to water calibration are now available for ^{60}Co beams in several ADCLs.
  - Some ADCLs have extended their calibration services to high energy photon and electron beams from accelerators.

Ionometric standard for absorbed dose to water

- A graphite cavity ionization chamber with accurately known active volume, constructed as a close approximation to a Bragg–Gray cavity, is used in a water phantom at a reference depth.
  - Absorbed dose to water at the reference point is derived from the cavity theory using the mean specific energy imparted to the air in the cavity and the restricted stopping power ratio of the wall material to the cavity gas.

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Chemical dosimetry standard for absorbed dose to water

- In chemical dosimetry systems the dose is determined by measuring the chemical change produced by radiation in the sensitive volume of the dosimeter.
- The most widely used chemical dosimetry standard is the Fricke dosimeter

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Chemical dosimeter: Fricke Dosimeter

- The Fricke dosimeter is a solution of the following composition in water:
  - 1 mM $FeSO_4$ [or $Fe(NH_4)_2(SO_4)_2$]
  - plus 0.8 N H_2SO_4 , air saturated
  - plus 1 mM NaCl
- Irradiation of a Fricke solution oxidizes ferrous ions Fe^{2+} into ferric ions Fe^{3+}.
- Ferric ions Fe^{3+} exhibit a strong absorption peak at a wavelength of 304 nm, whereas ferrous ions Fe^{2+} do not show any absorption at this wavelength.

Chemical dosimeter: Fricke Dosimeter

- The Fricke dosimeter response is expressed in terms of its sensitivity, known as the radiation chemical yield or G value.
- The G value is defined as the number of moles of ferric ions produced per joule of the energy absorbed in the solution.
- The chemical dosimetry standard is realized by the calibration of a transfer dosimeter in a total absorption experiment and the subsequent application of the transfer dosimeter in a water phantom, in reference conditions.

Calorimetric standard for absorbed dose to water

- Calorimetry is the most fundamental method of realizing the primary standard for absorbed dose, since temperature rise is the most direct consequence of energy absorption in a medium.
  - Graphite is in general an ideal material for calorimetry, since it is of low atomic number *Z* and all the absorbed energy reappears as heat, without any loss of heat in other mechanisms (such as the heat defect).

Calorimetric standard for absorbed dose to water

- The conversion to absorbed dose to water at the reference point in a water phantom may be performed by an application of the photon fluence scaling theorem or by measurements based on cavity ionization theory.

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Personal Monitoring

Results of external exposure monitoring is used:

- To assess workplace conditions and individual exposures;
- To ensure acceptably safe and satisfactory radiological conditions in the workplace;
- To keep records of monitoring over a long period of time, for the purposes of regulation or as good practice.

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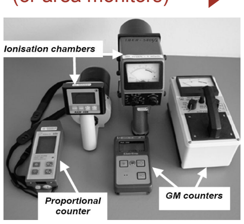
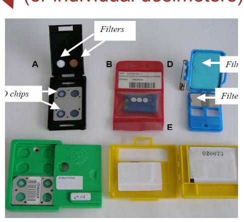
Personal Monitoring

Radiation monitoring instruments are classified as:

Area survey meters (or area monitors)



Personal dosimeters (or individual dosimeters)



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QUANTITIES FOR RADIATION MONITORING

Radiation monitoring instruments must be calibrated in terms of appropriate quantities for radiation protection.

Two issues must be addressed:

- Which quantities are used in radiation protection?
- Which quantities are in particular appropriate for
  - –Area monitoring ?
  - –Individual monitoring ?

Dosimetric quantities for radiation protection

- Recommendations regarding dosimetric quantities and units in radiation protection dosimetry are set forth by the International Commission on Radiation Units and Measurements (ICRU).
- The recommendations on the practical application of these quantities in radiation protection are established by the International Commission on Radiological Protection (ICRP).

Dosimetric quantities for radiation protection

Brief introduction of radiation protection quantities:

- Absorbed dose is the basic physical dosimetry quantity.
- However, it the absorbed dose is not entirely satisfactory for radiation protection purposes, because the effectiveness in damaging human tissue differs for different types of ionizing radiation.
- To account also for biological effects of radiation upon tissues, specific quantities were introduced in radiation protection.

Dosimetric quantities for radiation protection

The basic quantity in radiation protection is equivalent dose *H.*

The definition for equivalent dose *H* deals with two steps:

- The assessment of the organ dose D_T
- Introduction of radiation-weighting factors to account for the biological effectiveness of the given radiation in inducing deleterious health effects.

Dosimetric quantities for radiation protection

Radiation-weighting factors w_R:

- for x rays, gamma rays and electrons: $w_R = 1$
- for protons: $w_R = 5$
- for α particles: $w_R = 20$
- for neutrons, w_R depends on energy $w_R =$ 5 to 20

AREA SURVEY METERS

Radiation instruments used as survey monitors can be divided into two groups of detectors:

Gas filled detectors:

- ionization chambers
- proportional counters
- Geiger-Mueller (GM) counters

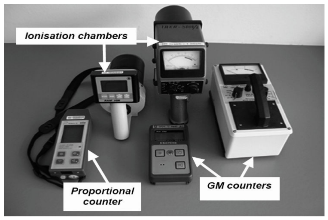
Solid state detectors:

- scintillator
- semiconductor detectors).

AREA SURVEY METERS

Properties of gas-filled detectors:

- Survey meters come in different shapes and sizes depending upon the specific application.



AREA SURVEY METERS

Properties of gas-filled detectors:

- Noble gases are generally used in these detectors.

Reasons:

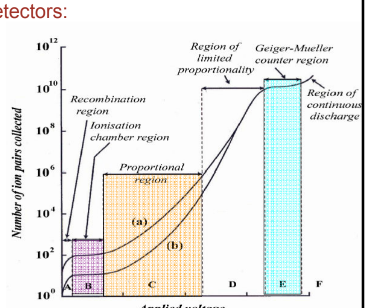
- The limit of the dose rate that can be monitored should be as high as possible: ⇨ a high charge-collection time is required.
- A high charge-collection time results from a high mobility of charge carriers.
- The charge carriers are electrons and negative ions.
- The mobility of negative ions is about three orders of magnitude smaller than that of electrons.
- Noble gases are non-electronegative gases in which negative ion formation by electron attachment is avoided.

AREA SURVEY METERS

Properties of gas-filled detectors:

Depending upon the voltage applied, the detector can operate in one of three regions:

- Ionization region B
- Proportional region C
- Geiger-Müller (GM) region E

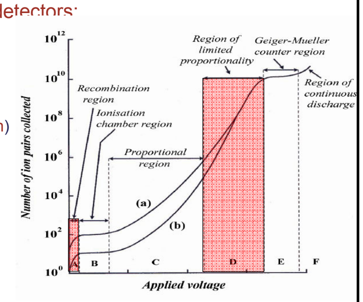


AREA SURVEY METERS

Properties of gas-filled detectors:

Regions not used for survey meters:

- Region A (recombination)
- Region D (limited proportionality in the "signal versus applied voltage")



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AREA SURVEY METERS

- Properties of gas-filled detectors:
  - Because of their high sensitivity, the tubes of GM-based gamma monitors are smaller in size compared to ionization chamber-type detectors.
  - The detectors can operate in a 'pulse' mode or in the 'mean level' or current mode. The proportional and GM counters are normally operated in the pulse mode.
  - Because of the time required by the detector to regain its normal state after registering a pulse, 'pulse' detectors will saturate at high intensity radiation fields. Ionization chambers, operating in the current mode, are more suitable for higher dose rate measurements.

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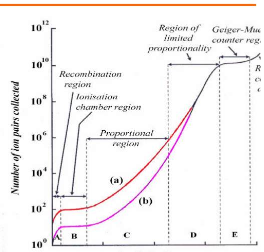
Ionization chambers

- In the ionization region the number of primary ions of either sign collected is proportional to the energy deposited by the charged particle tracks in the detector volume.
- Because of the linear energy transfer (LET) differences, the particle discrimination function can be used:
  - for 1 MeV beta particles
  - for 100 keV beta particles



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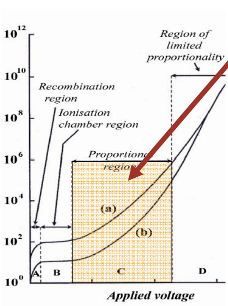
Ionization chambers

- Build-up caps are required to improve detection efficiency when measuring high-energy photon radiation, and they should be removed when measuring lower energy photons (10 - 100 keV) and beta particles.
  - Beta-gamma survey meters have a thin end-window to register weakly penetrating radiation.
  - The gamma efficiency of these detectors is only a few percent (as determined by the wall absorption), while the beta response is near 100% for beta particles entering the detector.

Proportional counters



At a sufficiently high voltage charge multiplication may occur (proportional region).

Charge multiplication occurs when the primary ions gain sufficient energy between successive collisions, in particular in the neighborhood of the thin central electrode.

The amplification is about 10^3-fold to 10^4-fold.

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Proportional counters

The amount of charge collected from each interaction is proportional to the amount of energy deposited in the gas of the counter by the interaction.

Proportional counters are more sensitive than ionization chambers.

Proportional counters are suitable for measurements in low intensity radiation fields.

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Neutron area survey meters

- Neutron area levels are normally associated with a photon background.
- ⇨ Neutron area survey meters require discrimination against the photon background.

Neutron area survey meters

A mixed neutron-photon radiation field has two components:

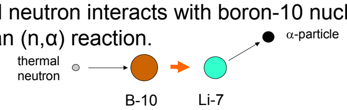
Neutrons which produce secondary particles (reaction products with high LET)	Photons which produce secondary electrons (with low LET)

- Because of differences in LET, the particle discrimination function of gas-filled detectors can be used.
- A high efficiency of discrimination is obtained when the gas-filled detector is operating in the proportional region.

Neutron area survey meters

Thermal neutrons can be detected very efficiently:

- A thermal neutron interacts with boron-10 nucleus causing an (n,α) reaction.



- The alpha particles can be detected easily by their ionizing interactions.
- Therefore, thermal neutron detectors usually
  - have a coating of a boron compound on the inside of the wall or
  - the counter is filled with BF_3 gas.

Neutron area survey meters

To also detect fast neutrons, the counter is surrounded by a moderator made of hydrogenous material.

- The fast neutrons interacting with the moderator get thermalized.
- Subsequently they are detected by the BF_3 counter placed inside the moderator.

The whole assembly is now a fast neutron counter.

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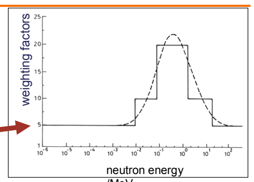
Neutron area survey meters

Filter compensation is required to reduce the over-response to thermal neutrons so that the response follows the weighting factors w_R. (broken line, solid line is a useful approximation)



The output is approximately proportional to equivalent dose in soft tissue over a wide range (10 decades) of neutron energy spectra.

Other neutron detectors work on the same principles.

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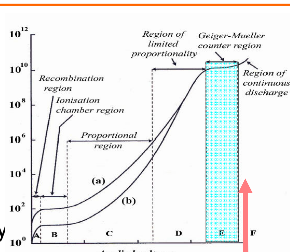
GM counters

In the GM region the discharge spreads throughout the volume of the detector.

⇨ The pulse height becomes independent of the primary ionization or the energy of the interacting particles.



Gas-filled detectors cannot be operated at voltages beyond this region because they continuously discharge.

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GM counters

- Because of the large charge amplification (9 to 10 orders of magnitude), GM survey meters are widely used at very low radiation levels.
  - GM counters exhibit strong energy dependence at low photon energies and are not suitable for the use in pulsed radiation fields.
  - They are considered 'indicators' of radiation, whereas ionization chambers are used for more precise measurements.

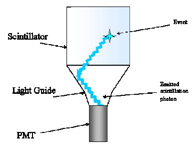
GM counters

Disadvantage of GM counters:

- GM detectors suffer from very long dead-times, ranging from tens to hundreds of ms.
- For this reason, GM counters are not used when accurate measurements are required of count rates of more than a few 100 counts per second.
  - A portable GM survey meter may become paralyzed in a very high radiation field and yield a zero reading.
  - Therefore ionization chambers should be used in areas where radiation rates are high.

Scintillator detector

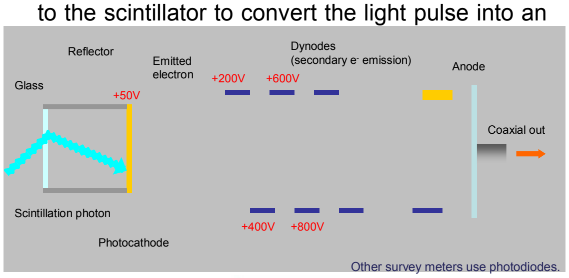
- Detectors based on scintillation (light emission) are known as scintillation detectors and belong to the class of solid-state detectors.
- Certain organic and inorganic crystals contain activator atoms and emit scintillations (light) upon absorption of radiation.



- High atomic number phosphors are mostly used for the measurement of gamma rays, while the plastic scintillators are mostly used with beta particles.

Scintillator detector

A photomultiplier tube (PMT) is optically coupled to the scintillator to convert the light pulse into an



Other survey meters use photodiodes.

Semiconductor detector

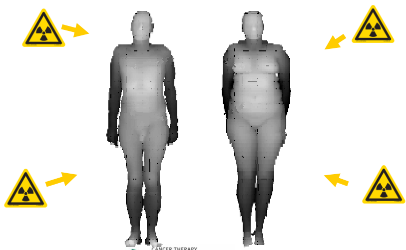
- Semiconductor detectors belong to the class of solid-state detectors.
- Semiconductor detectors act like solid-state ionization chambers when exposed to radiation.
- The sensitivity of solid state detectors is about 10^4 times higher than that of gas-filled detectors because:
  - Average energy required to produce an ion pair is one order less
  - Material density is typically 3 larger than the density of gases.

Semiconductor detector

- The high sensitivity of semiconductor detectors helps in miniaturizing radiation-monitoring instruments.
- Example:
  A commercial electronic pocket dosimeter based on a semiconductor detector

INDIVIDUAL MONITORING

Individual monitoring is the measurement of radiation doses received by individuals working with radiation.



INDIVIDUAL MONITORING

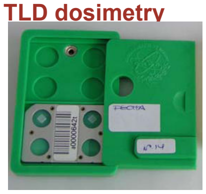
Individual monitoring is used for those who regularly work in controlled areas or those who work full time in supervised areas:

- To have their doses monitored on a regular basis.
- To verify the effectiveness of radiation control practices in the workplace.
- To detect changes in radiation levels in the workplace.
- To provide information in case of accidental exposures.

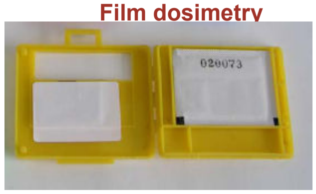
INDIVIDUAL MONITORING

The most widely used individual monitoring systems are based on either TLD or film dosimetry:

TLD dosimetry



Film dosimetry



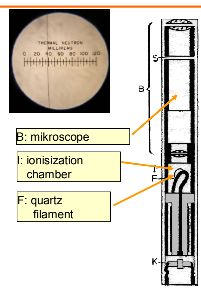
INDIVIDUAL MONITORING

Other measuring techniques used for individual monitoring systems:

- Radiophotoluminesce (RPL)
- Optically simulated luminescence (OSL)
- In case of fast neutron doses:
  - Albedo dosimeter
  - Nuclear track emulsion

INDIVIDUAL MONITORING

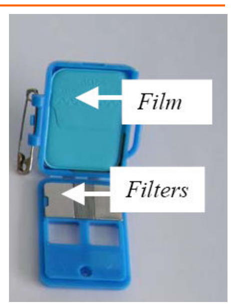
Self-reading pocket dosimeters and electronic personal dosimeters are direct reading dosimeters and show both the instantaneous dose rate and the accumulated dose at any time.



Setup of a simple pocked dosimeter

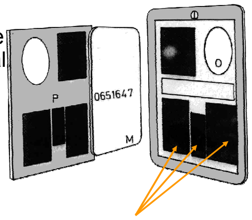
Film badge

- A film badge is a special emulsion photographic film in a light-tight wrapper enclosed in a case or holder with windows with appropriate filters.
- The badge holder creates a distinctive pattern on the film indicating the type and energy of the radiation received.



Film badge

- The film is a non-tissue equivalent radiation detector.
- The film has not the response of a tissue-equivalent material.
- A filter system is therefore required to adjust the energy response.
- One filter is adequate for photons of energy above 100 keV.
- A multiple filter system is used for lower energy photons.



Film badge

Evaluation: Cumulative doses from beta, x, gamma, and thermal neutron radiation are evaluated by:

- Production of calibration films (exposed to known doses of well defined radiation of different types).
- Measuring the optical density of the film under different filters.
- Comparing the optical density with the calibration films.

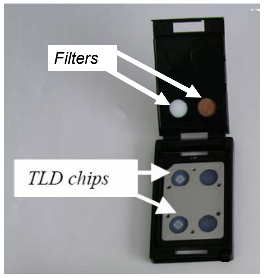
Film badge

A film can also serve as a monitor of neutron doses.

- Thermal neutrons:
  A cadmium window absorbs thermal neutrons and the resulting gamma radiation blackens the film below this window as an indication of the neutron dose.
- Fast neutrons:
  Nuclear track emulsions are used. The neutrons interact with hydrogen nuclei in the emulsion and surrounding materials, producing recoil protons by elastic collisions. These particles create a latent image, which leads to darkening of the film along their tracks after processing.

Thermoluminescent dosimetry (TLD) badge

- A TLD badge consists of a set of TLD chips enclosed in a plastic holder with filters.
- The most frequently used TLD materials (also referred to as phosphors) are:
  - LiF:Ti,Mg
  - CaSO4:Dy
  - CaF2:Mn



TLD badge

- If the TLD material incorporates atoms with a high Z, it is not tissue equivalent. Then a filter system similar to film badges must be provided to achieve the required energy response.
- TLD badges using low Z phosphors do not require such complex filter systems.
- The TLD signal exhibits fading, but this effect is less significant than with films.

TLD badge

- Because of the small size of TLDs, they are convenient for monitoring doses to parts of the body (e.g., eyes, arm or wrist, or fingers) using special type of dosimeters, including extremity dosimeters.

Finger ring dosimeter

TLD badge

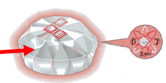
A TLD dosimeter can also serve as a monitor for neutrons

Techniques:

- Using the body as a moderator to thermalize neutrons (similarly to albedo dosimeters)
- Using LiF enriched with lithium-6 for enhanced thermal neutron sensitivity due to the (n,α) reaction of thermal neutrons in lithium-6.

Optically stimulated luminescence (OSL) systems

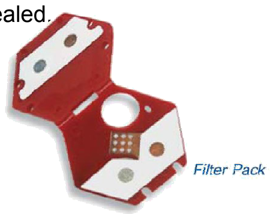
- Optically stimulated luminescence is now commercially available also for measuring personal doses.
  - OSL dosimeters contain a thin layer of aluminum oxide (Al203:C).



  - During analysis the aluminum oxide is stimulated with selected frequencies of laser light producing luminescence proportional to radiation exposure.

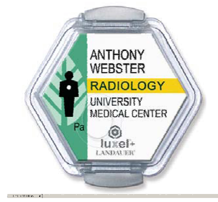
OSL

- Commercially available badges are integrated, self contained packets that come preloaded, incorporating an Al203 strip sandwiched within a filter pack that is heat-sealed.
- Special filter patterns provide qualitative information about conditions during exposure.



OSLs

- OSL dosimeters are highly sensitive; e.g., the Luxel® system can be used down to 10 µSv with a precision of ±10 µSv.
- This high sensitivity is particularly suitable for individual monitoring in low-radiation environments.



OSL

- The dosimeters can be used in a wide dose range up to 10 Sv.
- Photon Energy range is from 5 keV to 40 MeV.
- OSL dosimeters can be re-analysed several times without loosing the sensitivity and may be used for up to one year.

IONIZATION CHAMBERS

Advantage	Disadvantage
❑ Accurate and precise ❑ Recommended for beam calibration ❑ Necessary corrections well understood ❑ Instant readout	❑ Connecting cables required ❑ High voltage supply required ❑ Many corrections required

FILM

Advantage	Disadvantage
❑ 2-D spatial resolution ❑ Very thin: does not perturb the beam	❑ Darkroom and processing facilities required ❑ Processing difficult to control ❑ Variation between films & batches ❑ Needs proper calibration against ionization chambers ❑ Energy dependence problems ❑ Cannot be used for beam calibration

TLD

Advantage	Disadvantage
❑ Small in size: point dose measurements possible ❑ Many TLDs can be exposed in a single exposure ❑ Available in various forms ❑ Some are reasonably tissue equivalent ❑ Not expensive	❑ Signal erased during readout ❑ Easy to lose reading ❑ No instant readout ❑ Accurate results require care ❑ Readout and calibration time consuming ❑ Not recommended for beam calibration

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SILICON DIODE

Advantage	Disadvantage
❑ Small size ❑ High sensitivity ❑ Instant readout ❑ No external bias voltage ❑ Simple instrumentation	❑ Requires connecting cables ❑ Variability of calibration with temperature ❑ Change in sensitivity with accumulated dose ❑ Special care needed to ensure constancy of response ❑ Cannot be used for beam calibration

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Recall Questions

- Best method of measuring Cobalt-60 head leakage – GM counter, film?
- Filter in film badge used for?
- Determine the corrected reading for an thimble chamber where the gas is air: (TP correction factor – temp, pressure, reading given)
- The factors that affect the reading on ion chamber, temperature and pressure. What is the relation for 2 different situations t1, t2, v1, v2. So, when the temperature will increase, how this will affect the reading?

Recall Questions

- Linac machine's ion chamber monitors 1) symmetry, 2) dose rate, 3) integrated dose
- Different graphs are given and the question is to point to the H&D graph.
- What are the advantages of the pocket dosimeter?
- What dosimeter can you use for MLC QA?
- What other detectors are used for QA?