Patient dosimetry in radiography: What to measure and estimate, why & how

ICTP/IAEA Training Course on Radiation Protection of Patients
September 16 - 27, 2013, Trieste, Italy

Topics

- Dose Quantities
- Parameters influencing patient exposure
- Dosimetric methods applicable to diagnostic radiology:
  - Dosemeters
  - Dose measurements
  - Dose calculations

Patient Dose

- The mean absorbed dose in a tissue or organ DT is the energy deposited in the organ divided by the mass of that organ → except for invasive methods, **no organ doses can be measured**
- The only way in radiography is:
  - Measure the Entrance Surface Air Kerma (ESAK)
  - Use mathematical models based on Monte Carlo simulations (the history of thousands of photons is calculated) to estimate internal dose.
  - Dose to the organ tabulated as a fraction of the entrance dose for different projections
  - Since filtration, field size and orientation play a role: long lists of tables (See NRPB R262 and NRPB SR262)

Factors influencing dose in radiography

Beam energy

- Depending on peak kV and filtration
- Regulations require minimum total filtration to absorb lower energy photons
- Added filtration reduces dose ($\rightarrow$ use of highest kV resulting in acceptable image contrast)

Factors influencing dose in radiography

- Grids
  - Reduce the amount of scatter reaching image receptor
  - But at the cost of increased patient dose
  - Typically 2-5 times: "Bucky factor" or grid ratio
- Patient size
  - Thickness, volume irradiated…and dose increases with patient size
  - Technique charts with suggested exposure factor for various examinations and patient thickness helpful to avoid retakes

Parameters influencing patient exposure

Tube voltage
Tube current
Effective filtration
} Kerma rate [mGy/min]

Exposure time .... [min]
} Kerma [μGy]

Field size .... [m^2]
} Area exposure product [$\mu Gy\ m^2$]

Operational dose quantities

Quantities related to patient dose:

- Radiation output of X Ray tubes
- Entrance surface dose
- Dose-Area Product (DAP)

KERMA and Dose

- KERMA (kinetic energy released in a material) is the sum of the initial kinetic energies of all charged ionizing particles liberated by uncharged ionizing particles in a material of mass dm

- Absorbed dose is the energy absorbed per unit mass

In diagnostic radiology, Kerma and D are equal

- The SI unit of kerma and dose is the joule per kilogram (J/kg), termed gray (Gy).

Incident Air Kerma (iAK)

Incident air kerma is the air kerma from the incident beam on the central X ray beam axis at the focal-spot-to surface distance at the skin entrance plane.

Only primary radiation incident on the patient or phantom and not backscattered radiation is included.

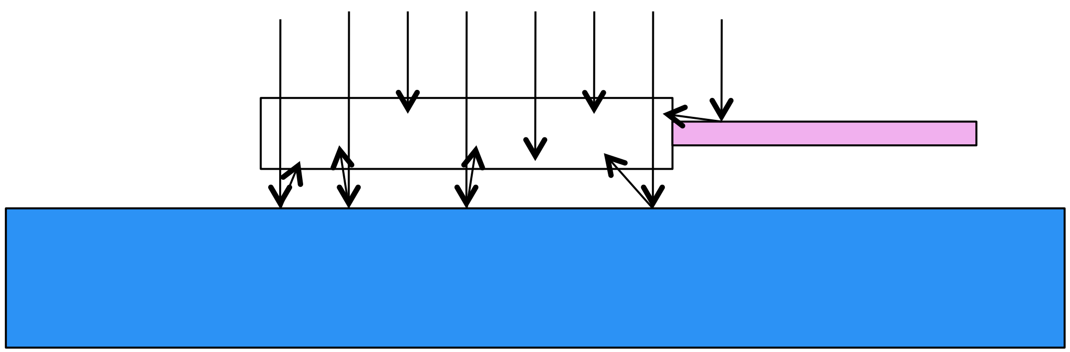
Entrance-surface air kerma (ESAK)

Entrance-surface air kerma (ESAK) is the air kerma on the central X ray beam axis at the point where X ray beam enters the patient or phantom.

The contribution of the backscattered radiation is included.

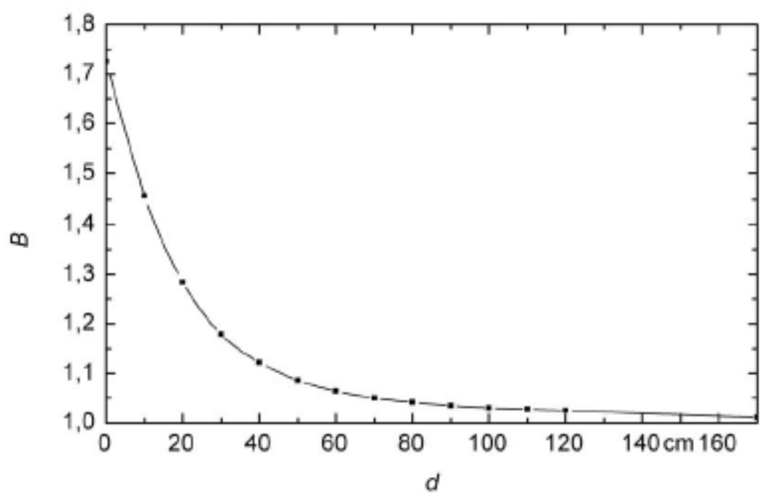
Effect of scatter

- Radiation is scattered from any surface
- Lighter materials such as tissue scatter more radiation than heavier ones such as lead
- This may affect dose measurements recorded
- If the radiation detectors is placed directly on any surface, it will be exposed to backscattered radiation

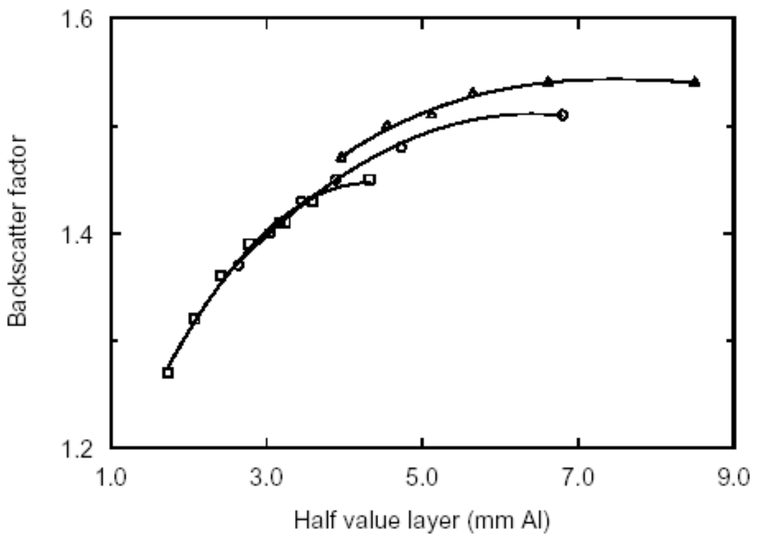


Influence of BS radiation on measurements

The contribution of scattered radiation to the air kerma at the point of measurement is below 3% (5%) if there is no material in the beam in the space of 1 m (0.7 m) behind the point of measurement.



10 cm PMMA, 60x60 cm^2, beam quality RQR10



Backscatter factors; 25x25 cm^2; 2.5 mm total filtration

Backscatter factors (water)

HVL (mm Al)	Field size (cm x cm)				
	10 x 10	15 x 15	20 x 20	25 x 25	30 x 30
2.0	1.26	1.28	1.29	1.30	1.30
2.5	1.28	1.31	1.32	1.33	1.34
3.0	1.30	1.33	1.35	1.36	1.37
4.0	1.32	1.37	1.39	1.40	1.41

Absorbed dose in soft tissue

- Values of absorbed dose to tissue will vary by a few percent depending on the exact composition of the medium that is taken to represent soft tissue.
- The following value is usually used for 80 kV and 2.5 mm Al of filtration :

$$\mathbf{Fc} = \left(\left(\frac{\mu_{en}}{\rho} \right)_{water} \Big/ \left(\frac{\mu_{en}}{\rho} \right)_{air} \right) \cong \mathbf{1.06}$$

Detectors for X-Ray dose measurements

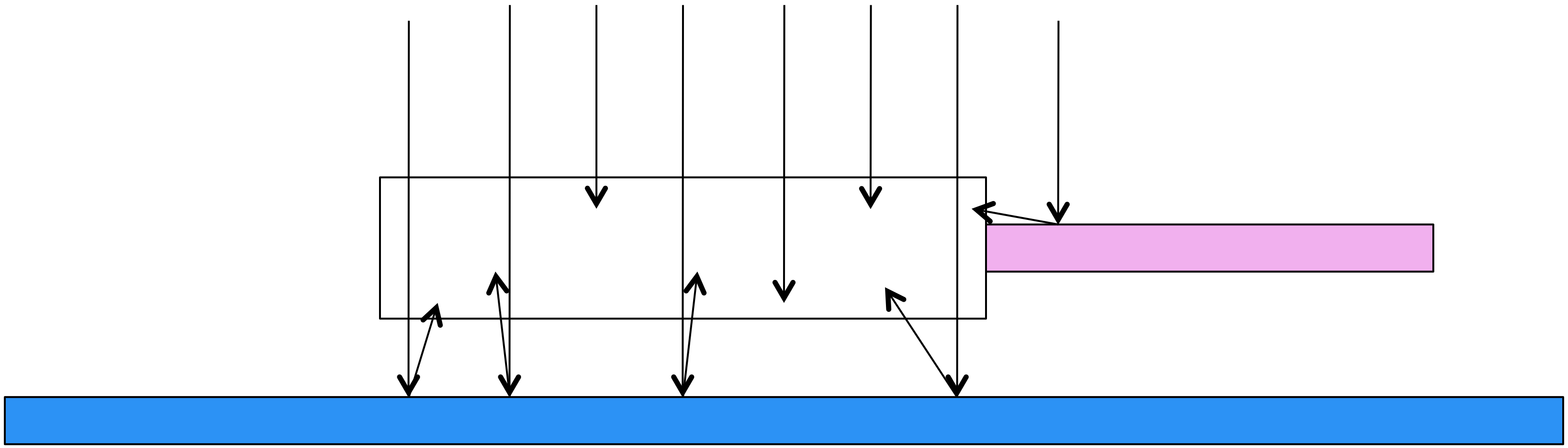
- Ionisation chambers
- Semiconductor detectors

Ionisation Chambers

- Collect ions produced by interactions in air
- Atomic Numbers similar to tissue → similar interactions
- Different sizes → also related to dose and dose rate (larger sizes of chambers used for measurement of low doses, which produce less charge)
- IC are sensitive to radiation incident from all directions and this has an influence on scatter radiation detected.

Ionisation Chambers

Ionisation chambers are thin walled and usually detect radiation from all directions



Ionisation Chambers

Thimble Ionisation Chamber

- Cylindrical shape

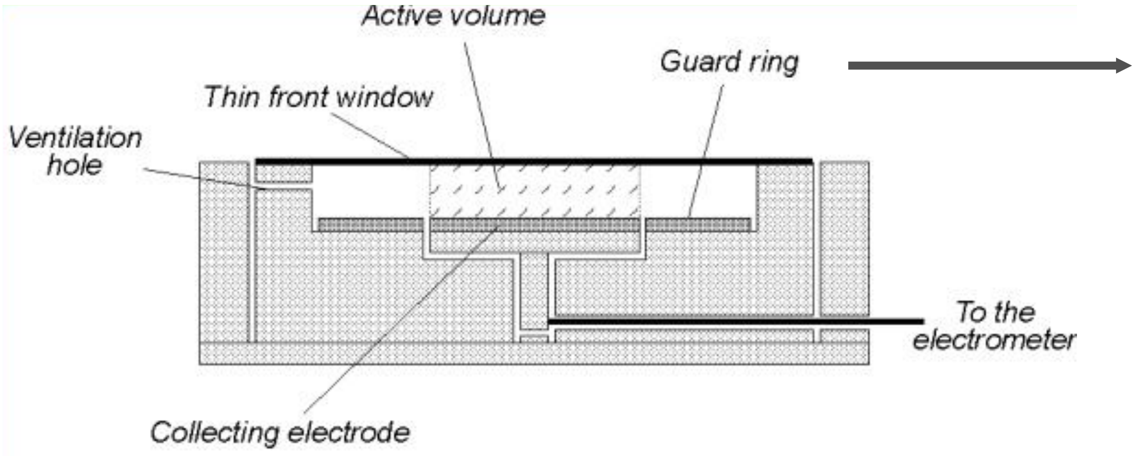
- Two electrodes: the external wall of the chamber constitutes the cathode; the anode is a filament placed in the centre of the volume.

Thimble Ionisation Chamber

- Cap material is air-equivalent (same absorption as the same mass of air)
- Electrons used to measure change in charge are produced in cap.
- Cap thickness is important:
  - Too thin: insufficient electrons enter the chambers
  - Too thick: too much radiation absorbed
- Response is symmetrical with respect to the chamber axis

Parallel Plate Ionisation Chamber

- Most common type of IC used for diagnostic radiological measurement of air kerma (to improve spatial resolution at least in one dimension).



Reduce distorsions

- Two parallel flat electrodes separated by few millimeters. The chamber window thickness should be sufficient to allow full buildup of the secondary electron spectrum

Parallel Plate Ionisation Chamber

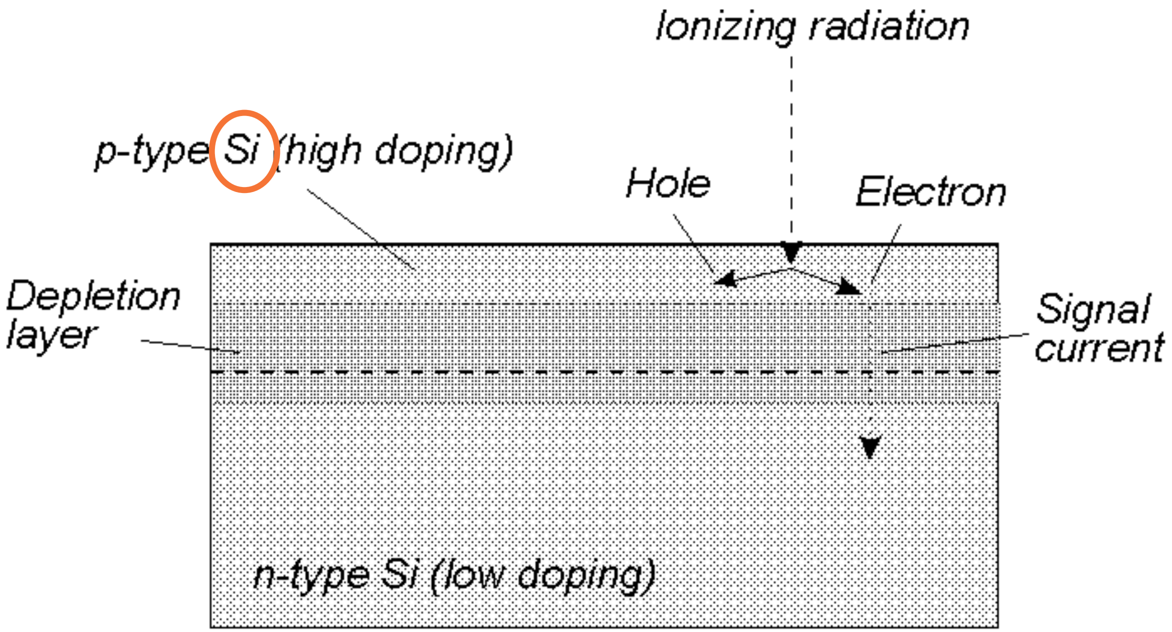
- Size of IC is important: it should be large enough to collect sufficient charge to give a measurement (1Gy produces approximately 36 nC in 1cc of air) but taking into account x-ray beam size
- IC is calibrated with plates oriented perpendicularly to the beam axis.
- If parallel plate IC has different entrance and exit windows, it's important that the entrance window faces the focal spot.
- IC chambers are calibrated at the calibration laboratories in term of free in air kerma

Transmission chamber

- Detector is “transparent” to X rays: attenuation can be neglected.
- Generally consists of layers of PMMA coated with conducting material.
- Graphite could not be used because is not transparent to light.
- Used materials contains elements of high atomic number (indium, tin) → energy dependence.
- Used as KAP meters.

Semiconductors dosimeters

- **<u>Diode</u>**: simplest semiconducting devices (based on a p-n junction)

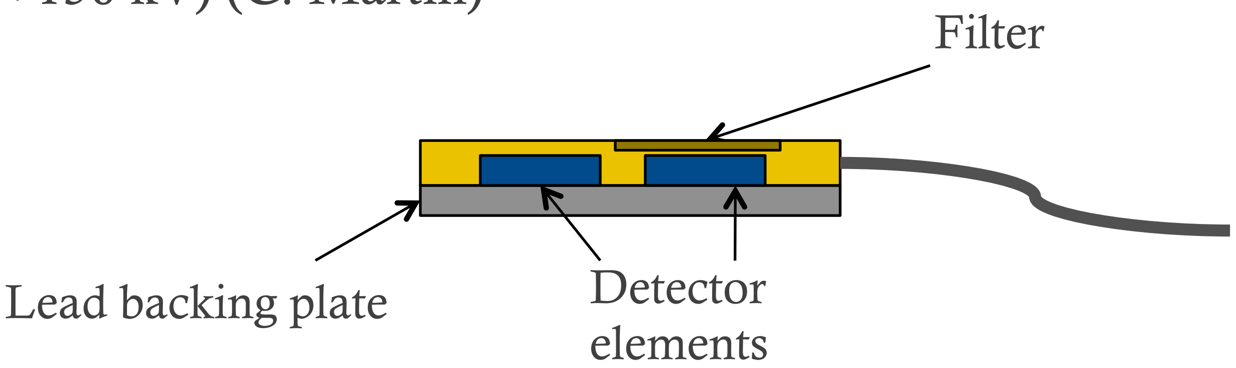


Semiconductors Detectors

- X-rays excite electrons in semiconductor
- Atomic numbers (Si) significantly higher atomic number than tissue → different mechanisms of interactions

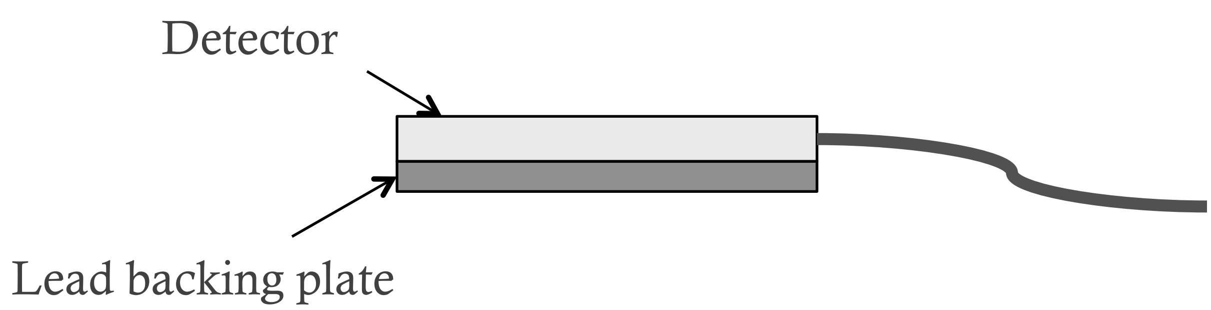
Semiconductors Detectors

- Similar response with photon energy is achieved through using 2 or more detector elements with one or more positioned behind a thin metal filter
- Readings are combined using an algorithm to give a similar response with photon energy to tissue → with his technique accuracy within +5% over the range of X-ray beam energies (50÷150 kV) (C. Martin)



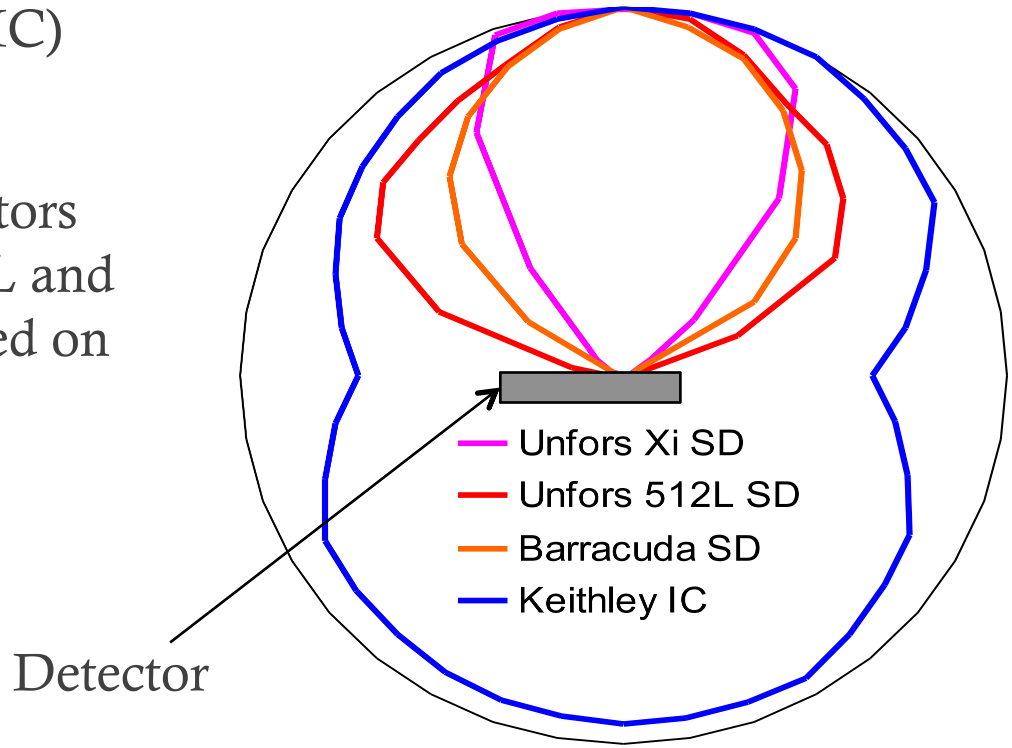
Semiconductor Detectors

- Detectors are placed on lead backing plate to attenuate radiation incident from the rear, which would alter the ratios of radiations incident on the different elements
- Lead backing plates affect the angular responses of the detectors → angles ranged from 40° to 120°.



Polar response of different detectors

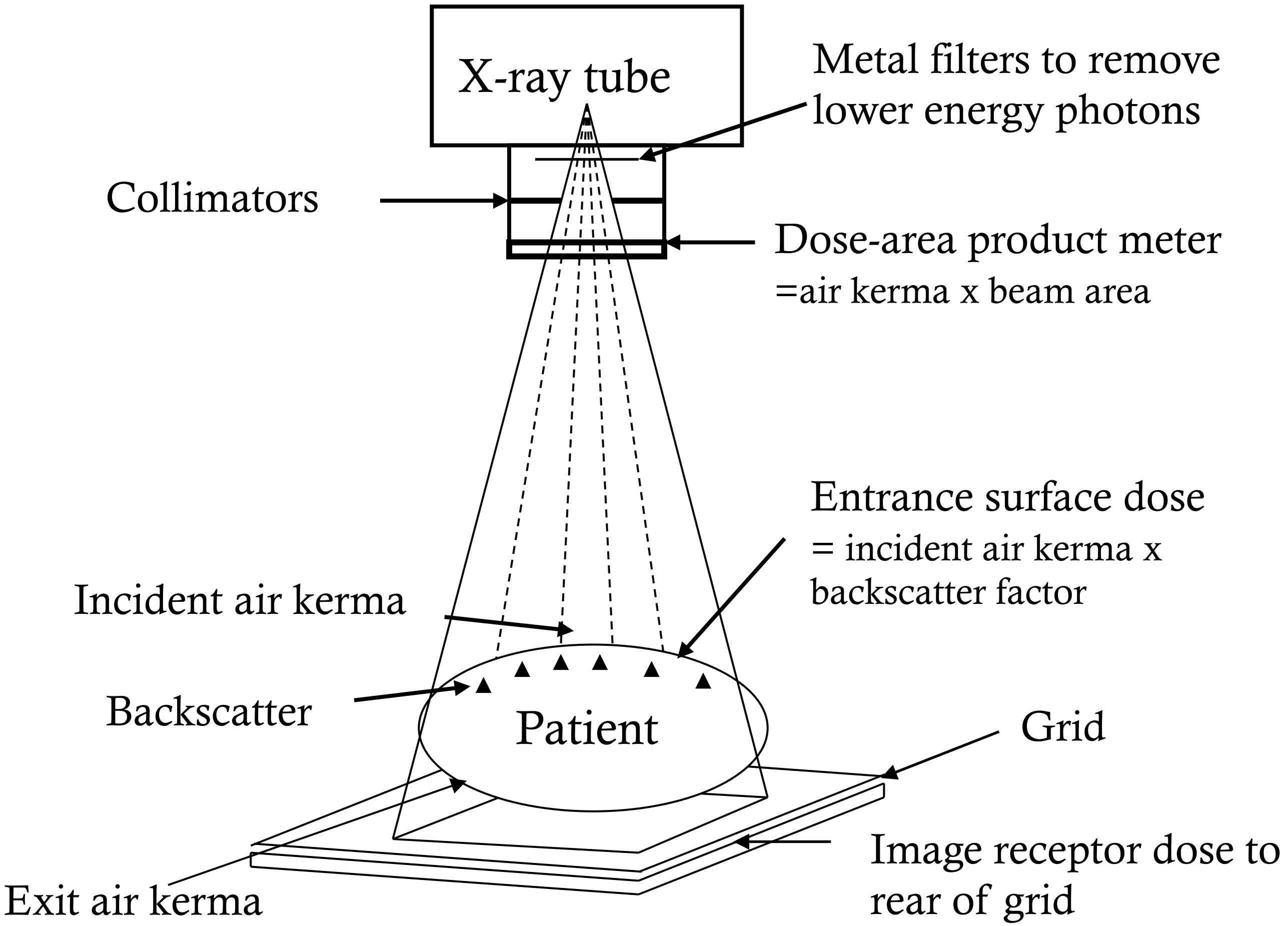
- Ionisation Chamber (IC) Keithley
- Semiconductor Detectors (SDs) Unfors Xi, 512L and Barracuda are mounted on lead backing plates



Multimeters

Multimeters produced by different manufacturers allow measurement of dose, kVp and other parameters such as exposure time with one meter

X-Ray System

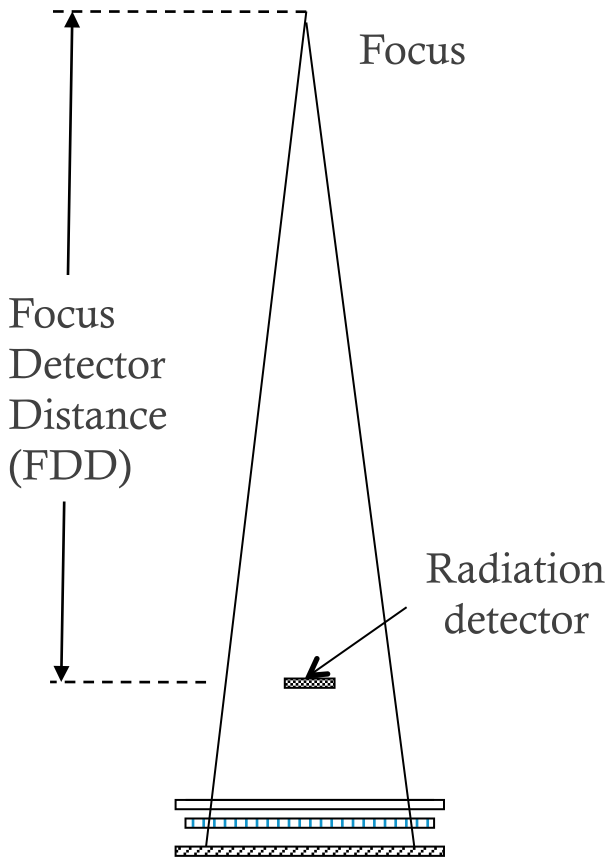

X-ray tube
Metal filters to remove lower energy photons
Collimators
Dose-area product meter
=air kerma x beam area
Entrance surface dose
= incident air kerma x backscatter factor
Incident air kerma
Backscatter
Patient
Grid
Image receptor dose to rear of grid
Exit air kerma

X-Ray Tube Output

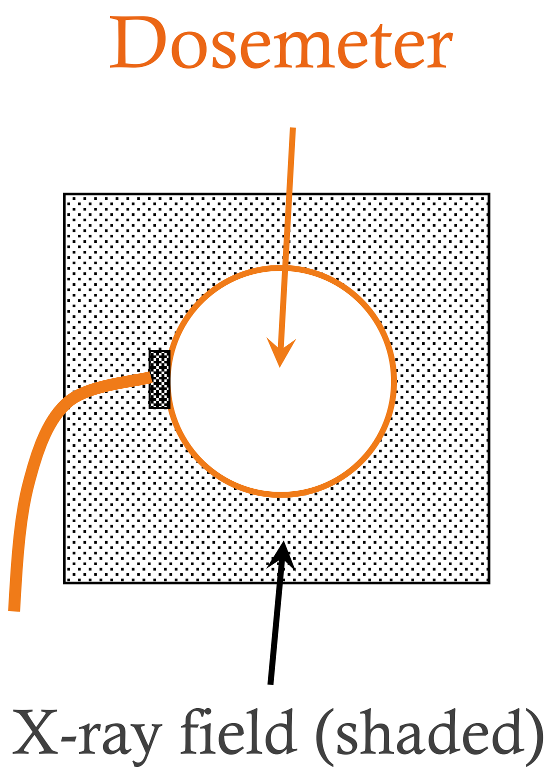
The X ray tube output is the air kerma at a specified distance from the X ray tube focal spot, divided by the *mAs* (tube-current exposure-time product).

Measurement set-up

- Detector at a known distance from the x-ray tube focus (FFD normally 50 cm)
- Away from objects which might scatter radiation
- Radiation field size at least 10x10 cm^2
- Measurement repeated for different kV values
- mAs setting depends on tube loading and conditions of normal use



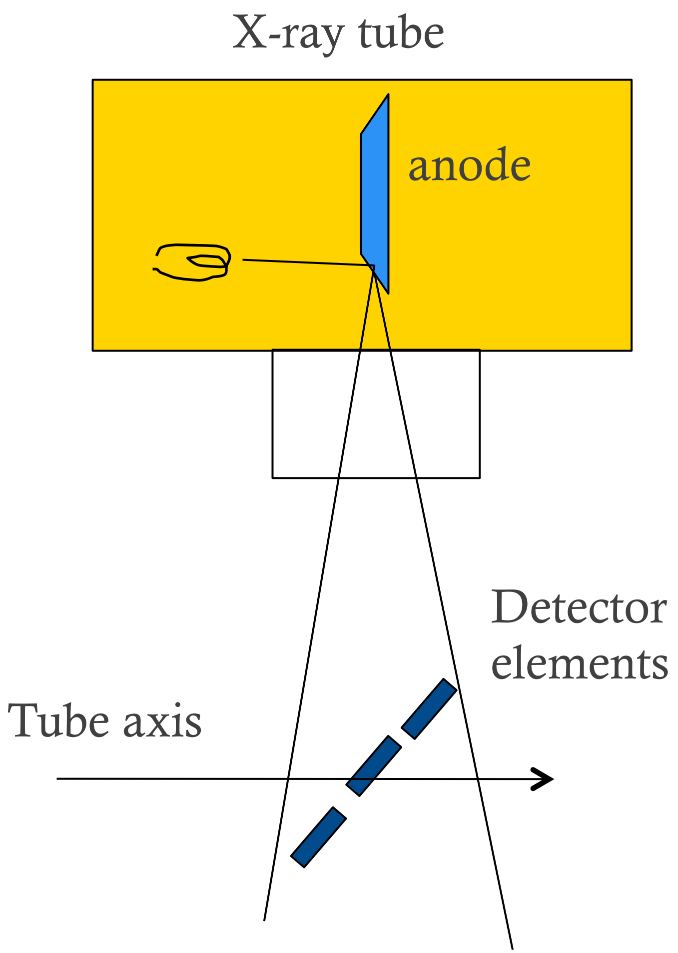
Measurement set-up



Air kerma measurements are made with the detector positioned entirely within the X-ray beam

Measurements with diodes

- Detectors should be positioned with detector elements aligned perpendicular to x-ray tube axis
- This avoids variation in air kerma along the axis due to the 'anode heel effect'



X-Ray Tube Output

Air Kerma $K_a\ (FDD) = M \, . \, N_k \, . \, k_Q$

M = dosimeter reading

N_k = Air kerma calibration factor

k_Q = Energy calibration adjustment

Tube output $Y(kVp, FDD) = K_a$ / mAs

Dependence of Output on kVp

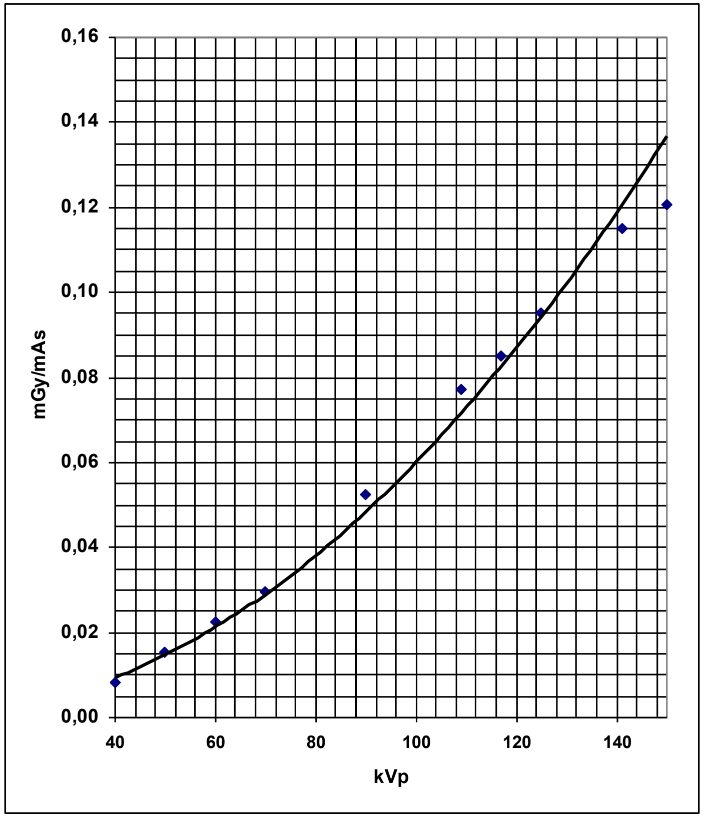
Tube output is proportional to kVp^2

Air kerma at intermediate kVps may be calculated using a square adjustment:

$$K_{a\,exp} = K_{a\,meas} \cdot (kVp_{exp}/kVp_{meas})^2$$

$K_{a\,exp}$ = K_a Exposure required

$K_{a\,meas}$ = K_a Measurement

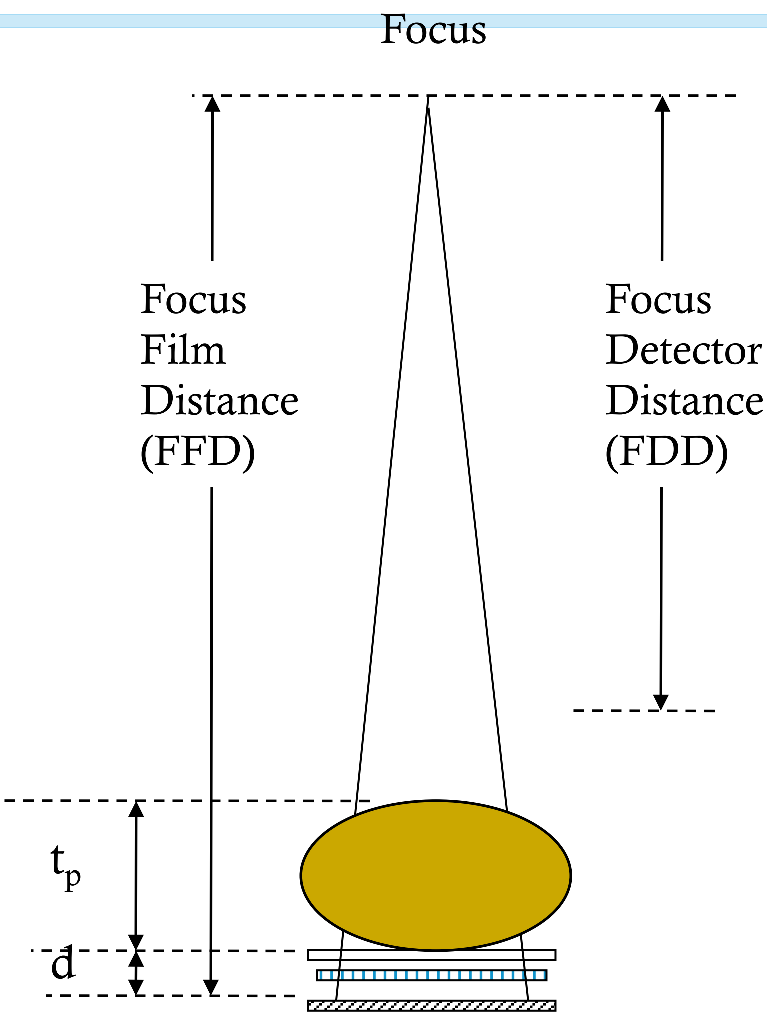


Incident Air Kerma

- Air kerma is inversely proportional to the distance from the tube focus
- An inverse square law adjustment is applied to derive the air kerma incident on the patient
- $K_a \, . \, [FFD-(tp + d)]^2 \, / \, FDD^2$

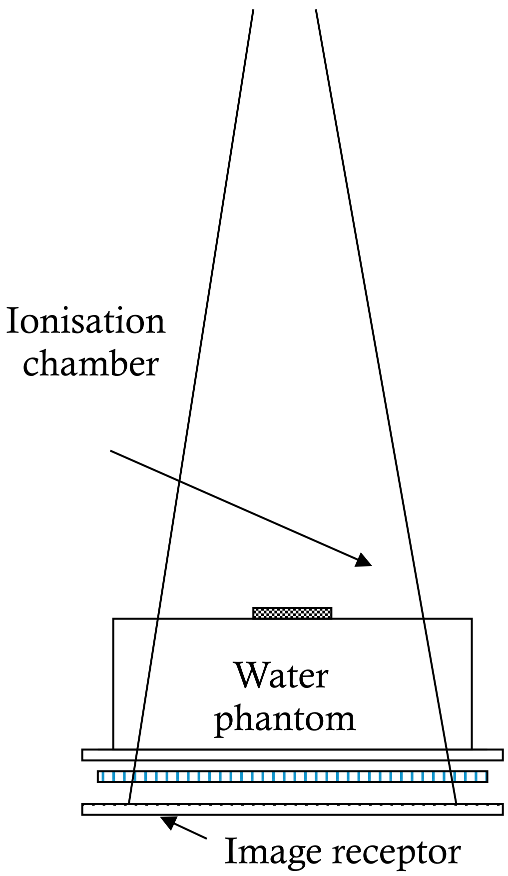
  t_p = patient thickness

  d = couch to film distance



Entrance Surface Air Kerma

- The dose to the skin surface includes backscattered radiation
- A perspex (PMMA) or water phantom can be used for measurement of entrance surface dose with an ionisation chamber
- This provides an assessment of the dose rate received by the skin of a patient
- A 20 cm thick phantom may be used as standard, but other thicknesses used in evaluating equipment performance



Entrance Surface Air Kerma

ESAK = iAK . BSF

$= Y(kVp, FDD) . mAs . \{FDD/(FFD-(t_p+d)\}^2 . BSF$

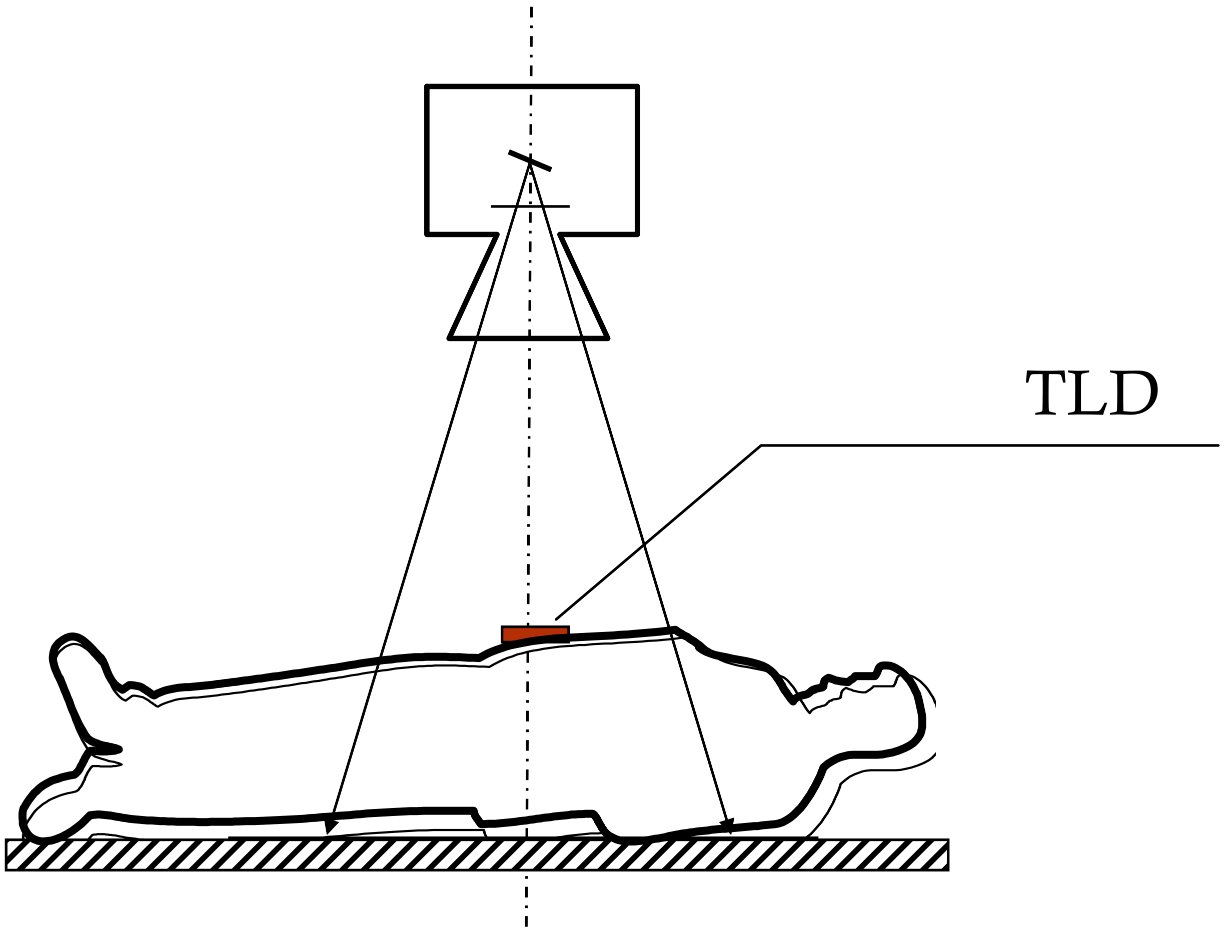
FDD = Focus detector distance

FFD = Focus film distance

t_p = patient thickness + couch to film distance

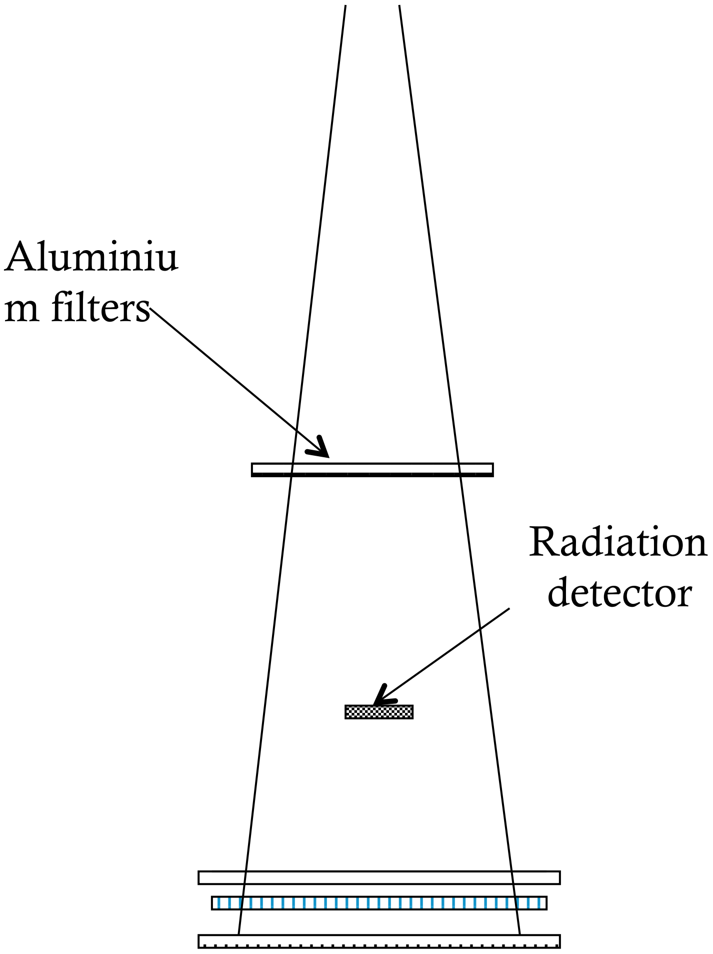
BSF = backscatter factor (approx. 1.3 – 1.4)

Entrance Surface Air Kerma



Half Value Layer

- Similar criteria apply to the measurement of the half value layer (HVL)
- The HVL is the thickness of aluminium required to halve the air kerma
- Measurement of the HVL for an x-ray beam at a particular tube potential is used to assess the amount of filtration in the x-ray beam

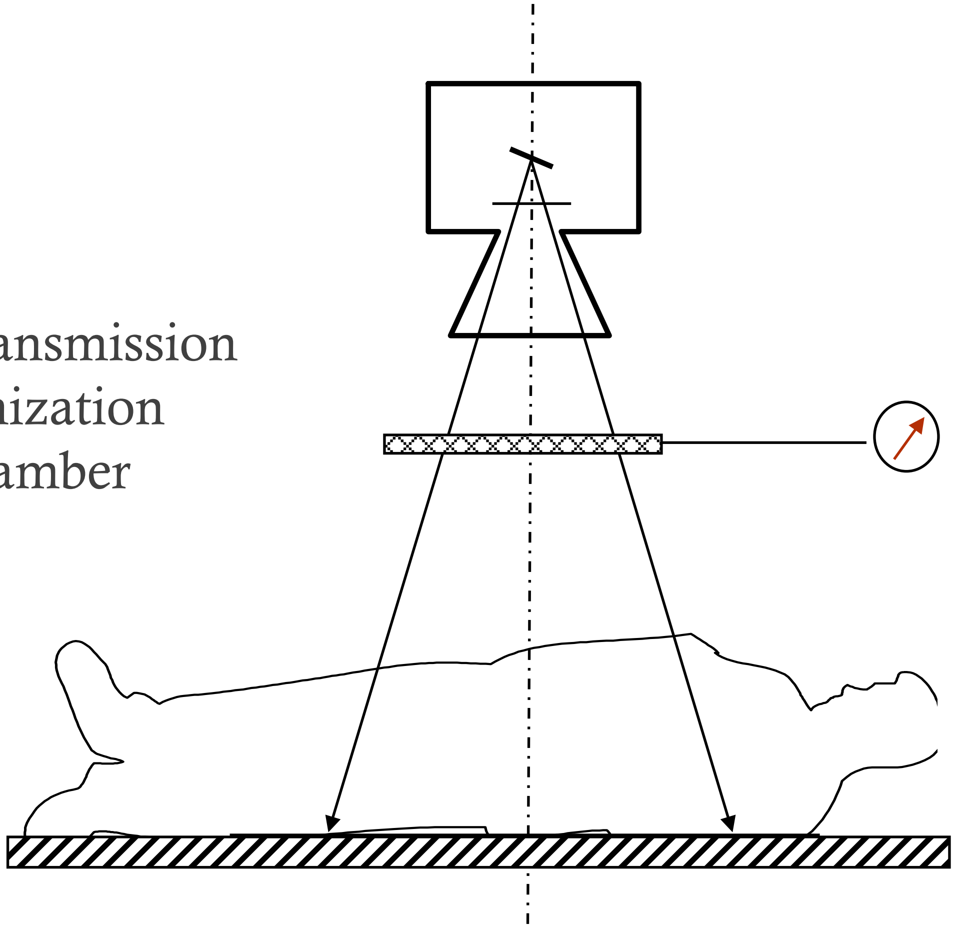


Air Kerma-Area Product

- The air kerma-area product (KAP) is defined as the air kerma in a plane, integrated over the area of interest
- KAP is a measure of the total amount of radiation incident on a patient
- KAP can be related to effective dose since KAP can be assessed for multiple projections, field sizes

Air Kerma-Area Product

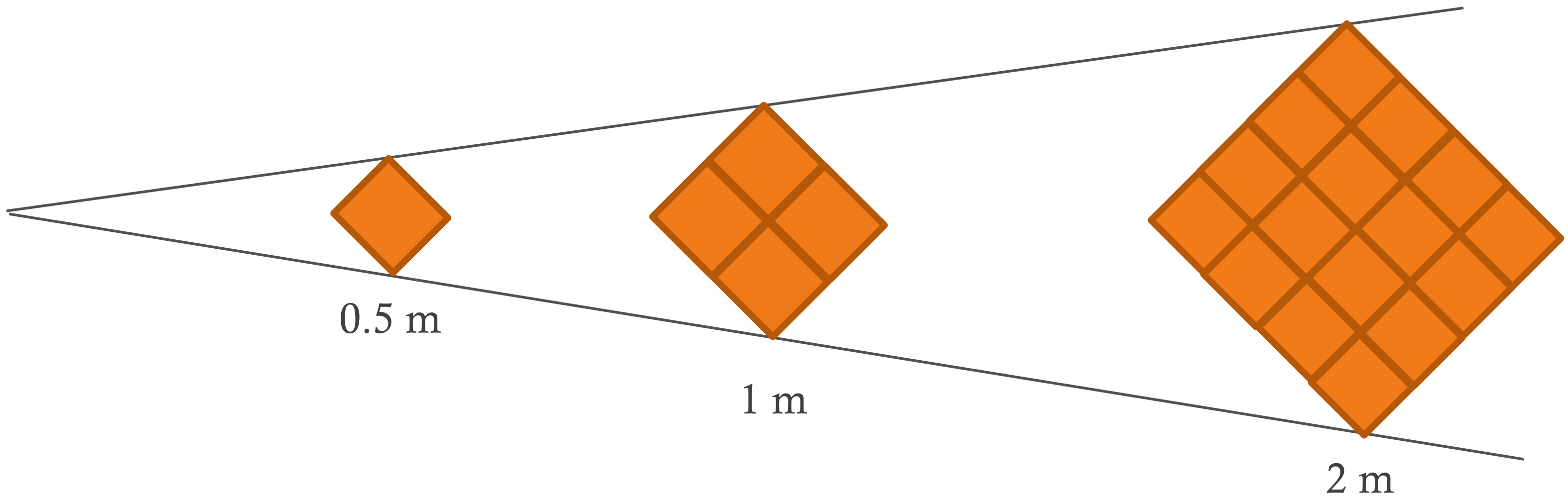
Transmission
ionization
chamber



Air Kerma-Area Product

- The KAP ($cGy \cdot cm^2$ or $Gy.cm^2$ or $\mu Gy.m^2$) is constant with distance since the cross section of the beam is a quadratic function which cancels the inverse quadratic dependence on dose
- This is true neglecting absorption and scattering of radiation in air and even for X Ray housing near the couch table

Air Kerma-Area Product



Air Kerma:	40×10^{3} μGy	10×10^{3} μGy	2.5×10^{3} μGy
Area:	2.5×10^{-3} m^2	10×10^{-3} m^2	40×10^{-3} m^2
KAP:	100 μGy m^2	100 μGy m^2	100 μGy m^2

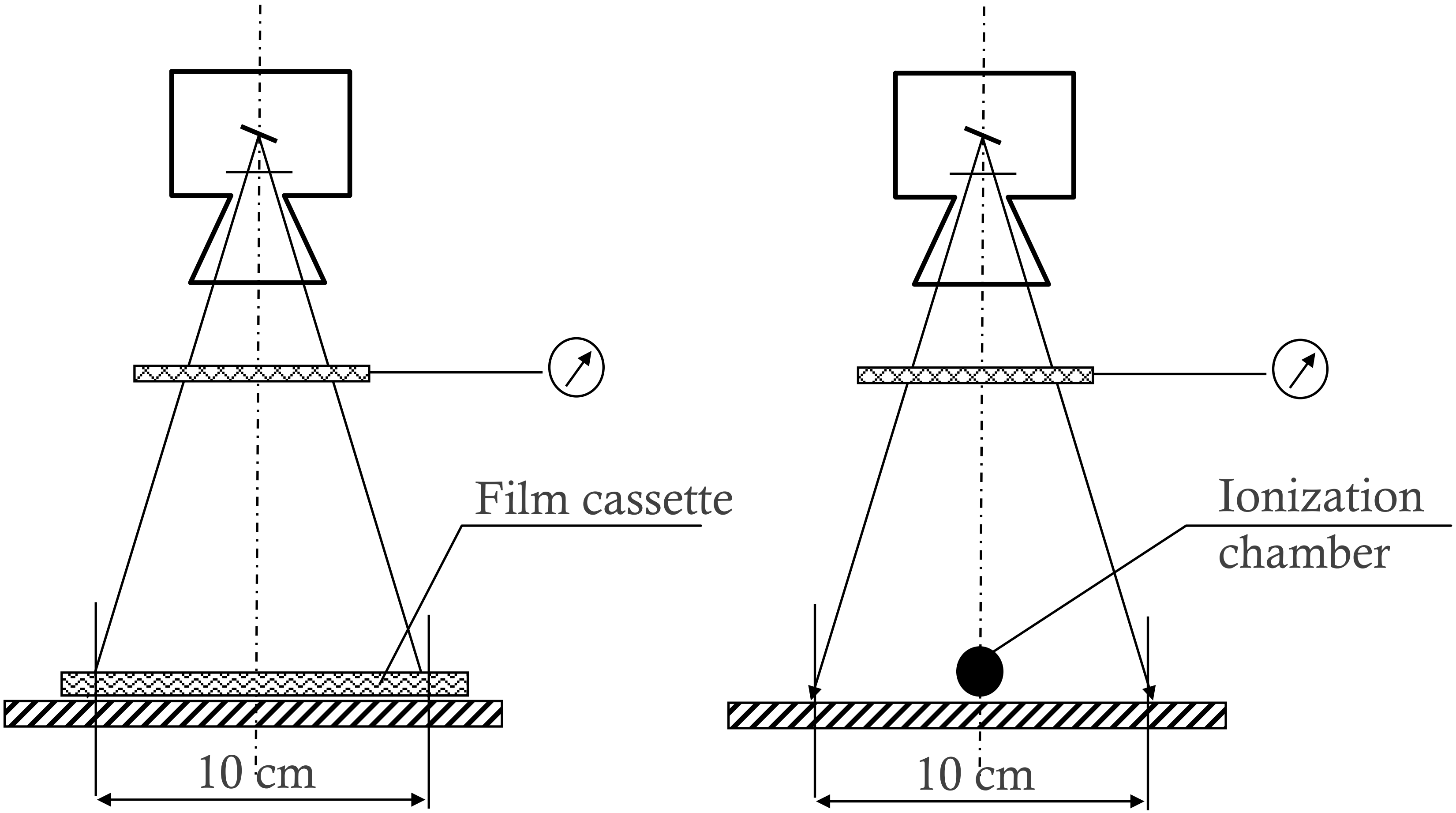
Calibration of KAP meter

- It is always necessary to calibrate and to check the transmission chamber for the X Ray installation in use
- In some European countries, it is compulsory that new equipment is equipped with an integrated ionization transmission chamber or with automatic calculation methods
- It is convenient, in this case, also to check the read-out as some systems overestimate the real KAP value

Calibration of KAP meter

- Measure air-kerma at a defined point using an appropriate radiation detector.
- Measure the X-ray field size at a defined point.
- KAP = measured air-kerma • field size
  (assumes that the X-ray field is uniform)

Calibration of KAP meter



X-ray field

- Field size measurements are influenced by penumbra and scatter.
- Film (of any kind) may be difficult to obtain.
- Many digital systems apply electronic shutters. These limit the visibility of the edges of the X-ray field on video monitors.

  Problem if collimator is not properly aligned.

  (Bigger problem for collimator limited max FS)

Parameters and conditions

- Air kerma area product (KAP) defined under low scatter conditions
- All removable attenuators (e.g. table-top) are removed from the beam while testing.
  - Common EU practice is measure through the table
  - Some systems may have a manufacturer's factor to account for the "through the table" fraction.

Accuracy and stability

- Accuracy limits (IEC and FDA) are ± 35%

  Based on an IEC accuracy of ± 25% for a physical DAP chamber.

- Precision of a specific system's readings is usually better than ± 5% over many years. This assumes:
  - No equipment failures.
  - No changes in service procedures.
- Individual systems median values vary.
- Increased accuracy is needed (proposed ± 10 %)

Correction Factor (CF)

- CF < 1.0 means that the system over-reads.
- CF > 1.0 means that the system under-reads

$CF = truth / \mathbf{display}$

AAPM TG - 190

Accuracy and Calibration of Integrated Radiation Output Indicators in Diagnostic Radiology

- Included equipment
  - Interventional Fluoroscopes
  - Conventional (and Multipurpose) R/F rooms
  - Mobile C-arm Fluoroscopy
  - Portable (and Fixed) Radiographic Units
- Collect information on "the calibration procedure" from major x-ray equipment manufacturers

Working measurement proposal

- Single measuring point is likely to work
  - Provided that manufacturers use this data to maintain accuracy of their systems over their entire working range.
  - Physicists will occasionally test using other conditions.
- For now, DICOM and IEC standards should provide slots for multiple correction factors
  - Include indicators of validity (e.g. kV/filter range)
- Consider TG-190 as an IEC standard