Chapter 21: Instrumentation for Dosimetry

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J. C. Hourdakis and R. Nowotny
of the IAEA publication (ISBN 978-92-0-131010-1):

Diagnostic Radiology Physics:
A Handbook for Teachers and Students

Objective:

To familiarize students with the instrumentation used for dosimetry in diagnostic radiology.

Slide set prepared
by E.Okuno (S. Paulo, Brazil,
Institute of Physics of S. Paulo
University)

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21.1. INTRODUCTION

Patient dosimetry is a primary responsibility of the medical physicist in diagnostic radiology

Radiation measurement is also critical for exposure control of {
- worker
- public

Measurements of absorbed dose (or air kerma) are required in different situations in diagnostic radiology

The radiation fields vary from:

- plain projection geometry
- slit geometry
- point geometry

and may be

- stationary
- moving including rotational

21.1. INTRODUCTION

Dose measurements are essential in { acceptance testing
quality control

Dosimeter

- it is important to have a satisfactory energy response, due to the use of low photon energies in diagnostic radiology
- accuracy requirements less stringent than for radiotherapy
- must not interfere with the examination
- ionization chambers of a few cm³ or specifically designed solid state detectors can be used

Special types of ionization chambers are employed in dosimetry for { CT
mammography
interventional radiology

21.2. RADIATION DETECTORS AND DOSIMETERS

21.2.1. General characteristics of radiation detectors

Dosimeter

- is an instrument that measures dose of ionizing radiation
- usually comprises a measuring assembly - electrometer and one or more detector assemblies which may or may not be an integral part of the measuring assembly
- can be classified as:

active or **passive**

active: displays the dose value directly

passive: cannot display the dose value directly, but record a signal which must be *subsequently retrieved* and converted to dose (or air kerma) by a reading device

21.2. RADIATION DETECTORS AND DOSIMETERS

21.2.1. General characteristics of radiation detectors

Active dosimeters

Ionization chambers and/or semi-conductor detectors used to measure:

- air kerma (K)
- air kerma rate ($\dot{K}$)
- air kerma length product (P_{KL})
- air kerma area product (P_{KA})

in primary beam conditions

Measurements of patient exit dose and CT phantom dose are also performed with ionization chambers

Passive dosimeters

Solid state devices (dosimeters) such as:

- thermoluminescent (TLD)
- optically stimulated luminescence (OSL)
- film (including radiochromic film)

that may be placed on patient's skin or inside cavities to measure skin or organ doses

Similar measurements can be performed in phantoms

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21.2. RADIATION DETECTORS AND DOSIMETERS

21.2.1. General characteristics of radiation detectors

Other instruments are needed to measure:

- **X ray tube voltage (kV meter)**
- **exposure time (timer)**

They can be used without direct connection into the electrical circuits of the X ray units

There are also a variety of devices used for:

- **occupational**
- **public**

} dose assessment

including

- ionization chambers for direct measurements
- TLD, OSL and film for indirect use as either personal dosimeters or area monitors

21.2. RADIATION DETECTORS AND DOSIMETERS

21.2.2. Properties of diagnostic radiology dosimeters

Many types of **diagnostic radiology dosimeter**
- ionization chambers
- solid state detectors

are commercially available for the measurement of **air kerma** (and its derivatives)

Solid state detectors have found wide spread use recently in the area of quality control measurements, mainly because of their small size, ruggedness, and convenience of use

The measurement assembly analyses and processes the electrical signals from the detector in order to display the value of the radiological quantity being measured:

K (Gy), $\dot{K}$ (Gy·s^{-1}), P_{KL} (Gy·m) and P_{KA} (Gy·m^2)

21.2. RADIATION DETECTORS AND DOSIMETERS

21.2.2. Properties of diagnostic radiology dosimeters

Most commercial dosimeters can be used for:

- fluoroscopic
- radiographic

} applications

using

- the accumulated air kerma over time (integrate mode)
- air kerma rate mode

In most cases, the **calibration coefficient** is applied through the system's software to convert the measured charge (current) to air kerma at a given beam quality

Some dosimeter models have internal sensors for the measurement of the environmental temperature and pressure, so as to perform corrections for the air density automatically

21.2. RADIATION DETECTORS AND DOSIMETERS

21.2.2. Properties of diagnostic radiology dosimeters

The **air kerma,** K (or any other associate dosimetric quantity), is obtained from:

$$K = M_Q k_{TP} N_{K,Q_0} k_Q \prod k_j$$

M_Q is the reading of the dosimeter for a beam quality Q

k_{TP} is the air density correction factor for T and P

$N_{K,Qo}$ is the calibration coefficient

k_Q is the correction factor for the applied X ray spectrum

k_j are the other correction factors:
for ion recombination, polarizing voltage, radiation incident angle, humidity

21.2. RADIATION DETECTORS AND DOSIMETERS

21.2.2. Properties of diagnostic radiology dosimeters

Dosimeters are used for various types of X ray units and exposure conditions

The choice of the appropriate instrument is important, in order for the radiation measurement to be sufficiently accurate

Properties of radiation dosimeters:

- sensitivity
- linearity
- energy dependence
- directional dependence
- leakage current

21.2. RADIATION DETECTORS AND DOSIMETERS

21.2.2.1. Sensitivity

- **Sensitivity** is related to the minimum air kerma required to produce a signal output (charge or current produced by the detector and collected by the measuring assembly)
- The better the sensitivity of the dosimeter, the higher the charge (or current) produced for the same air kerma (rate) and consequently the better the air kerma (rate) resolution and detectability
- Ionization chambers with larger active (effective) volumes exhibit higher sensitivity than those with smaller volumes
- For this reason large ionization chambers are preferred for low air kerma rate measurements such as in fluoroscopy or for scattered radiation
- In radiography, where the air kerma rates are higher, smaller chambers can be used, allowing better spatial resolution for the measurement

21.2. RADIATION DETECTORS AND DOSIMETERS

21.2.2.1. Sensitivity

In general, **semi-conductor detectors** have a sensitivity which can be orders of magnitude higher than that of ionization chambers

- This property, among others, makes the use of semi-conductor detectors advantageous for a wide range of applications
- However their intrinsic energy dependence makes their use problematic in non calibrated beams and for scattered radiation measurements

21.2. RADIATION DETECTORS AND DOSIMETERS

21.2.2.2. Linearity

- The dosimeter **reading M** should be linearly proportional to the air kerma (rate)
- All dosimeters exhibit linear response for a certain range of air kerma (rate)

The linearity range and the non-linear behaviour depend on the type of dosimeter and its physical characteristics

Among other factors, the:

- scale/reading resolution of the measuring assembly
- sensitivity
- leakage/dark current of the dosimeter

restrict the rated range to a lower value, while saturation (over ranging) effects determine the upper value

The air kerma (rate) range in which the dosimeter response is linear (rated range) should be stated by the manufacturer

21.2. RADIATION DETECTORS AND DOSIMETERS

21.2.2.3. Energy dependence

- For diagnostic dosimeters, the X ray spectrum, often referred to as the radiation or beam quality, is specified by the beam HVL and is one of the important quantities that affect the response of a dosimeter

- Within the range 25 kV to 150 kV of the clinical X ray radiation qualities, the variation in the dosimeter response with energy may be significant

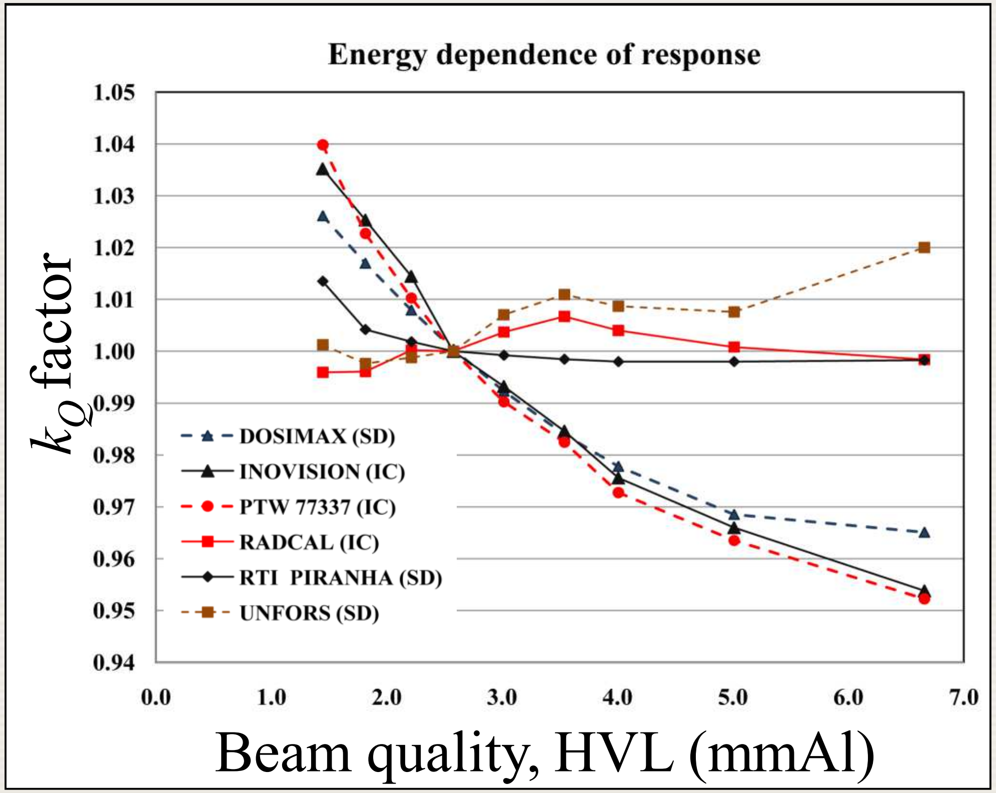
  This depends on the detector type and its physical and structural properties

- The variation in response to different radiation qualities is taken into account by the use of a beam quality correction factor k_Q

21.2. RADIATION DETECTORS AND DOSIMETERS

21.2.2.3. *Energy dependence*

- For a radiation quality Q, k_Q is the ratio of the calibration factors for quality Q to the reference radiation quality
- By definition, k_Q is unity at the reference beam quality



The beam qualities (x-axis) correspond to the RQR series described in the IEC 61267 standard

For dosimeters used as reference instruments at calibration laboratories

- IEC 61674 standard imposes a ± 5% upper limit of variation of energy response in the 50 - 150 kV range
- IAEA proposes the limit of ± 2.6%

21.2. RADIATION DETECTORS AND DOSIMETERS

21.2.2.4. Directional dependence

The response of a dosimeter may vary when the radiation is incident on the detector from different angles

The directional or angular dependence primarily depends on:

- the detector construction and physical size
- the energy of the incident radiation

The directional dependence of:

- cylindrical or spherical ionization chambers is negligible
- parallel plate chambers might be significant at large incident angles

21.2. RADIATION DETECTORS AND DOSIMETERS

21.2.2.4. Directional dependence

- Most commercial **solid state detectors** are mounted on lead backing plates, to attenuate radiation incident from the rear
- Some models incorporate several semiconductor elements covered with filters to attenuate the radiation. In such cases the **directional dependence** is important and care should always be taken to ensure that the radiation is incident on the elements through the filters at right angles

The IEC 61674 standard imposes:
± 3% upper limit of variation of response at incident angles
of ± 5^o from normal direction

21.2. RADIATION DETECTORS AND DOSIMETERS

21.2.2.5. Leakage current

Leakage current refers to any signal change recorded by the measuring assembly that is not generated by radiation

This could be:

- electronic noise
- current from resistor-capacitor circuits
- damaged cables or bad cable connections
- lack of electronic or environmental equilibrium or humidity etc

According to IEC 61674 standard:

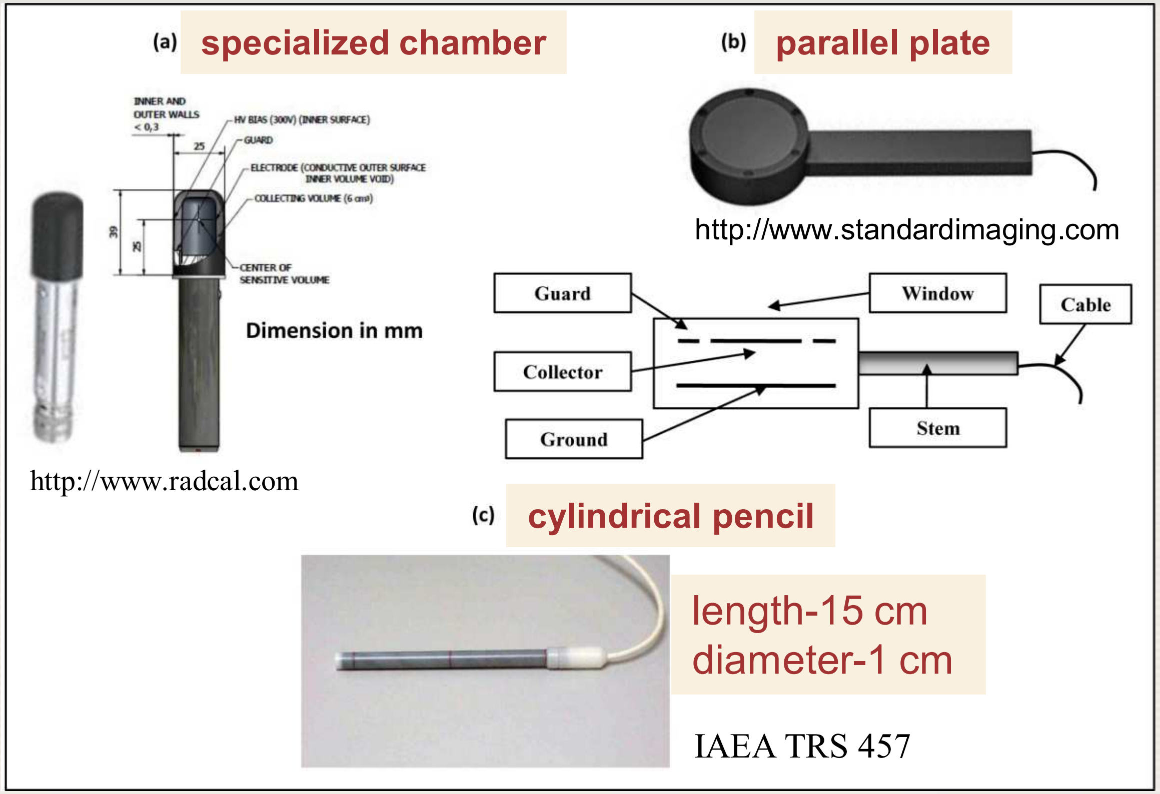
- the leakage current shall not exceed 5% of the minimum effective air kerma rate for the range in use
- the indicated value shall not change by more than 1% per minute, when a dosimeter is left in measurement mode after being exposed to the maximum effective air kerma value

21.3. IONIZATION CHAMBERS

- The ionization detector is an air filled chamber, in which an electric field is formed by the application of a polarizing voltage across two electrodes to collect all charges liberated by the ionization of the air contained within the chamber
- The electric field is sufficient to collect almost all of the liberated charges that reach the electrodes but insufficient to induce gas/charge multiplication and collision ionization of other molecules (in contrast with Geiger Müller and proportional counters)
- The number of ions collected or the rate of their collection is the recorded signal, which is multiplied by the average energy required to produce an ion pair in dry air:

$$\overline{W}_{air} = 33.97 \text{ eV/ion pair} = 33.97 \text{ J}\cdot\text{C}^{-1}$$

21.3. IONIZATION CHAMBERS



http://www.radcal.com

http://www.standardimaging.com

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In **parallel plate chambers**, the electrode separation is of the order of 1 cm and the electrodes are parallel to each other and to the entrance window

- In cylindrical and spherical shape chambers, the central electrode stands at the geometrical centre of the cavity, while the wall of the chamber is coated by a conductive material which is often at ground potential (ground electrode)
- The wall (ground) and the collecting electrode are separated with a high quality insulator to reduce the leakage current
- A third electrode, the guard, reduces chamber leakage current by allowing any leakage to flow to ground, bypassing the collecting electrode and ensuring high uniformity of the electrical field in the chamber volume

21.3. IONIZATION CHAMBERS

Ionization chambers used in diagnostic radiology should be vented, i.e. the air inside the volume communicates with the environment, rendering the mass of air dependent on temperature, pressure and humidity conditions

- **Humidity** has insignificant effect on air mass changes
- **Temperature** affect the air mass within the chamber
- **Pressure** significantly

21.3. IONIZATION CHAMBERS

The air density correction factor $k_{TP} = \frac{P_0 T}{P T_0}$

should always be applied to the dosimeter's readings

$$\left.\begin{array}{l} P_0 = 101.3 \text{ kPa (1 atm)} \\ T_0 = 293.2 \text{ K or } 295.2 \text{ K} \end{array}\right\} \text{are the values of the calibration reference conditions}$$

P and T are the ambient pressure and temperature during the air kerma measurement

According to the IEC 61674 standard:

- sealed chambers, in which the air volume does not change, are not suitable for diagnostic radiology dosimetry; their necessary wall thickness may cause unacceptable energy dependence, while the long term stability of the chambers is not guaranteed

21.3. IONIZATION CHAMBERS

21.3.1. Clinical application of ionization chambers

21.3.1.1. Chambers for air kerma (dose) measurements

The determination of the air kerma (dose) in common diagnostic radiology applications:

- radiography
- fluoroscopy
- mammography

is performed by ionization chambers
- cylindrical or
- parallel plate (p-p)

The major disadvantage of p-p chambers is the directional dependence of their response

The p-p chamber should always be placed perpendicular to the radiation beam

In mammography, p-p ionization chambers with a thin entrance window, made of a low density material (kapton film, acrylic, mylar, etc) of (20 – 50 μm, 3 – 10 mg/cm^2) thickness, are used

21.3. IONIZATION CHAMBERS

21.3.1.1. Chambers for air kerma (dose) measurements

- Commercial **parallel plate** (p-p) chambers are disc shaped with diameters of several cm and thickness of few cm
- The most common chambers with effective volumes (air cavity) from about 1 cm^3 to several hundreds of cm^3 are then suitable for application in a wide range of exposure rates
- Due to their shape, they can be safely inserted in hollow spaces, such as on the X ray table under a phantom, or in contact with the image intensifier, or inside the film cassette holder (Bucky) etc

Cylindrical chambers are uniformly sensitive around their central geometrical axis. The chambers used for measurement in the X ray beam have effective volume of 3 cm^3 to 6 cm^3

21.3. IONIZATION CHAMBERS

21.3.1.2. Cylindrical pencil type chambers

Cylindrical pencil type ionization chambers are used in several diagnostic radiology applications, for the measurement of the air kerma length product, P_{KL}

For the last decades, these chambers have mainly been used in computed tomography (CT) dosimetry but they are also used in dental application

- In contrast to other detectors used in diagnostic radiology, the chamber is partially irradiated
- It is positioned with its axis at right angles to the central beam axis
- The response of the active volume should be uniform along its entire axial length

21.3. IONIZATION CHAMBERS

21.3.1.3. KAP chambers

Air kerma-area-product (KAP) chambers:

- have a large surface area
- are transparent to radiation and light
- measure the integral of the air kerma over the area of the chamber
- measure the incident radiation or the transmitted radiation
- are usually used for patient dosimetry in

    interventional radiology
    fluoroscopy
    general radiography
    pantomographic dental radiography

This is reflected in the use of KAP for diagnostic reference levels

Because of the presence of extra-focal and scatter radiation, they should be calibrated in-situ

21.3. IONIZATION CHAMBERS

21.3.2. Application hints for ionization chambers

The following practical points should be considered:

- Appropriate ionization chambers should be selected, for the application and the measuring procedure required
- Corrections for air density should always be applied to the dosimeter reading. Great care should be taken for dosimeters that incorporate internal sensors for automatic temperature and/or pressure corrections, in order to interpret their reading correctly
- In general, ionization chambers detect radiations from all directions, thus they measure all scatter, extra focal and leakage radiation. When the incident air kerma is being measured, the chamber should be at a distance from all supporting devices, in order to avoid backscatter radiation, while other objects should not interfere with the X ray beam

21.3. IONIZATION CHAMBERS

21.3.2. Application hints for ionization chambers

More practical points should be considered:

- The ionization chamber should be totally covered by the radiation field, except for pencil type and KAP chambers. Good practice is to use field sizes at least twice the detector cross section
- Ionization chambers should be calibrated at several qualities

This is especially important for chambers with a large energy dependence. At least the qualities RQR3 (50 kV), RQR5 (70 kV) and RQR9 (120 kV) should be used for radiography and fluoroscopy, and RQR-M1 (25 kV), RQR-M2 (28 kV) and RQR-M4 (35 kV) for mammography

- The user should know the limitations and the rated ranges for all the quantities affecting the measurements. It is important to check that the leakage (dark) current is negligible

21.3. IONIZATION CHAMBERS

21.3.2. Application hints for ionization chambers

BASIC CHARACTERISTICS OF DIAGNOSTIC RADIOLOGY DOSIMETERS

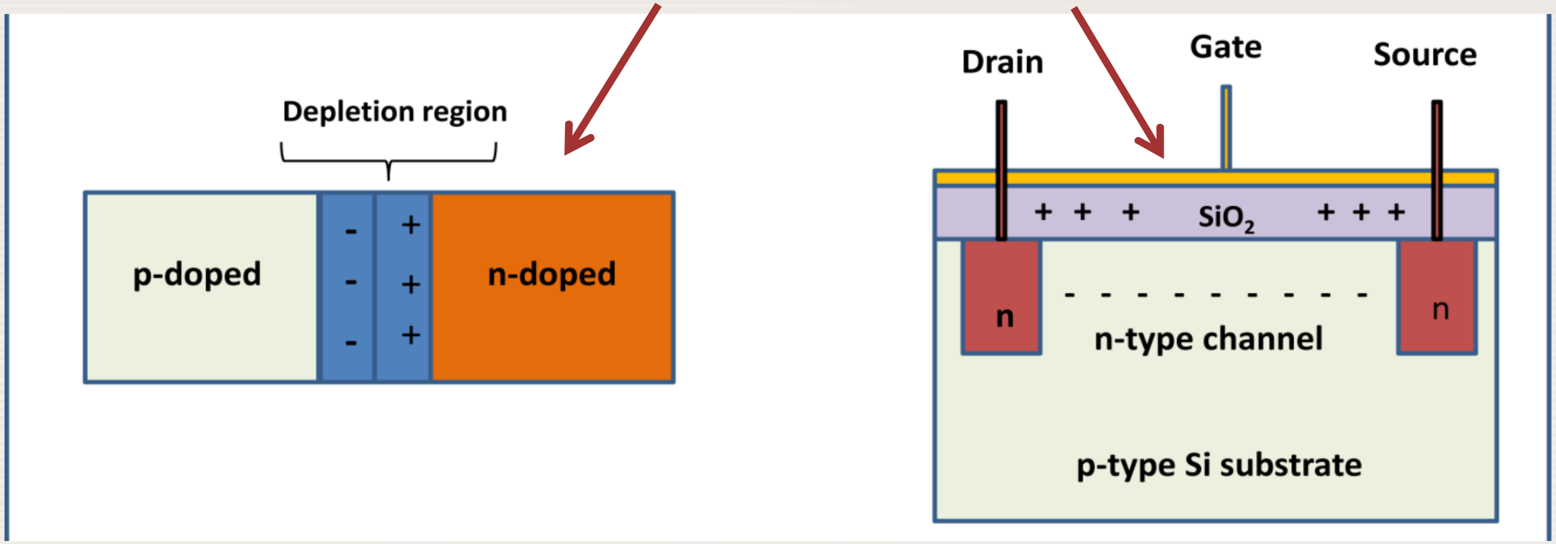
Application	**Type of Detector**	**Range of X ray tube voltage kV**	**Range of air kerma or air kerma rate**	**Intrinsic Error**	**Variation of energy response**	**Kair rate dependence**	**Angular dependence**
General Radiography	Cylindrical, spherical, or plane parallel IC ST detectors	60 – 150	10 μGy – 1 Gy 1 mGy/s – 500 mGy/s [a] 10 μGy/s – 5 mGy/s [b]	5%	± 5%	± 2%	±3% @ ± 5°
Fluoroscopy, Interventional radiology [e]	Plane parallel IC ST detectors	50 – 120	10 μGy/s – 10 mGy/s [a,d] 0.1 μGy/s – 100 μGy/s [b,d]	5%	± 5%	± 2%	±3% @ ± 5°
Fluoroscopy, Interventional radiology [f]	KAP meters	50-150	10^{-1} – 10^{6} μGy·m^2 10^{-1} – 10^{3} μGy·m^2/s	10%	± 8%	± 5%	--
Mammography	Plane parallel IC ST detectors	22 – 40	10 μGy – 1 Gy 10 μGy/s – 10 mGy/s [a]	5%	± 5%	± 2%	±3% @ ± 5°
CT	Cylindrical pencil type IC of 100 mm active length [c]	100 – 150	0.1 mGy/s – 50 mGy/s	5%	± 5%	± 2%	±3% @ ± 180°
Dental radiography	Cylindrical, spherical, or plane parallel IC ST detectors KAP meters Cylindrical pencil type IC	50 - 100	10 μGy – 100 mGy 1 mGy/s – 10 mGy/s	5%	± 5%	± 2%	±3% @ ± 5°

IC : Ionization chamber , **ST** : solid state (semiconductor) [a] Unattenuated beam [b] attenuated beam [c] In the light of new CT technologies and the revision of CT dosimetry methodology new types of detectors may be proposed [d] that will be suitable for measuring pulsed radiation as well [e] for air kerma rate measurements [f] for air kerma area product (rate) measurements

21.4. SEMICONDUCTOR DOSIMETERS

Diagnostic radiology dosimeters based on semiconductor technology have found wide spread use

Two types are used: **silicon diodes** or **MOSFETs**

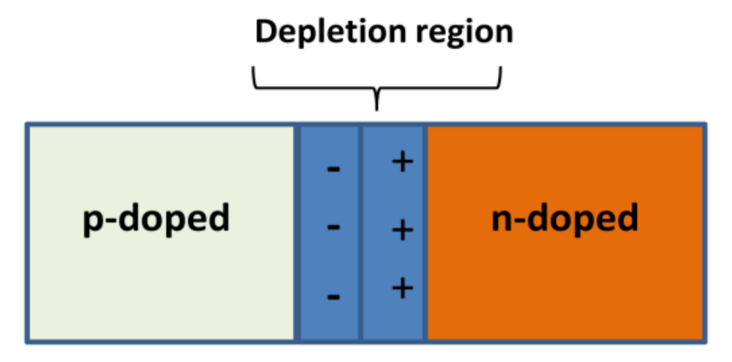


- Due to their small size and rigidness, they are convenient for use in many applications
- MOSFETs often require a connection to a bias voltage during irradiation
- They are mainly used in patient dosimetry

21.4. SEMICONDUCTOR DOSIMETERS

21.4.1. Theory of operation

A **silicon diode dosimeter** is a p–n junction diode. In most cases p–type (rather than n-type) diodes are used for diagnostic radiology dosimeters, since they are less affected by radiation damage and have a much smaller dark current (noise)



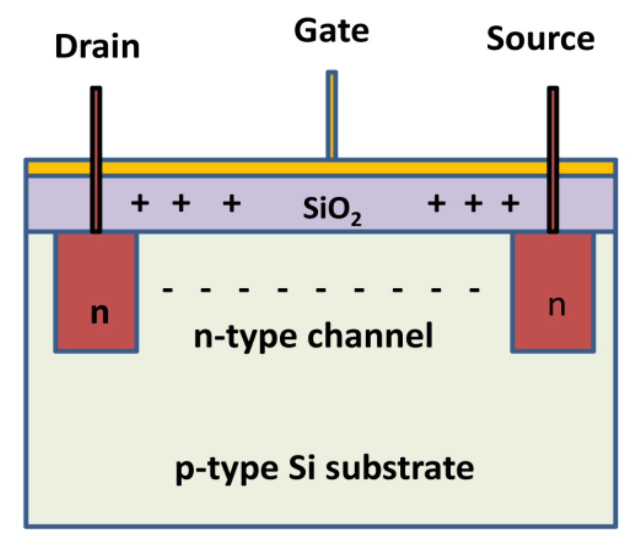
- When radiation falls on the diode, it produces electron–hole pairs in the body of the diode and a current, is generated in the reverse direction in the diode
- The number of such pairs is proportional to the incident radiation dose

- Due to the diode structure and the intrinsically formed potential difference, there is no need to apply a bias voltage across the p and n type diode regions to collect the charge liberated by the radiation

21.4. SEMICONDUCTOR DOSIMETERS

21.4.1. Theory of operation

A metal-oxide semiconductor field effect transistor **(MOSFET),** is a miniature silicon transistor. Its structure is equivalent to a planar capacitor with one of the electrodes replaced by a semiconductor



- When MOSFET dosimeters are exposed to radiation, electron-hole pairs are produced in the SiO_2. The positive charge carriers move in the direction of Si - SiO_2 interface, where they are trapped, building up a positive charge, which causes changes to the current in the n-type channel and leads to change of the gate bias voltage
- The gate bias voltage change is a linear function of absorbed dose. The integrated dose may be measured in real time or after irradiation

21.4. SEMICONDUCTOR DOSIMETERS

21.4.2. Application hints for semiconductors

The following practical points should be considered:

- The response of diodes and MOSFETs generally has a more pronounced energy dependence than that of ionization chambers

  The user should investigate the dosimeter's energy dependence characteristics. In this respect, measurements of the HVL with semiconductor detectors should be avoided

- The angular dependence of semiconductor detectors is comparable to that of plane parallel ionization chambers

  However, semiconductor detectors are sensitive to their positioning in the X ray field, especially to the direction of the heel effect

21.4. SEMICONDUCTOR DOSIMETERS

21.4.2. Application hints for semiconductors

The following practical points should be considered:

- When a semiconductor detector is used for dose measurements on a surface of a phantom (or patient), backscatter and side scatter radiation may not contribute significantly to the dosimeter reading due to the presence of backing plates

- Semiconductor detector response does not depend on temperature or pressure

  For the sake of a standard dosimetric formalism : $k_{TP} = 1$

21.4. SEMICONDUCTOR DOSIMETERS

21.4.2. Application hints for semiconductors

The following practical points should be considered:

- Semiconductors have a limited useful life due to accumulated radiation damage

  Although the doses measured in diagnostic radiology dosimetry are low, it is a good practice to recalibrate the detectors at regular intervals

- Research with MOSFET devices is currently in the experimental stages for dose measurements in some aspects of diagnostic radiology. These may be potentially beneficial in some high dose applications, such as interventional radiology, where high skin doses need to be avoided

  However, they exhibit a high energy dependence and therefore frequent calibration is essential in order to achieve adequate measurement accuracy

21.5. OTHER DOSIMETERS

21.5.1. Film dosimetry: radiographic film and radiochromic film

21.5.1.1. Radiographic film

Radiographic film still finds application as a dosimeter in personal radiation monitoring using film badges

- The emulsion in a film dosimeter directly absorbs ionizing radiation and can be correlated to the optical density of the developed film
- The sensitometric curve is very different from that for screen-film systems
- A radiographic emulsion is far from tissue equivalent and the energy response of a film badge is modified by addition of several filters
- The provision, processing and analysis of such dosimeters are the task of specialized departments and companies, and commonly not within the duties of a medical physicist

21.5. OTHER DOSIMETERS

21.5.1.2. Radiochromic film

- **Radiochromic films** (e.g. Gafchromic®) contain colourless dyes (diacetylene) that become blue after exposure due to radiation induced polymerization. This process is self-developing and requires no chemical process but needs some time for full development Depending on the material a density increase of about 10 % from 1 to 24 h after exposure is typical

- The film comprises of an active dye layer (15 - 20 µm thick) sandwiched between two transparent polyester sheets each containing a yellow dye
The yellow dye enhances visual contrast and reduces the effects of exposure to blue and UV light
Some films use an opaque white backing sheet

21.5. OTHER DOSIMETERS

21.5.1.2. Radiochromic film

- **Film optical density** is measured with densitometers or film scanners. For films having an opaque backing a reflective densitometer is needed

  The blue coloured polymer exhibits a maximum in optical absorption at around 635 nm. Accordingly a densitometer with a red light source should be used

- The composition of the film is near tissue equivalence

  Some types of film incorporate barite compounds in the white backing to increase radiation absorption and sensitivity

- Radiochromic films can be used for relative dosimetry in diagnostic radiology. The measurement and mapping of patient skin dose in interventional procedures is such an application

21.5. OTHER DOSIMETERS

21.5.1.2. Radiochromic film

- Several types of radiochromic films are optimized for applications in diagnostic radiology

- Their energy response and other properties can differ and the specifications should be collected from the supplier or from literature

  Sensitivity ranges from ~1 mGy to ~50 Gy depending on film type

  The sensitometric response is not linear and suitable calibration curves need to be applied

- The handling of radiochromic films is simple

  Dark rooms are not required and ambient conditions are of little concern except for exposure to intensive light sources or humidity

  The film can be obtained in large format (35 cm x 43 cm, maximum), and can be bent and cut to size as required

21.5. OTHER DOSIMETERS

21.5.2. Thermoluminescent dosimetry (TLD)

A large and growing number of solid state materials exhibit the phenomena of thermoluminescence (TL) which can be used for dosimetric purposes

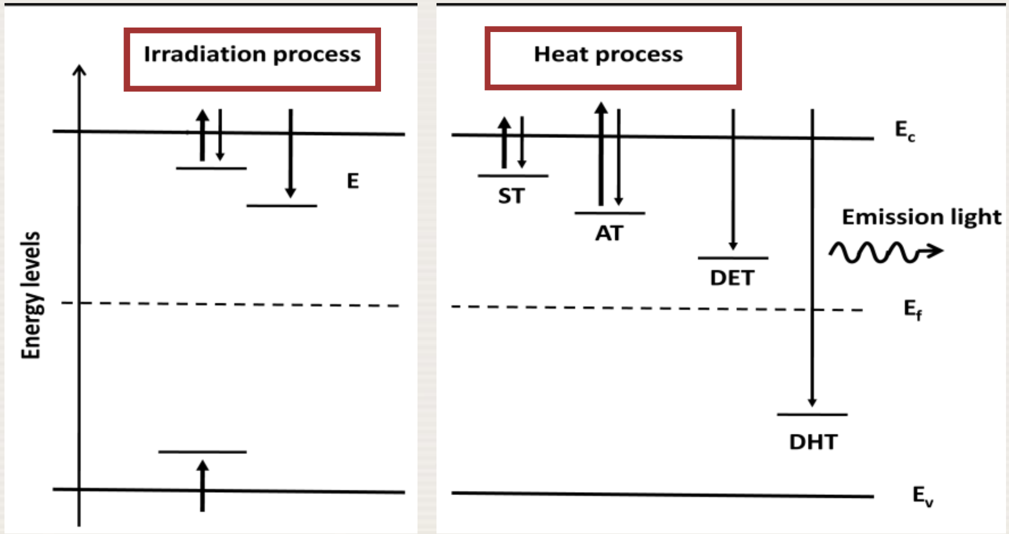
TL process consists of 2 stages:

- the first stage being the transference of an equilibrium TLD material to a metastable state through irradiation
- the second stage being application of energy (through heat) to return to the metastable state back to equilibrium

In the band structure model used to explain TL, electron energies are not localized and the gap between the valence and conduction bands is populated with trap sites that are caused by defects within the material

21.5. OTHER DOSIMETERS

21.5.2. Thermoluminescent dosimetry (TLD)



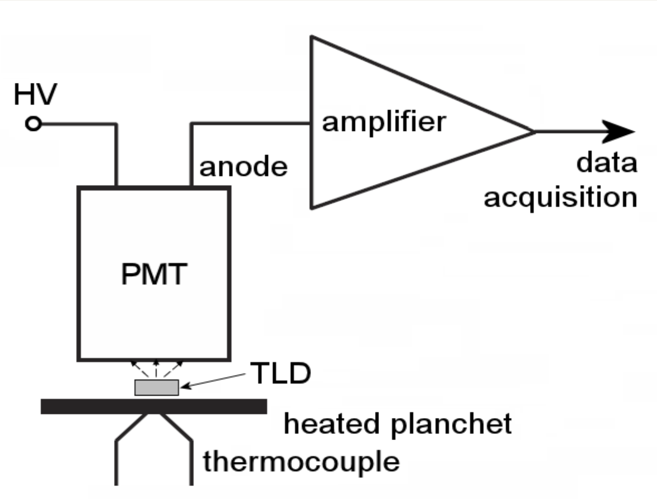
Energy levels in a TLD material showing the process of free electron and hole creation, followed by non-radiative charge trapping

The release of thermally stimulated electrons is shown for energy level E_c-E

- The released electron may be retrapped or can recombine with trapped holes. If this process is radiative, **TL emission occurs**
- E_c and E_v are the conduction and valence band edges. E_f is the Fermi level
- ST(shallow) and AT(active) traps
- DET and DHT deep electron and hole traps respectively

21.5. OTHER DOSIMETERS

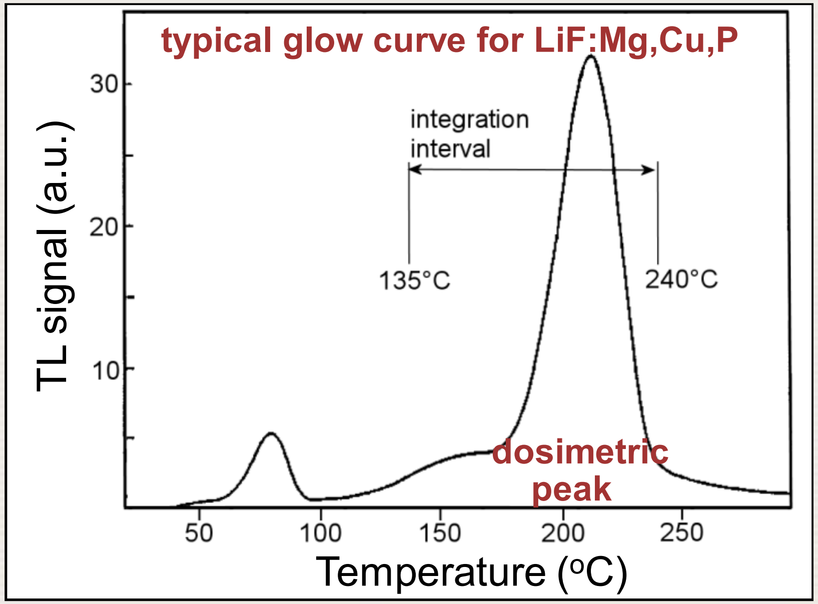
21.5.2. Thermoluminescent dosimetry (TLD)



- In a typical **TLD-reader** the dosimeters are placed on a planchet heated directly by an electric current
- The temperature is measured with a thermocouple welded to the planchet
- Other methods of heating the TLD are also used such as hot nitrogen jets, laser heating or infrared lamps
- The TL signal (glow curve) is detected with a photomultiplier tube

21.5. OTHER DOSIMETERS

21.5.2. Thermoluminescent dosimetry (TLD)



If a linear temperature ramp is applied the TL signal (glow-curve) shows various peaks at characteristic temperatures attributable to the traps present

Each type of TLD requires a specific optimized reading cycle

The reading cycle of a TLD is divided into preheat, signal integration and annealing

- During preheat the dosimeter is maintained for some seconds at a constant temperature sufficient to remove all low temperature signals
- Then the temperature is raised up to the maximum temperature
- Finally, the dosimeter is annealed in a dedicated oven to remove all remaining signals, resetting the dosimeter to zero

21.5. OTHER DOSIMETERS

21.5.2. Thermoluminescent dosimetry (TLD)

- The commonly used LiF:Mg,Ti (e.g. TLD100) is a well standardized dosimeter but less sensitive than LiF:Mg,Cu,P (GR200, TLD100H, MCP-N) that has a:

  detection threshold of about 0.1 μGy

- TLDs are available in many forms and shapes:

  chips, rods, cubes, ribbons and powder

- The relationship of dose to TL signal is linear up to

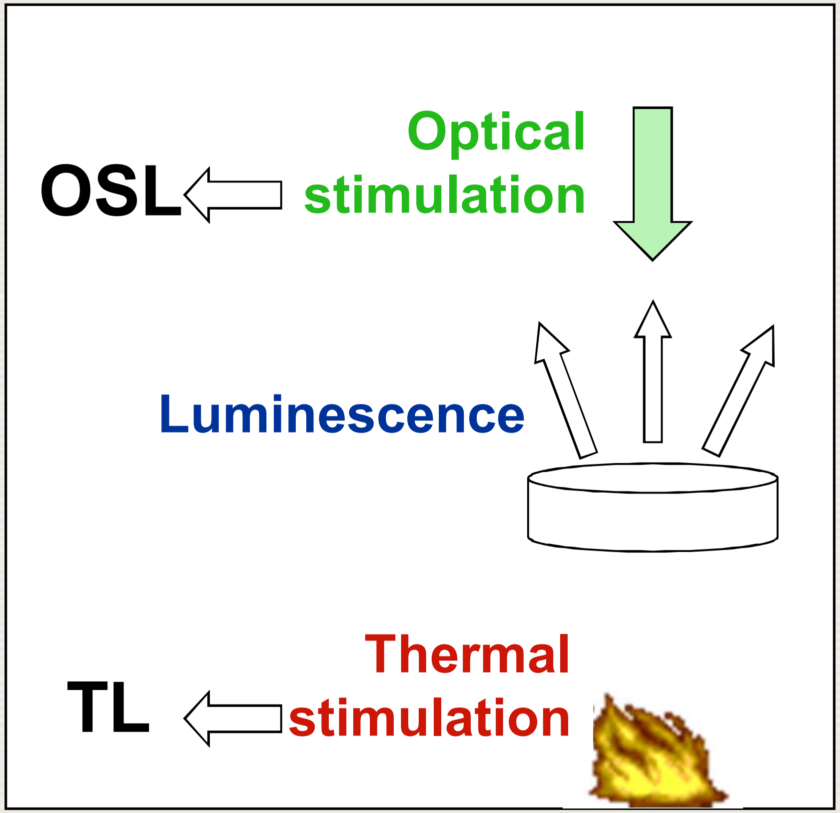
  doses < 1 Gy

- For higher doses correction factors for a non-linear response can be applied

21.5. OTHER DOSIMETERS

21.5.3. Optically stimulated luminescence (OSL)

Optically stimulated luminescence (OSL) is the luminescence emitted from an irradiated solid state material (OSL dosimeter), after being illuminated by stimulating visible or infra red light



Adapted from E. Yukihara, 2008

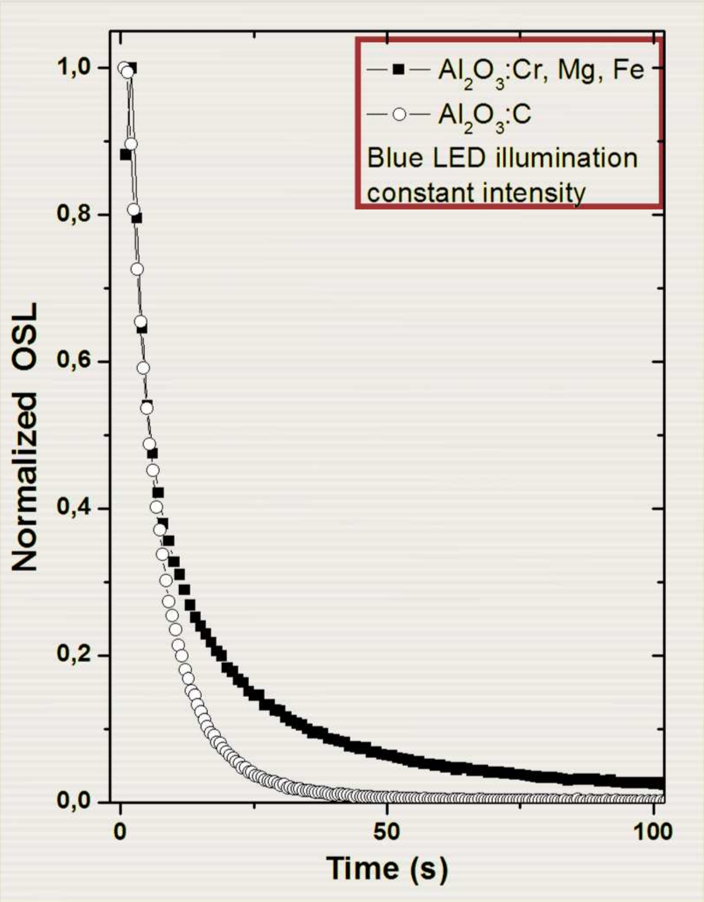
OSL is closely related to TL with the basic difference being the use of light instead of heat as the added energy for the trapped electron

Usually the stimulating light used for OSL has a lower photon energy than the emitted light

21.5. OTHER DOSIMETERS

21.5.3. Optically stimulated luminescence (OSL)

Typical OSL curve



Adapted from E. Yoshimura, 2007

- The intensity of the emitted light is related to the rate at which the system returns to equilibrium, resulting in a characteristic luminescence – time curve
- In a typical measurement using an OSL dosimeter, the sample material is illuminated with an appropriate light source
- The emitted light is passed through an optical filter to suppress unwanted light and then detected with a photomultiplier tube
- The arrangement of a OSL reader is similar to a TLD reader
- An improvement in signal to noise can be achieved by pulsing the stimulating light

21.5. OTHER DOSIMETERS

21.5.3. Optically stimulated luminescence (OSL)

- One **OSL dosimeter** commercially available uses $Al_2O_3:C$ whose dominant OSL trapping levels require thermal energies above 200°C to create thermoluminescence
- Consequently the OSL signal is thermally stable and signal fading is negligible
- Some transient signals due to shallow traps will disappear after a few minutes
- Dominant emission occurs in a band centred at around 420 nm
- Stimulation of OSL is carried out by green light, either from green LEDs or a laser
- Since a single reading with useful signal intensities requires only 0.05% of the signal stored, re-reading or intermittent reading of the dosimeter is feasible and the dosimeter can be kept as a permanent dose record

21.5. OTHER DOSIMETERS

21.5.3. Optically stimulated luminescence (OSL)

- Care must be taken to avoid exposure of the dosimeter to light (particularly UV) as electrons from deep traps could be transferred to dosimeter traps (phototransfer) changing the response of the dosimeter

- Doses in the range from 10 μGy to 15 Gy can be measured using commercial systems

- The OSL principle is also utilized for imaging using computed radiography (CR) systems

IAEA

21.5. OTHER DOSIMETERS

21.5.4. Dosimetric applications of TLD and OSL

Solid state dosimeters can be used for

- patient dosimetry external to the body or phantom in the same way as an ionisation chamber
- for internal measurements, typically in a phantom
- for occupational and public exposure monitoring

For internal dosimetry a near tissue-equivalent composition may have advantages in determining energy deposition within the body

Material	tissue	water	LiF:Mg, Ti	$Li_2B_4O_7$:Mn	Al_2O_3	BeO
Effective atomic number	7.22	7.42	8.31	7.40	11.30	7.21

21.5. OTHER DOSIMETERS

21.5.4. Dosimetric applications of TLD and OSL

- It must be remembered however that the primary dosimetry system in diagnostic radiology is based on air kerma and not absorbed dose to water or tissue
- Further, solid state dosimetry is a relative methodology that requires standardized calibration procedures
- Care must be exercised if TLD or OSL dosimeters are used in radiation fields that differ from the calibration conditions
- Consequently careful consideration must be given before LiF and Al_2O_3 dosimeters are used in applications such as CT phantom dosimetry

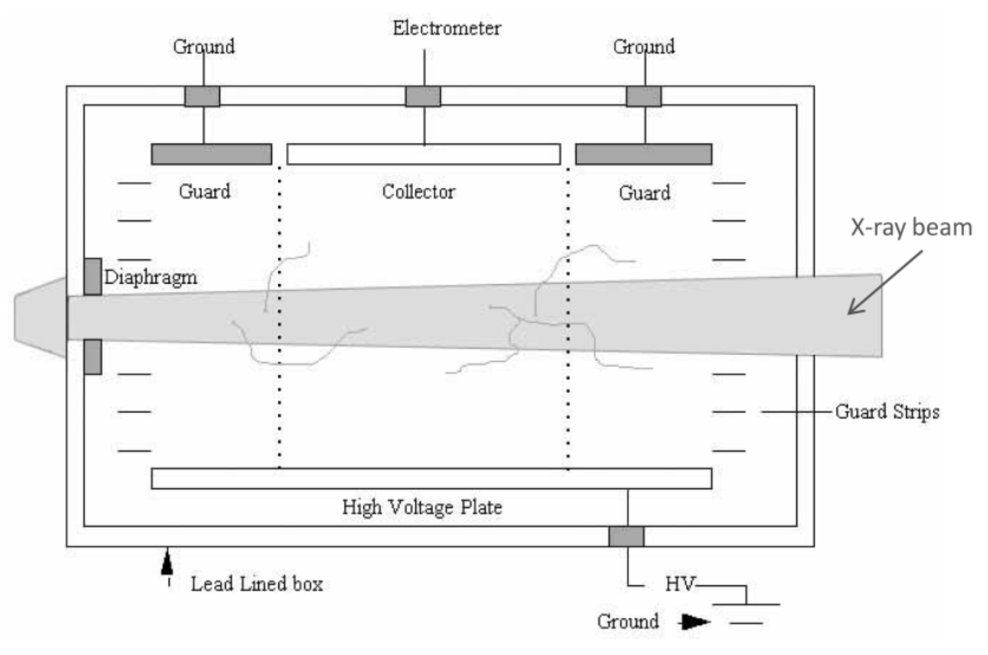
21.6. DOSIMETER CALIBRATION

All instruments used for dosimetric measurement in the clinical environment should have a calibration traceable to a recognized dosimetry standard

- The measurement of a dosimetric quantity, such as air kerma, prerequisites that there is a SI that determines the quantity and its unit
- Primary Standards Dosimetry Laboratories (PSDLs) employ free air ionization chambers for the measurement of absorbed dose traceable to the fundamental SI absorbed dose unit of Gray (Gy)
- Secondary Standards Dosimetry Laboratories (SSDLs) calibrate their reference class instruments at PSDLs and use these as their local dosimetry standards
- Therefore the traceability of the measurements to the specific PSDL is maintained. The main role of the SSDL is to bridge the gap between PSDL and dosimeter user

21.6. DOSIMETER CALIBRATION

21.6.1. Standard free air ionization chamber



Free air ionization chambers are often used by PSDLs as the primary standard for the determination of air kerma against which the secondary standard chambers from SSDLs are calibrated

The charge liberated by X rays in the mass of the air inside the chamber volume is measured

The air kerma is deduced according to its definition $K = \frac{dE_{tr}}{dm} = \frac{dQW_{air}}{dm}$ from measurements of basic physical quantities (charge and mass) and applying physical constants and relative correction factors

21.6. DOSIMETER CALIBRATION

21.6.2. SSDL calibration

Most SSDLs apply the substitution method for the dosimeter calibration

At a given beam quality, Q, the true value of air kerma $K_Q^{\text{"true"}}$ is measured using the reference dosimeter

The reference point of the user's dosimeter is placed at the same point and the dosimeter's reading is used to derive the calibration coefficient from the ratio

$$N_{K,Q}^{user} = \frac{K_Q^{\text{"true"}}}{M_Q^{user}}$$

M_Q^{user} is the reading of the user's instruments corrected for air density

21.6. DOSIMETER CALIBRATION

21.6.2. SSDL calibration

The calibration of the diagnostic radiology dosimeters are performed at the radiation qualities which are described in the IEC 61267 standard and which are produced using appropriate tube filtration at the specified tube voltage

Depending on the application of the dosimeter, a series of different beam qualities are used. For example: series

- RQR simulates the primary beams incident on the patient
- RQT, the beam qualities used in CT
- RQA, the transmitted radiation qualities through the patient
- RQR-M, mammography beams

Each series consists of several beams with different combinations of tube voltage and filtration

21.6. DOSIMETER CALIBRATION

21.6.2. SSDL calibration

Characterization of Radiation Quality Series RQR (according to IEC 61267, 2005) used for unattenuated beams for General Radiography Applications

Spectra are for an X ray tube with a W target and Al filters

Radiation Quality	**X ray Tube Voltage (kV)**	**First HVL (mm Al)**	**Homogeneity coefficient (h)**
RQR 2	40	1.42	0.81
RQR 3	50	1.78	0.76
RQR 4	60	2.19	0.74
RQR 5 *	70	2.58	0.71
RQR 6	80	3.01	0.69
RQR 7	90	3.48	0.68
RQR 8	100	3.97	0.68
RQR 9	120	5.00	0.68
RQR 10	150	6.57	0.72

*This quality is generally selected as the reference of the RQR series

21.6. DOSIMETER CALIBRATION

21.6.2. SSDL calibration

Characterization of Radiation Quality Series RQR-M (according to IEC 61267, 2005) used for unattenuated beams for Mammography Applications. Spectra are for an X ray tube with a Mo target / Mo filter

Radiation Quality	**X ray Tube Voltage (kV)**	**First HVL (mm Al)**
RQR-M 1	25	0.28
RQR-M 2 *	28	0.31
RQR-M 3	30	0.33
RQR-M 4	35	0.36

* This quality is generally selected as the reference of the RQR-M series

21.6. DOSIMETER CALIBRATION

21.6.2. SSDL calibration

Characterization of Radiation Quality Series RQT (according to IEC 61267, 2005) used for unattenuated beams for Computed Tomography (CT). Applications Spectra are for an X ray tube with a W target and Al and Cu filters

Radiation Quality	**X ray Tube Voltage (kV)**	**First HVL (mm Al)**
RQT 8	100	6.90
RQT 9 *	120	8.40
RQT 10	150	10.1

* This quality is generally selected as the reference of the RQT series

21.6. DOSIMETER CALIBRATION

21.6.2. SSDL calibration

A general purpose dosimeter should be calibrated in terms of air kerma at the RQR (RQR 2 to RQR 10) radiation qualities

- According to common practice, the calibration coefficient, N_K of a dosimeter is obtained at the RQR 5 (70 kV)
- For the other radiation qualities of the RQR series, further correction factors (k_Q) are provided to take into account the energy dependence of the dosimeter response
- For a given radiation quality Q, k_Q is defined as the ratio of the calibration coefficients at radiation quality Q to that at the radiation quality RQR 5
- By definition k_Q equals 1 at RQR 5
- For mammography the standard beam quality is the RQR-M2 (28 kV) and for CT the RQT 9 (120 kV)

21.6. DOSIMETER CALIBRATION

21.6.3. Field calibration

In some cases, for practical, economic and other reasons, users may calibrate their field instruments themselves

- For example, when many dosimeters are being used in a large hospital, the user may prefer to calibrate them against a reference dosimeter, rather than send all of them to an SSDL
- Some dosimetry equipment, such as KAP meters, are permanently installed on X ray systems and they must be calibrated on-site
- Generally, cross-calibration of a field instrument refers to its direct comparison in a suitable user's beam quality, Q, against a reference instrument that has been calibrated at an SSDL

21.6. DOSIMETER CALIBRATION

21.6.3. Field calibration

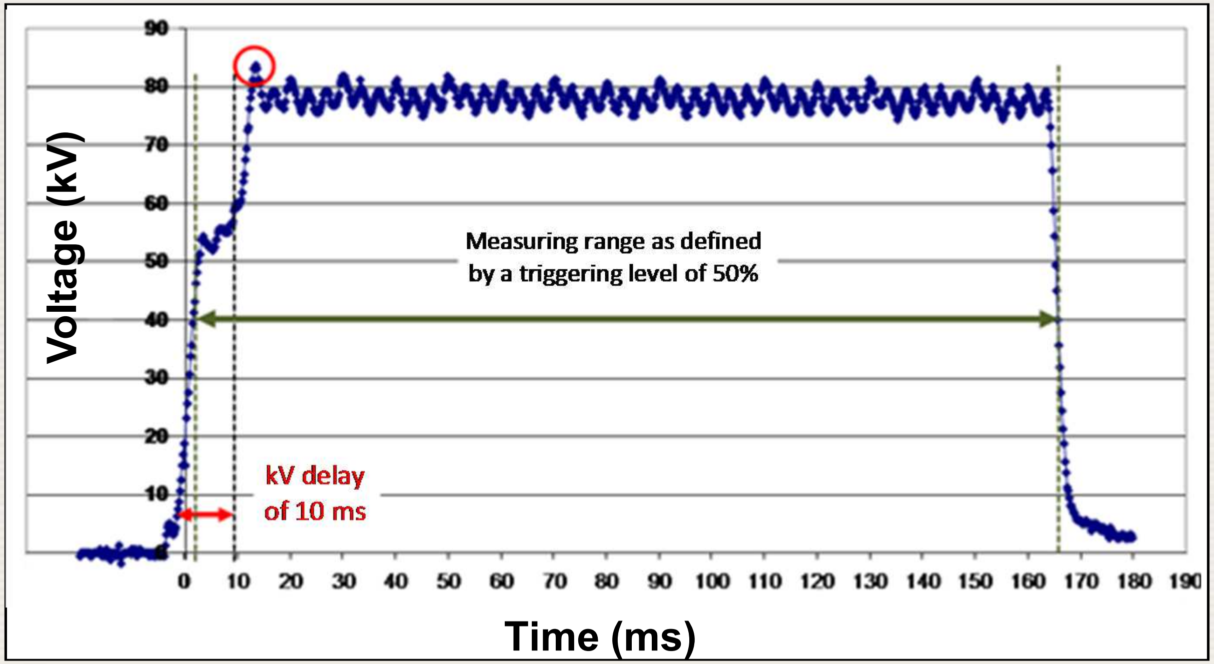
The **calibration coefficient** is obtained from equation :

$$N_{K,Q}^{field} = \frac{K_Q^{ref}}{M_Q^{field}} = \frac{M_Q^{ref} N_{K,Q_0}^{ref} k_Q^{ref}}{M_Q^{field}}$$

- ‘field’ and ‘ref’ refer to the field and the reference instruments, respectively
- M values are readings of the reference and the field instruments and have been corrected for the influence of all quantities except beam quality
- Since the calibration coefficient refers to a specific beam quality, the cross-calibration should be performed at the whole range of beam qualities that are used in the hospital
- It is important to note that other essential elements of traceability of measurement, such as uncertainty evaluation, evidence of competence, documentation, etc. should be taken into account and be declared for cross-calibrations

21.7. INSTRUMENTS FOR MEASURING TUBE VOLTAGE AND TIME

Measurement of the X ray tube voltage and exposure duration (often referred as “exposure time”, are usually performed with non-invasive, portable, electronic devices, often called kV-meters and timers



Typical X ray tube voltage waveform from a three phase six pulse generator operating at 80 kV tube voltage and 165 ms exposure time

Depending on the model, the kV-meter measures the

- *absolute peak voltage,* (the maximum value of the voltage during the exposure - circled point)
- *average peak voltage*
- *average voltage*
- *effective peak voltage,* (the voltage that would give the same image contrast as a constant potential X ray system)
- *Practical Peak Voltage (PPV),* (defined as the equivalent value of a voltage of any waveform related to an ideal X ray generator that provides a constant voltage and that produces the same image contrast)

PPV has been proposed as the standard quantity for the X ray tube voltage

21.7. INSTRUMENTS FOR MEASURING TUBE VOLTAGE AND TIME

- The kV-meter is positioned in the primary X ray beam and measures the X ray tube voltage with methods based on attenuation measurements
- Such instruments usually incorporate two (or more) detectors covered with filters (usually made of copper) of different thickness
- The detectors, when exposed to radiation, produce different signals, due to the different attenuation of the X ray beam by the filters
- The signal ratio (or any other relationship of the signals) is a function of the incident X ray energy and consequently of the tube voltage
- During the initial calibration of the kV-meter at the factory, the signal output and/or the reading is appropriately adjusted to the ‘correct’ tube voltage value
- Many kV-meters digitize, process and store their detector signals and can supply voltage and/or exposure waveforms
- The kV-meter detectors’ long geometrical axis should be positioned perpendicular to the tube anode – cathode direction to eliminate the influence of the “heel” effect on the kV measurement

21.7. INSTRUCTIONS FOR MEASURING TUBE VOLTAGE AND TIME

The IEC 61676 standard specifies the performance requirements of instruments used for the non-invasive measurement of the X ray tube voltage up to 150 kV

- It recommends that the relative intrinsic error of the *PPV* measurement shall not be greater than ± 2% over the effective voltage ranges:

  60 kV to 120 kV for diagnostic
  24 kV to 35 kV for mammography

- Also, that a 1.5% limit of variation in response is acceptable at tube filtration ranges of 2.5 to 3.5 mm Al (for diagnostic radiology applications)

21.7. INSTRUMENTS FOR MEASURING TUBE VOLTAGE AND TIME

Exposure time is the time during which the X ray beam is generated

- It is measured as the radiation pulse width (time difference) between an “initial” and “final” point of the exposure, which are defined by a pre-set triggering level
- The proposed convention for timing measurements of X ray systems, is to measure the pulse width at a height of 50% of the waveform peak (the full width half maximum)
- Some manufacturers use different values of the triggering level (e.g. 10% or 75%)
- The exposure time may be measured using either invasive or non-invasive equipment

21.8. INSTRUMENTS FOR OCCUPATIONAL AND PUBLIC EXPOSURE MEASUREMENTS

Radiation monitoring is performed in diagnostic radiology facilities:

- to determine the radiation levels in and around work areas, around radiology equipment
- to assess the radiation protection of the workplace and individuals
- Such monitoring devices should typically measure in integrate mode and for direct (or real time) measurements include ionization chambers and some specifically developed semi-conductor detectors suitable for scattered radiation
- Longer term monitoring is typically achieved with film or increasingly with solid state devices

For personal dosimeters :TLD or film badges

21.8. INSTRUMENTS FOR OCCUPATIONAL AND PUBLIC EXPOSURE MEASUREMENTS

The use of survey meters (such as Geiger Müller (GM) counters or proportional counters) is not recommended for diagnostic radiology

Such devices are typically designed to detect isotope emissions and are used in nuclear medicine and have some application in radiation therapy particularly for

- Co-60 units
- brachytherapy usage
- radioactive iodine treatment of patients

The two main difficulties in diagnostic radiology for the use of GM counters, are their response time of several seconds, whereas diagnostic X ray exposures have a duration of only small fractions of a second, and the strong energy dependence of their response at low photon energies

21.8. INSTRUMENTS FOR OCCUPATIONAL AND PUBLIC EXPOSURE MEASUREMENTS

- Detectors used for **occupational** and **public exposure** measurement should be traceable to appropriate calibration standards at suitable X ray energies (e.g. ISO Narrow series N40 to N80)
- While the user should know or estimate the mean energy of the X ray beam for calibration factor application, in some situations, such as estimating the mean energy of radiation transmitted through protective barriers, this can be difficult
- In these cases it is acceptable to use measurements directly from a detector with a small energy response variation
- The uncertainty of measurement should be assessed with reference to the variation in the calibration coefficients within the energy range used

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