Chapter 9: Calibration of Photon and Electron Beams

Set of 189 slides based on the chapter authored by P. Andreo, J.P. Seuntjens, and E.B. Podgorsak of the IAEA publication:
Radiation Oncology Physics: A Handbook for Teachers and Students

Objective:

To familiarize the student with the basic principles of radiation dosimetry.

IAEA
International Atomic Energy Agency

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9.1 INTRODUCTION

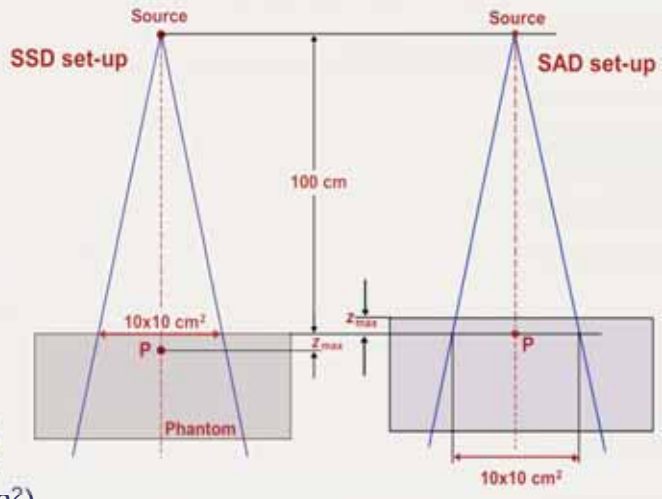
- Modern radiotherapy relies on accurate dose delivery to the prescribed target volume.
- ICRU recommends an overall accuracy in tumour dose delivery of ±5%, based on:
  - An analysis of dose response data.
  - An evaluation of errors in dose delivery in a clinical setting.
- Considering all uncertainties involved in the dose delivery to the patient, the ±5% accuracy is by no means easy to attain.

9.1 INTRODUCTION

- Accurate dose delivery to the target with external photon or electron beams is governed by a chain consisting of the following main links:
  - Basic output calibration of the beam
  - Procedures for measuring the relative dose data.
  - Equipment commissioning and quality assurance.
  - Treatment planning
  - Patient set-up on the treatment machine.

9.1 INTRODUCTION

- The basic output for a clinical beam is usually stated as:
  - Dose rate for a point P in G/min or Gy/MU.
  - At a reference depth z_{ref} (often the depth of dose maximum z_{max}).
  - In a water phantom for a nominal source to surface distance (SSD) or source to axis distance (SAD).
  - At a reference field size on the phantom surface or the isocentre (usually 10x10 cm^2).



9.1 INTRODUCTION

- Machine basic output is usually given in:
  - Gy/min for kilovoltage x-ray generators and teletherapy units.
  - Gy/MU for clinical linear accelerators.
- For superficial and orthovoltage beams and occasionally for beams produced by teletherapy machines, the basic beam output may also be stated as the air kerma rate in air (in Gy/min) at a given distance from the source and for a given nominal collimator or applicator setting.

9.1 INTRODUCTION

- The basic output calibration for photon and electron beams is carried out with:
  - Radiation dosimeters
  - Special dosimetry techniques.
- Radiation dosimetry refers to a determination by measurement and/or calculation of:
  - Absorbed dose

    or
  - Some other physically relevant quantity, such as air kerma, fluence or equivalent dose

  at a given point in the medium.

9.1 INTRODUCTION

- Radiation dosimeter is defined as any device that is capable of providing a reading *M* that is a measure of the dose *D* deposited in the dosimetr's sensitive volume *V* by ionizing radiation.
- Two categories of dosimeters are known:
  - Absolute dosimeter produces a signal from which the dose in its sensitive volume can be determined without requiring calibration in a known radiation field.
  - Relative dosimeter requires calibration of its signal in a known radiation field.

9.1 INTRODUCTION

- Basic output calibration of a clinical radiation beam, by virtue of a direct determination of dose or dose rate in water under specific reference conditions, is referred to as reference dosimetry.
- Three types of reference dosimetry technique are known:
  - Calorimetry
  - Fricke (chemical, ferrous sulfate) dosimetry
  - Ionization chamber dosimetry

9.1 INTRODUCTION
9.1.1 Calorimetry

- Calorimetry is the most fundamental of the three reference dosimetry techniques, since it relies on basic definition of either electrical energy or temperature.
  - In principle, calorimetric dosimetry is simple.
  - In practice, calorimetric dosimetry is very complex because of the need for measuring extremely small temperature differences. This relegates the calorimetric dosimetry to sophisticated standards laboratories.

Main characteristics of calorimetry dosimetry:

- Energy imparted to matter by radiation causes an increase in temperature ΔT.
- Dose absorbed in the sensitive volume is proportional to ΔT.
- ΔT is measured with thermocouples or thermistors.
- Calorimetric dosimetry is the most precise of all absolute dosimetry techniques.

9.1 INTRODUCTION
9.1.1 Calorimetry

- The following simple relationship holds:

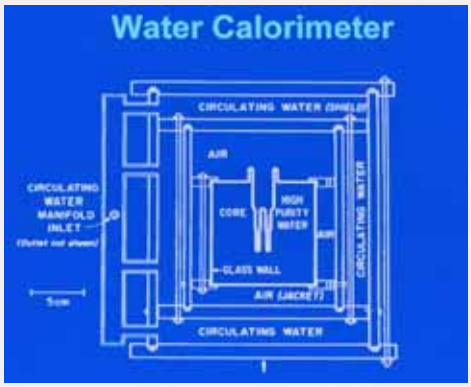
$$\bar{D} = \frac{dE}{dm} = \frac{C_p \Delta T}{1 - \delta}$$

  - $\bar{D}$ is the average dose in the sensitive volume
  - C_p is the thermal capacity of the sensitive volume
  - δ is the thermal defect
  - ΔT is the temperature increase

- Note: $\Delta T(\text{water, 1 Gy}) = 2.4 \times 10^{-4}$ K

9.1 INTRODUCTION
9.1.1 Calorimetry

- Two types of absorbed dose calorimeter are currently used in standards laboratories:
  - In graphite calorimeters the average temperature rise is measured in a graphite body that is thermally insulated from surrounding bodies (jackets) by evacuated vacuum gaps.
  - In sealed water calorimeters use is made of the low thermal diffusivity of water, which enables the temperature rise to be measured directly at a point in continuous water.



9.1 INTRODUCTION
9.1.2 Fricke (chemical) dosimetry

- Ionizing radiation absorbed in certain media produces a chemical change in the media and the amount of this chemical change in the absorbing medium may be used as a measure of absorbed dose.
- The best known chemical radiation dosimeter is the Fricke dosimeter which relies on oxidation of ferrous ions (Fe^{2+}) into ferric ions (Fe^{3+}) in an irradiated ferrous sulfate $FeSO_4$ solution.

9.1 INTRODUCTION
9.1.2 Fricke (chemical) dosimetry

- Concentration of ferric ions increases proportionally with dose and is measured with absorption of ultraviolet light (304 nm) in a spectrophotometer.
- Fricke dosimetry depends on an accurate knowledge of the radiation chemical yield of ferric ions.
- The radiation chemical yield *G* of ferric ions is measured in moles produced per 1 J of energy absorbed in the solution.

9.1 INTRODUCTION
9.1.2 Fricke (chemical) dosimetry

- An accurate value of the chemical yield *G* is difficult to ascertain because the chemical yield is affected by:
  - Energy of the radiation
  - Dose rate
  - Temperature of the solution during irradiation and readout.
- The chemical yield $G(Fe^{3+})$ in mole/J is related to an older parameter, the G value in molecules of Fe^{3+} per 100 eV of absorbed energy:

$$1\ \text{molecule/J} = 1.037 \times 10^{-4}\ \text{mole/J}$$

- Average absorbed dose in a Fricke solution is given as:

$$\bar{D} = \frac{\Delta M}{\rho G(\mathrm{Fe}^{3+})} = \frac{\Delta(O.D.)}{\rho \varepsilon \ell G(Fe^{3+})} = 278\Delta(O.D.)$$

- ΔM is the change in molar concentration of Fe^{3+}.
- ρ is the density of the Fricke solution.
- $\Delta(O.D.)$ is the increase in optical density after irradiation.
- ε is the extinction coefficient.
- ℓ is the thickness of the solution.
- $G(Fe^{3+})$ is the chemical yield of Fe^{3+} in mole/J.

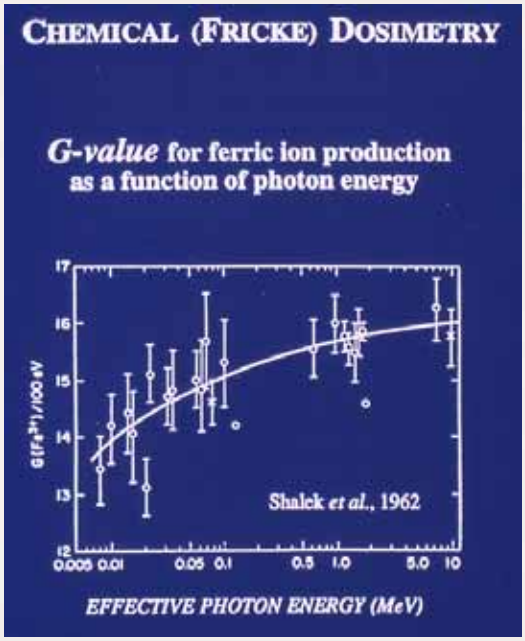
9.1 INTRODUCTION
9.1.2 Fricke (chemical) dosimetry

- Recommended G values in molecule/100 eV
  - Photon beams (ICRU 14)

Cs-137	15.3
2 MV	15.4
Co-60	15.5
4 MV	15.5
5 MV to 10 MV	15.6
11 MV to 30 MV	15.7

  - Electron beams (ICRU 35)

1 MeV to 30 MeV	15.7



9.1 INTRODUCTION
9.1.2 Fricke (chemical) dosimetry

- The best G value for Co-60 gamma rays is 15.6 molecules per 100 eV of absorbed energy, corresponding to a chemical yield of 1.607×10^{-6} mole/J.
- The typical dynamic range for ferrous sulphate Fricke dosimeters is from a few Gy to about 400 Gy.
- The relatively large dose required to produce a measurable signal makes Fricke dosimetry impractical for routine use in radiotherapy clinics.

9.1 INTRODUCTION
9.1.3 Ionization chamber dosimetry

- Ionization chamber is the most practical and most widely used type of dosimeter for accurate measurement of machine output in radiotherapy.
- It may be used as an absolute or relative dosimeter.
- Its sensitive volume is usually filled with ambient air and:
  - The dose related measured quantity is charge *Q*,
  - The dose rate related measured quantity is current *I*,

  produced by radiation in the chamber sensitive volume.

- Measured charge Q and sensitive air mass m_{air} are related to absorbed dose in air D_{air} by:

$$D_{air} = \frac{Q}{m_{air}} \left(\frac{\overline{W}_{air}}{e} \right)$$

  - $\overline{W}_{air}/e$ is the mean energy required to produce an ion pair in air per unit charge e.
  - Currently, the value of $\overline{W}_{air}/e$ for dry air is 33.97 eV/ion pair or 33.97 J/C.

9.1 INTRODUCTION
9.1.3 Ionization chamber dosimetry

- The subsequent conversion of the air cavity dose D_{air} to dose to medium (usually water) D_w is based on:
  - Bragg-Gray cavity theory
  - Spencer-Attix cavity theory
- The sensitive air volume or sensitive mass of air in ionization chamber is determined:
  - Directly by measurement (the chamber becomes an absolute dosimeter under special circumstances).
  - Indirectly through calibration of the chamber response in a known radiation field (the chamber is then used as a relative dosimeter).

9.1 INTRODUCTION

9.1.4 Mean energy expended in air per ion pair formed

- It is generally assumed that a constant value of $\overline{W}_{air}/e$ can be used for the complete photon and electron energy range used in radiotherapy dosimetry.
- There is no direct experimental support for such an assumption, as the data available have been obtained only from measurements with Co-60 and Cs-137 gamma ray beams and 2 MV x ray beams.

9.1 INTRODUCTION

9.1.4 Mean energy expended in air per ion pair formed

- $\overline{W}_{air}/e$ was determined using two dose measurement techniques:
  - Graphite calorimeter.
  - Graphite ionization chamber in a graphite phantom.
- The two techniques (graphite calorimeter and graphite ionization chamber in graphite phantom) for deriving the absorbed dose to graphite must yield the same dose value.

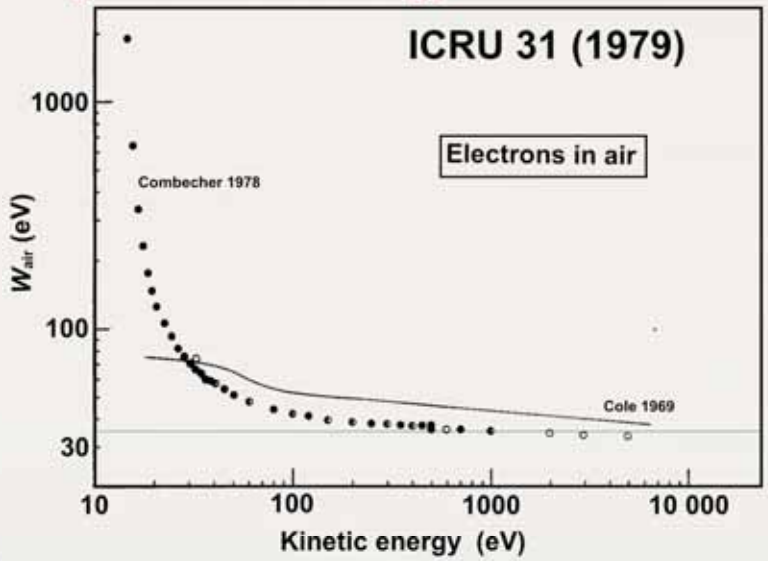
- Dose to graphite is given as:

$$D_{\text{calorimeter}} = D_{\text{ionization chamber}} \equiv \frac{Q}{m_{\text{air}}} \left(\frac{\overline{W}_{\text{air}}}{e} \right) \overline{s}_{\text{air}}^{\text{graphite}}$$

  - Q/m_{air} is the charge Q collected in the chamber sensitive air per unit mass m_{air} and corrected for influence quantities.
  - $\overline{s}_{\text{air}}^{\text{graphite}}$ is the ratio of mass collision stopping powers for graphite and air calculated for the photon energy used in irradiation.

- $\overline{W}_{\text{air}}/e$ is given as: $\dfrac{\overline{W}_{\text{air}}}{e} = \dfrac{D_{\text{calorimeter}}}{\dfrac{Q}{m_{\text{air}}} \overline{s}_{\text{air}}^{\text{graphite}}}$

- $\overline{W}_{\text{air}}/e$ at T = 20° C and p = 101.3 kPa for dry air for electrons against kinetic energy.



9.1 INTRODUCTION

9.1.4 Mean energy expended in air per ion pair formed

- $\overline{W}_{air}/e$ depends on relative humidity of air:
  - For air at relative humidity of 50%, $(\overline{W}_{air}/e) = 33.77$ J/C
  - For dry air, $(\overline{W}_{air}/e) = 33.97$ J/C
- At air temperature T = 20°C and air pressure p = 101.3 kPa for the same amount of energy available for creating charge in air, 0.6% more charge will be created in air at 50% relative humidity than in dry air.

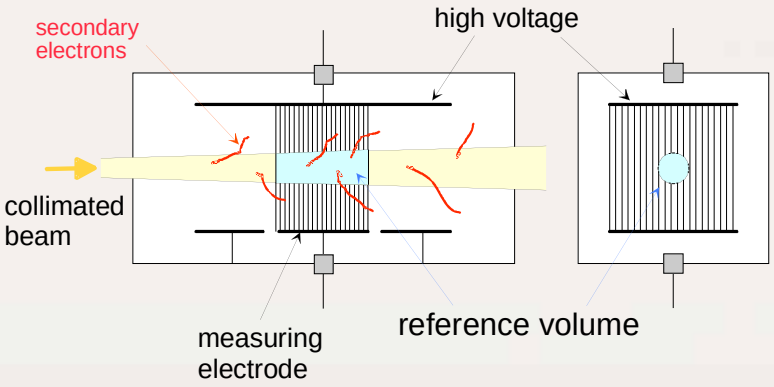
9.1 INTRODUCTION

9.1.5 Reference dosimetry with ionization chambers

- Three types of ionization chamber may be used in reference dosimetry as absolute dosimeter:
  - Standard free air ionization chamber
  - Cavity ionization chamber
  - Extrapolation chamber
- The “absoluteness” of dose determination with ionization chambers depends on the accurate knowledge of $\overline{W}_{air}/e$, the mean energy required to produce an ion pair in air.

9.1 INTRODUCTION
9.1.5 Reference dosimetry with ionization chambers

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



9.1 INTRODUCTION
9.1.5 Reference dosimetry with ionization chambers

- Standard free air ionization chambers are absolute dosimeters used for measuring the air kerma in air according to its definition by collecting all ions that:
  - Are produced by the radiation beam.
  - Result from the direct transfer of energy from photons to primary electrons in a defined volume of air.
- For practical reasons related to the range of charge carriers in air, the use of the standard free air ionization chamber is limited to photon energies below 0.3 MeV.

9.1 INTRODUCTION
9.1.5 Reference dosimetry with ionization chambers

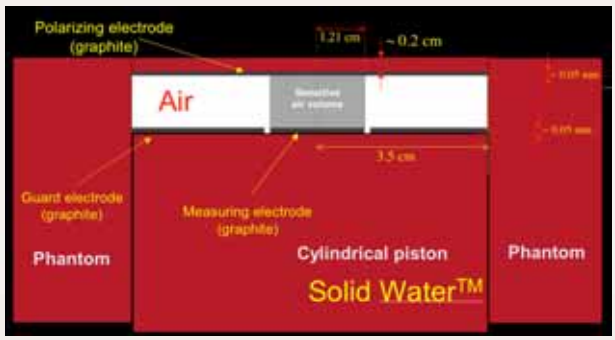
- Cavity ionization chambers may be used as absolute dosimeters measuring the air kerma in air for energies in the range from 0.6 to 1.5 MeV by making use of the Bragg-Gray cavity relationship.
- Analogously to standard free air ionization chambers, ions are collected in air, but here inside the air cavity with a known volume surrounded by a graphite wall thick enough to provide full buildup of secondary electrons.

9.1 INTRODUCTION
9.1.5 Reference dosimetry with ionization chambers

- Phantom-embedded extrapolation chambers are uncalibrated, variable air volume, extrapolation chambers built as integral part of a water equivalent phantom in which the dose is measured.
- They can serve as absolute radiation dosimeters in the measurement of absorbed dose for megavoltage photon and electron beams.

- Phantom-embedded extrapolation chamber

Movable piston allows controlled change in sensitive air volume and measurement of the ionization gradient against electrode separation.



9.1 INTRODUCTION

9.1.5 Reference dosimetry with ionization chambers

- Standard dosimetry protocols are based on the Bragg-Gray or Spencer-Attix cavity theories which provide a simple linear relationship between the dose at a given point in the medium and the ratio Q/m_{air}.
- In extrapolation chambers, the ratio Q/m_{air} is constant and may be replaced in the cavity relationship by the derivative dQ/dm_{air} which can be measured accurately through a controlled variation in the electrode separation.

9.1 INTRODUCTION

9.1.6 Clinical beam calibration and measurement chain

- Clinical photon and electron beams are most commonly calibrated with ionization chambers that
  - Are used as relative dosimeters.
  - Have calibration coefficients determined either in air or in water and are traceable to a national primary standards dosimetry laboratory (PSDL).
- The chamber calibration coefficient essentially obviates the need for an accurate knowledge of the chamber sensitive volume.

9.1 INTRODUCTION

9.1.6 Reference dosimetry with ionization chambers

- The traceability of a calibration coefficient to a national PSDL implies that:
  - Either the chamber was calibrated directly at the PSDL in terms of:
    - Air kerma in air
    - Absorbed dose in water
  - Or the chamber was calibrated directly at an accredited dosimetry calibration laboratory (ADCL) or at a secondary standards dosimetry laboratory (SSDL) that traces its calibration to a PSDL.
  - Or the chamber calibration coefficient was obtained through a cross-calibration with another ionization chamber, the calibration coefficient of which was measured directly at a PSDL, an ADCL or an SSDL.

9.1 INTRODUCTION

9.1.7 Dosimetry protocols or codes of practice

- Dosimetry protocols or codes of practice state the procedures to be followed when calibrating a clinical photon or electron beam.
- The choice of which protocol to use is left to individual radiotherapy departments or jurisdictions.
- Dosimetry protocols are generally issued by national, regional, or international organizations.

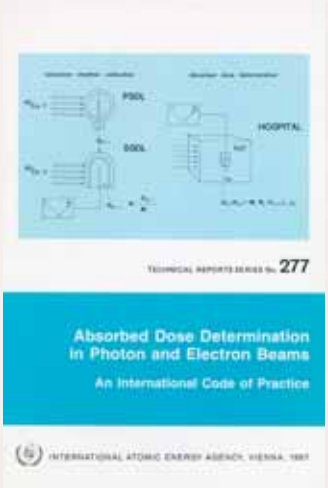
Examples of dosimetry protocols

- National:
  - Institution of Physics and Engineering in Medicine and Biology (IPEMB) for UK
  - Deutsches Institut fuer Normung (DIN) for Germany
- Regional:
  - American Association of Physicists in Medicine (AAPM) for North America
  - Nederlandse Commissie voor Stralingsdosimetrie (NCS) for Netherlands and Belgium
  - Nordic Association of Clinical Physics (NACP) for Scandinavia

9.1 INTRODUCTION
9.1.7 Dosimetry protocols or codes of practice

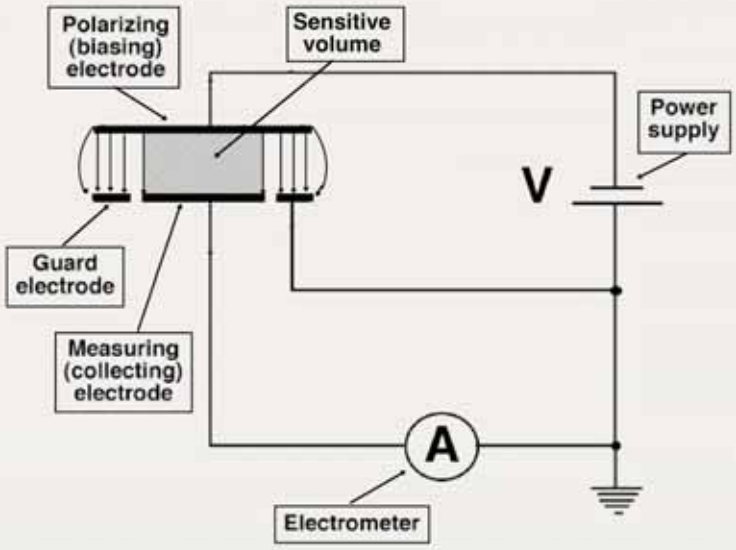
Examples of dosimetry protocols

- International:
  - International Atomic Energy Agency (IAEA)



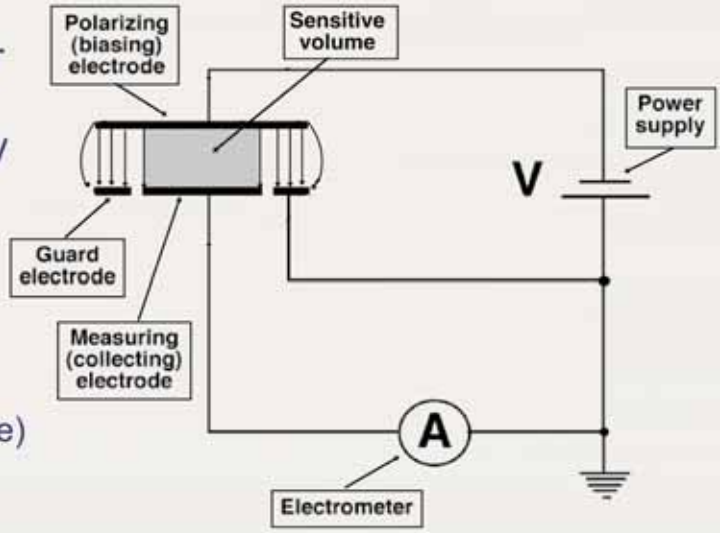
9.2 IONIZATION CHAMBER BASED DOSIMETRY SYSTEMS

- Dosimetry systems based on ionization chambers are in principle quite simple consisting of three major components:
  - Suitable ionization chamber
  - Electrometer
  - Power supply



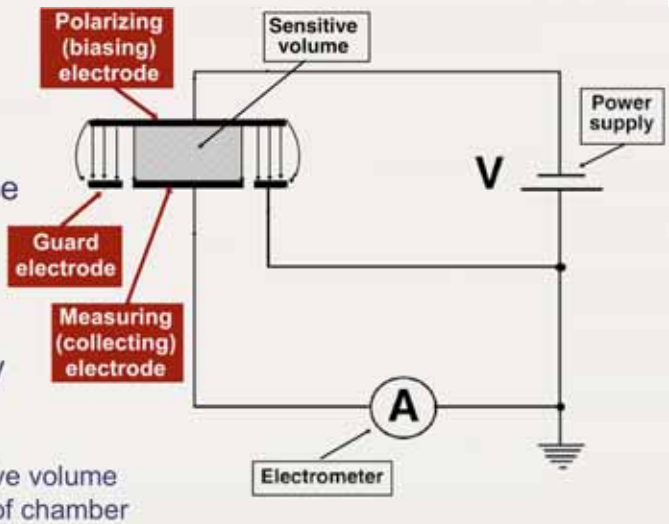
9.2 IONIZATION CHAMBER BASED DOSIMETRY SYSTEMS

- The circuitry of a simple ionization chamber-based dosimetry system resembles a capacitor (ionization chamber) connected to a battery (power supply).
- The electrometer measures
  - Capacitor charging or discharging current (in the differential mode)
  - Capacitor charge (in the integral mode).



9.2 IONIZATION CHAMBER BASED DOSIMETRY SYSTEMS
9.2.1 Ionization chambers

- Ionization chambers incorporate three electrodes which define the chamber sensitive volume:
  - Polarizing electrode is connected directly to the power supply.
  - Measuring electrode is connected to ground through the low impedance electrometer to measure the current or charge produced in the chamber sensitive volume.
  - Guard electrode is directly grounded and serves two purposes
    - Defines the chamber sensitive volume
    - Prevents the measurement of chamber leakage currents



9.2 IONIZATION CHAMBER BASED DOSIMETRY SYSTEMS
9.2.1 Ionization chambers

- The sensitive volume of ionization chambers used in calibration of clinical photon and electron beams is of the order of 0.1 to 1 cm^3.
- For indirectly ionizing radiation the initial event that triggers the chamber signal is the release of high energy charged particles (electrons or positrons) in the chamber wall through:
  - Photoelectric effect
  - Compton effect
  - Pair production.

9.2 IONIZATION CHAMBER BASED DOSIMETRY SYSTEMS
9.2.1 Ionization chambers

- Air is usually used as the sensitive gas in an ionization chamber.
- Some of the electrons released in the chamber wall enter the chamber sensitive volume and ionize the air through Coulomb interactions with the air molecules producing low energy electrons and positive ions.

9.2 IONIZATION CHAMBER BASED DOSIMETRY SYSTEMS
9.2.1 Ionization chambers

- In air, since oxygen is an electronegative gas, the low energy electrons produced by high-energy electrons interacting with air molecules, attach themselves to oxygen molecules and form negative ions.
- In standard air-filled ionization chambers, positive ions and negative ions are collected, rather than positive ions and free electrons.

9.2 IONIZATION CHAMBER BASED DOSIMETRY SYSTEMS
9.2.1 Ionization chambers

- Electronegativity is a measure of the ability of an atom or molecule to attract electrons to form a negative ion.
- Pauling scale ranging from 0.7 for cesium and francium (the least electronegative atoms) to 4 for fluorine (the most electronegative atom) is used to describe the level of electronegativity.
- Because oxygen is a strong electronegative atom, in-air based ionization chambers the charged particles collected in chamber electrodes are positive and negative ions, rather than positive ions and free electrons.

9.2 IONIZATION CHAMBER BASED DOSIMETRY SYSTEMS
9.2.1 Ionization chambers

Two types of ionization chamber are used for beam calibration:

- Cylindrical (also called thimble) chambers are used in calibration of:
  - Orthovoltage x-ray beams
  - Megavoltage x-ray beams
  - Electron beams with energies of 10 MeV and above
- Parallel-plate (also called end window or plane-parallel) chambers are used in calibration of:
  - Superficial x-ray beams
  - Electron beams with energies below 10 MeV
  - Photon beams in the buildup region and surface dose

9.2 IONIZATION CHAMBER BASED DOSIMETRY SYSTEMS
9.2.1 Ionization chambers

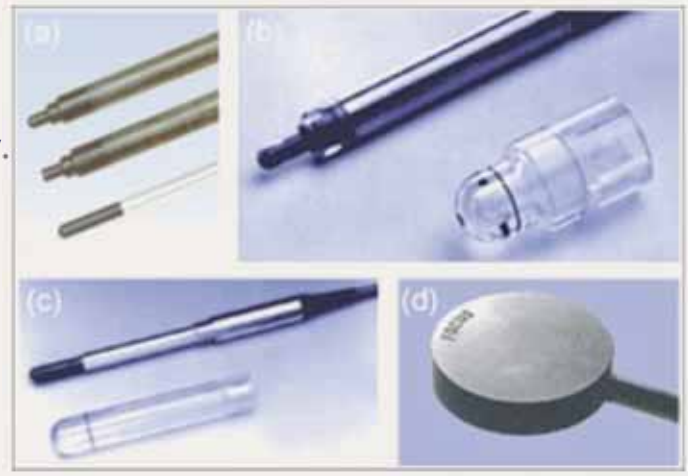
Examples of typical ionization chambers:

(a) Cylindrical chambers used for relative dosimetry.

(b) Pinpoint mini-chamber and Co-60 buildup cap.

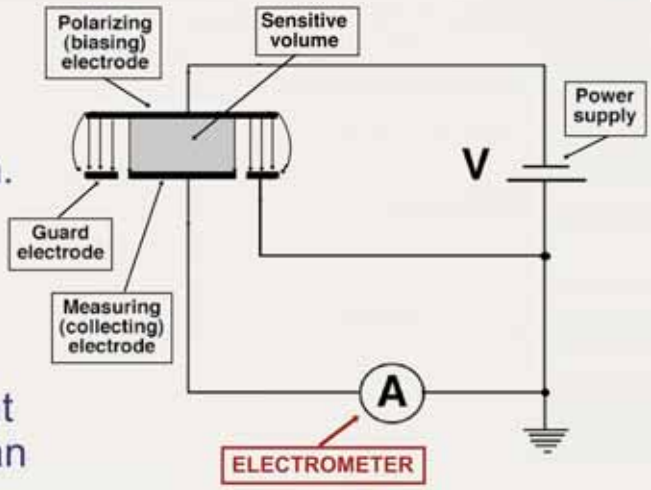
(c) Farmer type cylindrical chamber and cobalt-60 buildup cap.

(d) Parallel-plate Roos type electron beam chamber.



9.2 IONIZATION CHAMBER BASED DOSIMETRY SYSTEMS
9.2.2 Electrometer and power supply

- An ionization chamber is essentially a capacitor in which leakage current or leakage charge is induced through the action of a radiation beam.
- The charge or current induced in the chamber are very small and are measured by a very sensitive charge or current measuring device called an electrometer.



9.2 IONIZATION CHAMBER BASED DOSIMETRY SYSTEMS
9.2.2 Electrometer and power supply

- The power supply in ionization chamber/electrometer circuits is either a stand alone unit or forms an integral part of the electrometer.
- It is useful to be able to change the polarity and voltage provided by the power supply, so that the ion collection efficiency and polarity effects can be determined for a particular radiation beam and ionization chamber.

9.2 IONIZATION CHAMBER BASED DOSIMETRY SYSTEMS
9.2.3 Phantoms

- Phantom is a common name for materials that are used to replace the patient in studies of radiation interactions in patients.
- The phantom material should meet the following criteria:
  - Absorb photons in the same manner as tissue.
  - Scatter photons in the same manner as tissue.
  - Have the same density as tissue.
  - Contain the same number of electrons per gram as tissue.
  - Have the same effective atomic number as tissue.

9.2 IONIZATION CHAMBER BASED DOSIMETRY SYSTEMS
9.2.3 Phantoms

- Water is the standard and most universal phantom material for dosimetry measurements of photon and electron beams.
- For photon beams, tissue equivalency or water equivalency implies a match in:
  - Mass-energy absorption coefficient
  - Mass stopping power
  - Mass scattering power
- For electron beams, water equivalency implies a match in:
  - Linear stopping power
  - Linear scattering power

9.2 IONIZATION CHAMBER BASED DOSIMETRY SYSTEMS
9.2.3 Phantoms

- Some plastic phantom materials used in dosimetry measurements are:
  - Polystyrene (density: 0.96 to 1.04 g/cm3)
  - Lucite (also called acrylic, plexiglass, polymethylmethacrylate, PMMA) with density of 1.18 g/cm3.
  - A-150 tissue equivalent plastic
  - Solid Water
  - Plastic water
  - Virtual water

9.2 IONIZATION CHAMBER BASED DOSIMETRY SYSTEMS
9.2.3 Phantoms

- Plastic solid materials are not universal tissue substitutes, since not all required equivalency parameters for plastics can be matched adequately with those of water.
- The effective atomic number Z_{eff} of a phantom material depends upon:
  - Atomic composition of the phantom material
  - Type of the radiation beam.
  - Quality of the radiation beam.

- For low energy photons, for which the photoelectric effect is dominant over the Compton process and pair production cannot occur, Z_{eff} of a compound material is:

$$Z_{eff} = \sqrt[3.5]{\sum_i a_i Z_i^{3.5}}$$

  - a_i is the mass fraction of the constituent element i.
  - Z_i is the atomic number of the constituent element i.

- Z_{eff} for air is 7.8
- Z_{eff} for water is 7.5

9.2 IONIZATION CHAMBER BASED DOSIMETRY SYSTEMS
9.2.3 Phantoms

- For megavoltage photon and electron beams, Z_{eff} of a compound is defined as:

$$Z_{eff} = \frac{\sum_i a_i \frac{Z_i^2}{A_i}}{\sum_i a_i \frac{Z_i}{A_i}}$$

  - a_i is the mass fraction of the constituent element i.
  - Z_i is the atomic number of the constituent element i.
  - A_i is the atomic mass of the constituent element i.

9.2 IONIZATION CHAMBER BASED DOSIMETRY SYSTEMS
9.2.3 Phantoms

- Water is recommended as the phantom material for the calibration of megavoltage photon and electron beams.

- The depth of calibration is:
  - **10 cm for megavoltage photon beams**
  - **Reference depth z_{ref} for electron beams**
- To provide adequate scattering conditions there must be:
  - **A margin on the phantom around the nominal field size at least 5 cm of water in all directions.**
  - **At least 10 cm of water beyond the chamber.**

9.3 CHAMBER SIGNAL CORRECTIONS FOR INFLUENCE QUANTITIES

- For each ionization chamber, reference conditions are described by a set of influence quantities for which a chamber calibration coefficient is valid without any further corrections.
- Influence quantities are defined as quantities that are not the subject of a measurement but yet influence the value of the quantity that is being measured.
- If the chamber is used under conditions that differ from the reference conditions, then the measured signal must be corrected for the influence quantities.

9.3 CHAMBER SIGNAL CORRECTIONS FOR INFLUENCE QUANTITIES

- Examples of influence quantities in ionization chamber dosimetry measurements are:
  - Ambient air temperature
  - Ambient air pressure
  - Ambient air humidity
  - Applied chamber voltage
  - Applied chamber polarity
  - Chamber leakage currents
  - Chamber stem effects

9.3 CHAMBER SIGNAL CORRECTIONS

9.3.1 Air temperature, pressure, and humidity effects: $k_{T,P}$

- The signal produced by an ionization chamber depends on:
  - Effective chamber sensitive volume V_{eff}.
  - Gas (usually air) that is used in the chamber.
- Actually, it is the mass of air contained in the chamber sensitive volume that determines the chamber signal.
- The chamber sensitive air mass m_{air} is:

$$m_{air} = \rho_{air} V_{eff}$$

  - where ρ_{air}, the density of air, is a function of the atmospheric pressure, temperature, and humidity for chamber open to the ambient atmosphere.

9.3 CHAMBER SIGNAL CORRECTIONS

9.3.1 Air temperature, pressure, and humidity effects: $k_{T,P}$

- It is common practice to fix the value of ρ_{air} to certain conditions and convert the chamber reading to these conditions.
- Most standards laboratories use the value of

$$\rho_{air}(T_s, P_s) = 1.293 \times 10^{-3} \text{ g/cm}^3$$

for dry air density at standard conditions of T_s = 0ºC = 273.16 K and P_s = 101.325 kPa.

9.3 CHAMBER SIGNAL CORRECTIONS

9.3.1 Air temperature, pressure, and humidity effects: $k_{T,P}$

- Considering air as an ideal gas, the density $\rho_{air}(T,P)$ at an arbitrary temperature T(ºC) and pressure P(kPa) is:

$$\rho_{air}(T,P) = \rho_{air}(T_s,P_s)\frac{273.16}{(273.16+T)}\frac{P}{P_s}$$

- For $T > T_s$ and $P = P_s \rightarrow \rho_{air}(T,P_s) < \rho_{air}(T_s,P_s)$
- For $T < T_s$ and $P = P_s \rightarrow \rho_{air}(T,P_s) > \rho_{air}(T_s,P_s)$
- For $T = T_s$ and $P > P_s \rightarrow \rho_{air}(T_s,P) > \rho_{air}(T_s,P_s)$
- For $T = T_s$ and $P < P_s \rightarrow \rho_{air}(T_s,P) > \rho_{air}(T_s,P_s)$

9.3 CHAMBER SIGNAL CORRECTIONS

9.3.1 Air temperature, pressure, and humidity effects: $k_{T,P}$

- When calibrating an ionization chamber, the charge measured by the chamber depends on the air temperature, pressure and humidity, and therefore the chamber calibration coefficient must be given for stated reference values of these parameters.
- At most standards laboratories the chamber signal is corrected to normal conditions of T_n = 20°C (22°C in North America) and P_n = 101.325 kPa and no correction is applied for humidity of air (assumed to be about 50%).

9.3 CHAMBER SIGNAL CORRECTIONS

9.3.1 Air temperature, pressure, and humidity effects: $k_{T,P}$

- In the user's beam, the correction factor for air temperature and air pressure $k_{T,P}$ is:

$$k_{T,P} = \frac{273.16 + T}{273.16 + T_n} \times \frac{P_n}{P}$$

- This correction factor is applied to convert the measured signal to the reference (normal) conditions used for the chamber calibration at the standards laboratory:
  - T and P are chamber air temperature (°C) and pressure at the time of measurement.
  - T_n and P_n are chamber air temperature (°C) and pressure for the normal conditions at the standards laboratory.

9.3 CHAMBER SIGNAL CORRECTIONS

9.3.1 Air temperature, pressure, and humidity effects: $k_{T,P}$

- (W_{air}/e) and stopping powers that are used in dosimetry protocols are stated for dry air but are affected by air humidity.
- At 50% air humidity this results in an overall humidity correction factor to dry air values of 0.997 for a cobalt-60 beam consisting of:
  - 0.994 correction to the (W_{air}/e) dry air value of 33.97 J/C.
  - 1.003 correction to stopping powers.

9.3 CHAMBER SIGNAL CORRECTIONS

9.3.2 Chamber polarity effects: polarity correction factor k_{pol}

- Under identical irradiation conditions the use of potentials of opposite polarity in an ionization chamber may yield different readings. This phenomenon is called the polarity effect.
- When a chamber is used in a beam that produces a measurable polarity effect, the true reading is taken to be the mean of the absolute values of readings taken at the two polarities.

- Two types of polarity effect are known:
  - Voltage dependent
  - Voltage independent
- Basic characteristics of the polarity effects:
  - They are negligible for megavoltage photon beams at depths beyond the depth of dose maximum; i.e., at $z > z_{max}$.
  - They can be significant for orthovoltage beams and in the buildup region of megavoltage photon beams.
  - They are present in electron beams at all depths between the surface and the practical range R_P.

9.3 CHAMBER SIGNAL CORRECTIONS
9.3.2 Chamber polarity effects: polarity correction factor k_{pol}

- The polarity correction factor k_{pol} is defined as:

$$k_{pol}(V) = \frac{|M_+(V)| + |M_-(V)|}{2M}$$

  - M_+ is the chamber signal obtained at positive chamber polarity
  - M_- is the chamber signal obtained at negative chamber polarity
  - M is the chamber signal obtained at the polarity used routinely (either positive or negative).
- If the polarity correction factor k_{pol} for a particular chamber exceeds 3%, the chamber should not be used for output calibration.

- Voltage-dependent polarity effects are caused by:
  - Distortion of electric field by potential difference between the guard and the collecting electrode.
  - Space charge distortion of electric field lines defining the gas sensitive volume.
  - Difference in mobility of positive and negative ions causing differences in space charge distribution around the central electrode.

9.3 CHAMBER SIGNAL CORRECTIONS
9.3.2 Chamber polarity effects: polarity correction factor k_{pol}

- Voltage-independent polarity effects are caused by radiation induced currents referred to as Compton currents.
  - The Compton current - I_{Comp} results from interaction of photons and electrons with atoms of the collecting electrode.

$$I_{Comp} = \frac{|M_+(V)| - |M_-(V)|}{2}$$

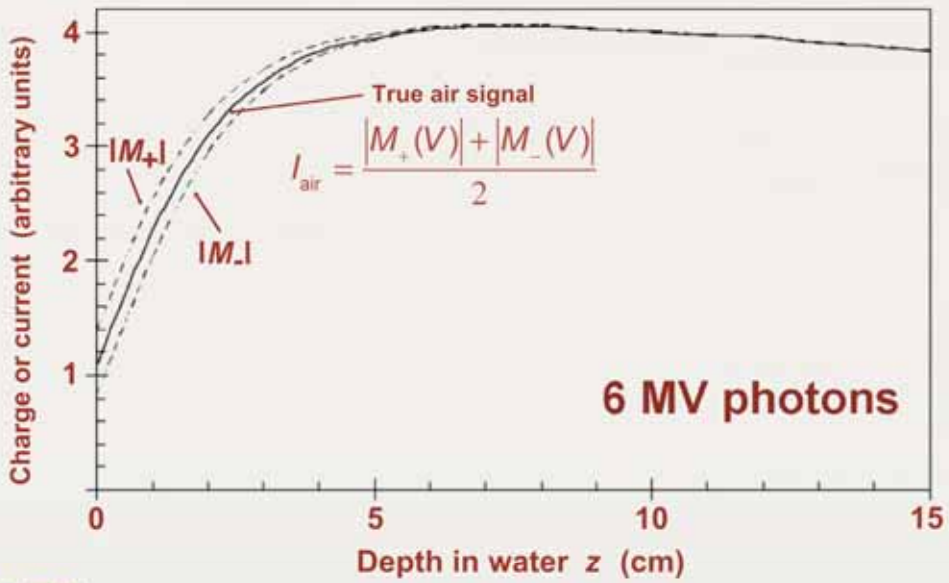
  - The true air ionization I_{air} in an ionization chamber, in the absence of any collection inefficiency and voltage dependent polarity effects, is equal to the mean of the absolute positive and negative polarity signals.

$$I_{air} = \frac{|M_+(V)| + |M_-(V)|}{2}$$

9.3 CHAMBER SIGNAL CORRECTIONS

9.3.2 Chamber polarity effects: polarity correction factor k_{pol}

- Origin of Compton current for photon beams



9.3 CHAMBER SIGNAL CORRECTIONS

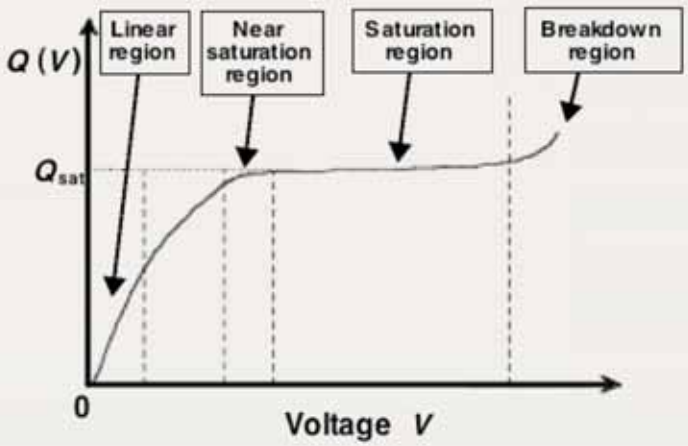
9.3.3 Chamber voltage effects: recombination correction factor k_{sat}

- The charges produced in an ionization chamber by radiation may differ from the charges that are actually collected in the measuring electrode.
- These discrepancies (charge loss caused by charge recombination or excess charge caused by charge multiplication and electrical breakdown) occur as a result of:
  - Constraints imposed by the physics of ion transport in the chamber sensitive volume.
  - Chamber mechanical and electrical design.

9.3 CHAMBER SIGNAL CORRECTIONS

9.3.3 Chamber voltage effects: recombination correction factor k_{sat}

- A plot of chamber response (current I or charge Q) against the applied voltage V is called a saturation curve.
- The saturation curve:
  - Rises linearly at low voltages (linear region).
  - Reaches saturation at relatively high voltages (saturation region).
  - Breaks down at very high voltages (breakdown region).



9.3 CHAMBER SIGNAL CORRECTIONS

9.3.3 Chamber voltage effects: recombination correction factor k_{sat}

- The ratios $Q(V)/Q_{sat}$ and $I(V)/I_{sat}$ are called the collection efficiency f of the ionization chamber at the applied voltage V.
- Q_{sat} and I_{sat} are the saturation values of $Q(V)$ and $I(V)$, respectively. In saturation, all charges produced by radiation are collected and produce directly the Q_{sat} and I_{sat} for use in dosimetry protocols.
- In radiation dosimetry, ionization chambers are commonly used in:
  - Near-saturation region where $f > 0.98$.
  - Saturation region where $f \approx 1$.

9.3 CHAMBER SIGNAL CORRECTIONS

9.3.3 Chamber voltage effects: recombination correction factor k_{sat}

- When the chamber is used below saturation, some of the charges produced by radiation actually recombine and are lost to the dosimetric signal.
- The charge loss occurs through three different mechanisms:
  - Initial recombination: opposite charges from same tracks collide and recombine.
  - General recombination: opposite charges from different tracks collide and recombine. This is by far the predominant mode of charge loss in an ionization chamber, and the other two are generally ignored.
  - Ionic diffusion loss: charges diffuse against the electric field.

9.3 CHAMBER SIGNAL CORRECTIONS

9.3.3 Chamber voltage effects: recombination correction factor k_{sat}

- For studies of ionic recombination losses, ionizing radiations are classified into three categories:
  - Continuous radiation (e.g., cobalt-60 beams and orthovoltage x rays)
  - Pulsed beams (e.g., non-scanned linac x-ray beams and electrons)
  - Scanned pulsed beams (e.g., scanned linac beams)
- The ionic recombination correction factor k_{sat} accounts for the loss of ions in the chamber sensitive volume due to initial recombination, general recombination, and diffusion loss.
  - k_{sat} is labelled P_{ion} in the AAPM TG 21 and TG 51 protocols.
  - k_{sat} equals $1/f$ in the ionic recombination theory.

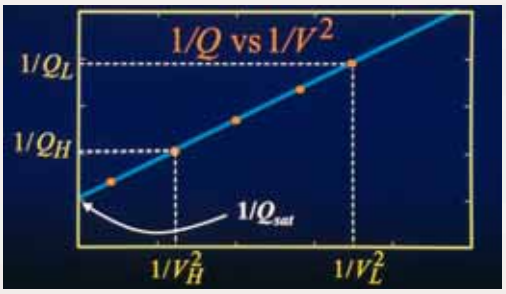
9.3 CHAMBER SIGNAL CORRECTIONS

9.3.3 Chamber voltage effects: recombination correction factor k_{sat}

- According to Boag, in the near saturation region ($f > 0.97$) the collection efficiency f_g^{cont} for general recombination in a continuous beam may be written as:

$$f_g^{cont} = \frac{Q}{Q_{sat}} = \frac{1}{1+\frac{\Lambda_g}{V^2}} \quad \text{or} \quad \frac{1}{Q} = \frac{1}{Q_{sat}} + \frac{\Lambda_g / Q_{sat}}{V^2} = \frac{1}{Q_{sat}} + \frac{\lambda_g}{V^2}$$

- The relationship for $1/Q$ suggests a linear relationship when plotted against $1/V^2$ with $1/Q_{sat}$ the ordinate intercept of the linear plot at $V \rightarrow \infty$



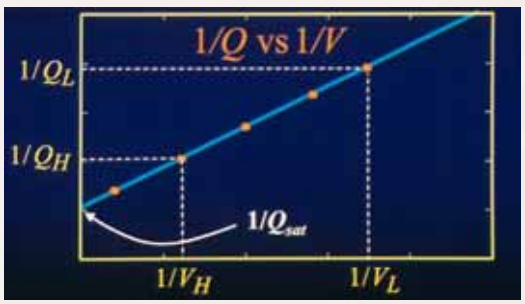
9.3 CHAMBER SIGNAL CORRECTIONS

9.3.3 Chamber voltage effects: recombination correction factor k_{sat}

- According to Boag, in the near saturation region ($f > 0.97$) the collection efficiency f_g^{pul} for general recombination in a pulsed beam may be written as:

$$f_g^{pul} = \frac{Q}{Q_{sat}} = \frac{V}{C}\ln\left[1+\frac{C}{V}\right] \quad \text{or} \quad \frac{1}{Q} = \frac{1}{Q_{sat}} + \frac{C / Q_{sat}}{2V} = \frac{1}{Q_{sat}} + \frac{C'}{V}$$

- The relationship for $1/Q$ suggests a linear relationship when plotted against $1/V$, with $1/Q_{sat}$ the ordinate intercept of the linear plot at $V \rightarrow \infty$

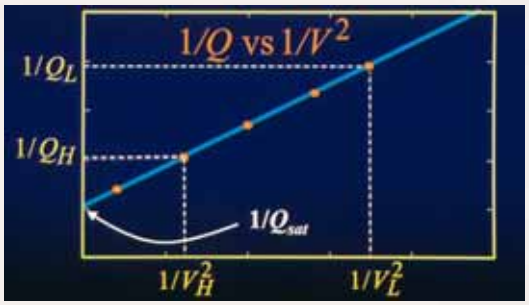


- Assuming the predominance of general recombination we can determine the collection efficiencies f_g^{cont} and f_g^{pul} for continuous and pulsed radiation beams, respectively, with the so called two-voltage method.
- Ionization chamber signals M are determined under same irradiation conditions at two voltages: the normal operating voltage V_H and a lower voltage V_L.
- The following conditions apply in the two-voltage method:
  - The ratio V_H/V_L should be equal or larger than 3.
  - Charge multiplication must be avoided which implies that V_H must not be too large.

- The collection efficiency $f_g^{cont}(V_H)$ at the normal chamber operating voltage V_H is for continuous beam given as:

$$f_g^{cont}(V_H) = \frac{M_H}{M_{sat}} = \frac{\frac{M_H}{M_L} - \left[\frac{V_H}{V_L}\right]^2}{1 - \left[\frac{V_H}{V_L}\right]^2}$$

$$k_g^{cont} \approx 1/f_g^{cont}$$



- For $V_H = 2V_L$ the expression simplifies to:

$$f_g^{cont}(V_H = 2V_L) = \frac{4}{3} - \frac{M_H}{3M_L}$$

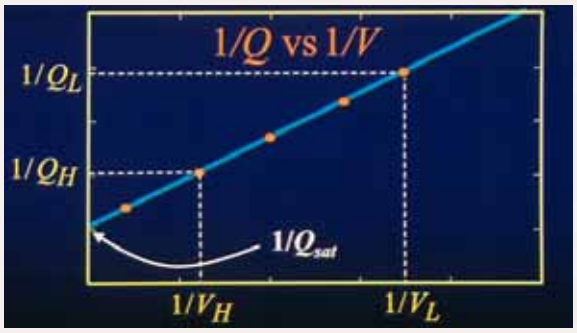
9.3 CHAMBER SIGNAL CORRECTIONS

9.3.3 Chamber voltage effects: recombination correction factor k_{sat}

- The collection efficiency $f_g^{pul}(V_H)$ at the normal chamber operating voltage V_H is for pulsed beam given as:

$$f_g^{pul}(V_H) = \frac{M_H}{M_{sat}} = \frac{\frac{M_H}{M_L} - \frac{V_H}{V_L}}{1 - \frac{V_H}{V_L}}$$

$$k_g^{pul} \approx 1/f_g^{pul}$$



- For $V_H = 2V_L$ the expression simplifies to:

$$f_g^{pul}(V_H = 2V_L) = 2 - \frac{M_H}{M_L}$$

9.3 CHAMBER SIGNAL CORRECTIONS

9.3.4 Chamber leakage currents

- Leakage currents represent non-dosimetric signal in an ionization chamber. Their effects on the true radiation induced dosimetric currents are minimized with:
  - Guard electrodes
  - Low noise triaxial cables
  - Sophisticated electrometers.
- In a well designed ionization chamber system the leakage current are at least two orders of magnitude lower than the measured dosimetric signal and are thus negligible or can be suppressed from the actual dosimetric signal.

9.3 CHAMBER SIGNAL CORRECTIONS
9.3.4 Chamber leakage currents

- Leakage currents fall into three categories:
  - Intrinsic (dark) leakage currents result from surface and volume leakage currents flowing between the polarizing and measuring electrodes of the ionization chamber.
  - Radiation induced leakage currents occur as a consequence of the irradiation of insulators and chamber parts, cables and electronics of the measuring equipment.
  - Mechanical stress induced and friction induced spurious cable currents result from bending and twisting of cables.

9.3 CHAMBER SIGNAL CORRECTIONS
9.3.5 Chamber stem effects

- Irradiation of ionization chamber stem results in a specific type of leakage current referred to as the stem effect.
- Two mechanisms of stem effect have been identified:
  - Stem scatter arises from the effect of scattered radiation in the stem that reaches the chamber volume.
  - Stem leakage arises as a consequence of a direct irradiation of this chamber volume as well as of the insulators and cables of the chamber.

9.4 DETERMINATION OF ABSORBED DOSE USING CALIBRATED IONIZATION CHAMBERS

- For practical reasons, outputs of clinical photon and electron beams are usually measured with ionization chambers that have calibration coefficients traceable to a standards laboratory and are thus used as relative dosimeters.
- These chambers are then used in radiation dosimetry in conjunction with a suitable dosimetry protocol (code of practice).

9.4 DETERMINATION OF ABSORBED DOSE USING CALIBRATED IONIZATION CHAMBERS

- A dosimetry protocol provides the formalism and the data to relate a calibration of a chamber at a standards laboratory to the measurement of absorbed dose to water under reference conditions in the clinical beam.
- Two types of dosimetry protocol are currently in use:
  - Protocols based on air kerma in air calibration coefficients.
  - Protocols based on absorbed dose to water calibration coefficients.
- Conceptually, both types of protocol are similar and define the steps to be used in the process of determining absorbed dose from a signal measured by an ionization chamber.

9.4 DETERMINATION OF ABSORBED DOSE USING CALIBRATED IONIZATION CHAMBERS

- The first step in the use of a dosimetry protocol involves the determination of the chamber signal M_Q at beam quality Q through correction of the measured chamber charge or current for influence quantities.
- Radiation dosimetry formalisms are based upon:
  - Cobalt-60 calibration coefficients for megavoltage photon and electron beams.
  - Calibration coefficients obtained for the particular beam quality used for superficial and orthovoltage x-ray beams.

9.4 USE OF CALIBRATED IONIZATION CHAMBERS
9.4.1 Air kerma based protocols

- Air kerma based protocols use the air kerma in air calibration coefficient $N_{K,Co}$ obtained for a local reference ionization chamber in a cobalt-60 beam at a standards laboratory.
- Two steps are involved in an air kerma based protocol for the calibration of megavoltage photon and electron beams.
  - The cavity air calibration coefficient $N_{D,air}$ is determined from the air kerma in air calibration coefficient $N_{K,Co}$.
  - Absorbed dose to water is determined using the Bragg-Gray relationship in conjunction with the chamber signal M_Q and the cavity air calibration coefficient $N_{D,air}$.

Calibration in a cobalt-60 beam at standards laboratory:

- The absorbed dose to air in the cavity $D_{air,Co}$ is determined from the total air kerma in air $(K_{air})_{air}$ as follows:

$$D_{air,Co} = (K_{air})_{air} \; (1-\bar{g}) \; k_m \; k_{att} \; k_{cel}$$

  - $\bar{g}$ is the radiative fraction, i.e., the fraction of the total transferred energy expended in radiative interactions on the slowing down of the secondary electrons in air.
  - k_m corrects for the non-air equivalence of the chamber wall and buildup cap needed for an air kerma in air measurement.
  - k_{att} corrects for attenuation and scatter in the chamber wall.
  - k_{cel} corrects for non-air equivalence of the chamber central electrode.

9.4 USE OF CALIBRATED IONIZATION CHAMBERS
9.4.1 Air kerma based protocols

Calibration in a cobalt-60 beam at standards laboratory:

- The cavity air calibration coefficient $N_{D,air}$ is defined as:

$$N_{D,air} = \frac{D_{air,Co}}{M_{Co}}$$

  - $D_{air,Co}$ is the absorbed dose to airin the chamber cavity.
  - M_{Co} is the chamber signal corrected for influence quantities.

- The air kerma in air calibration coefficient $N_{K,Co}$ is:

$$N_{K,Co} = \frac{(K_{air})_{air}}{M_{Co}}$$

Calibration in a cobalt-60 beam at standards laboratory:

- The absorbed dose to air in the cavity was given as:

$$D_{air,Co} = (K_{air})_{air}\ (1-\bar{g})\ k_m\ \ k_{att}\ \ k_{cel}$$

$$\frac{D_{air,Co}}{M_{Co}} \equiv N_{D,air} = \frac{(K_{air})_{air}}{M_{Co}}(1-\bar{g})\ k_m\ \ k_{att}\ \ k_{cel} = N_{K,Co}\ (1-\bar{g})\ k_m\ \ k_{att}\ \ k_{cel}$$

- The cavity air calibration coefficient $N_{D,air}$ is now:

$$N_{D,air} = N_{K,Co}\ (1-\bar{g})\ k_m\ \ k_{att}\ \ k_{cel}$$

9.4 USE OF CALIBRATED IONIZATION CHAMBERS
9.4.1 Air kerma based protocols

Calibration in a cobalt-60 beam at standards laboratory:

- The cavity air calibration coefficient $N_{D,air}$ is also directly related to the effective volume V_{eff} of the chamber by:

$$N_{D,air} = \frac{D_{air}}{M_{Co}} = \frac{1}{m_{air}}\frac{\overline{W}_{air}}{e} = \frac{1}{\rho_{air} V_{eff}}\frac{\overline{W}_{air}}{e}$$

- $N_{D,air}$ is a characteristic of the dosimetric device.
  - It depends only on the effective mass of the air in the chamber
  - Does not depend on radiation quality as long as (Wair/e) is independent of the radiation quality.

9.4 USE OF CALIBRATED IONIZATION CHAMBERS
9.4.1 Air kerma based protocols

- The absorbed dose to air $D_{air,Q}$ in the air cavity irradiated by a megavoltage beam of quality Q can be converted into absorbed dose to medium (e.g., water) $D_{w,Q}$ by making use of the Bragg-Gray (B-G) cavity relationship.
- Under special conditions, the Bragg-Gray (B-G) cavity theory provides the relationship between the absorbed dose in a dosimeter (cavity air) and the absorbed dose in the medium (water) containing the dosimeter (cavity).
  - The cavity must be small so as not to perturb the fluence of charged particles in the medium.
  - The dose in the cavity must be deposited solely by charged particles crossing the cavity.

9.4 USE OF CALIBRATED IONIZATION CHAMBERS
9.4.1 Air kerma based protocols

- Under these special conditions, according to the B-G cavity theory, the dose to the medium D_{med} is related to the dose to the cavity D_{cav} as:

$$D_{med} = D_{cav} \; (\bar{S} / \rho)_{med,cav}$$

  - $(\bar{S} / \rho)_{med,cav}$ is the ratio of the average unrestricted mass collision stopping powers medium to cavity.
- The Spencer-Attix (S-A) cavity theory is more general and accounts for the creation of secondary (delta) electrons. The dose to medium is given as:

$$D_{med} = D_{cav} \; \bar{s}_{m \; .c \; v})$$

  - $(\bar{S}_{med.cav})$ is the ratio of the average restricted mass collision stopping powers medium to cavity.

9.4 USE OF CALIBRATED IONIZATION CHAMBERS
9.4.1 Air kerma based protocols

- With a known value of the cavity air calibration coefficient $N_{D,air}$ for a specific chamber, the chamber signal corrected for influence quantities M_Q at a point in phantom allows determination of the absorbed dose to water $D_{w,Q}$:

$$D_{w,Q} = D_{air,Q}\ (\bar{s}_{w,air})_Q\ p_Q = M_Q\ N_{D,air}\ (\bar{s}_{w,air})_Q\ p_Q$$

  - $(s_{w,air})_Q$ is the ratio of average restricted collision stopping powers of water to air for a radiation beam of quality Q.
  - p_Q is a perturbation correction factor accounting for perturbations caused by the ionization chamber inserted into the medium (water).

9.4 USE OF CALIBRATED IONIZATION CHAMBERS
9.4.2 Absorbed dose to water based protocols

Calibration in a cobalt-60 beam at standards laboratory:

- Recent developments have provided support for a change in the quantity used to calibrate ionization chambers and provide calibration coefficients N_{D,w,Q_o} in terms of absorbed dose to water at beam quality Q_o .
- At the standards laboratory D_{w,Q_o}, the absorbed dose to water at the reference depth z_{ref} in water for a reference beam Q_o (usually cobalt-60) is known and used to determine the water dose calibration coefficient N_{D,w,Q_o}.

9.4 USE OF CALIBRATED IONIZATION CHAMBERS

9.4.2 Absorbed dose to water based protocols

Calibration in a quality Q_0 beam (usually cobalt-60) at the standards laboratory:

- The absorbed dose to water D_{w,Q_0} at the reference depth z_{ref} in water for a reference beam Q_0 (usually Co-60) is:

$$D_{w,Q_0} = M_{Q_0} N_{D,w,Q_0}$$

- M_{Q_0} is the chamber reading under the reference conditions used in the standards laboratory and corrected for influence quantities.
- N_{D,w,Q_0} is the water dose calibration coefficient for the chamber at beam quality Q_0 (usually cobalt-60).

9.4 USE OF CALIBRATED IONIZATION CHAMBERS

9.4.2 Absorbed dose to water based protocols

- When a chamber is used in a beam quality Q that differs from the quality Q_0 used in the chamber calibration at the standards laboratory, the absorbed dose to water is:

$$D_{w,Q} = M_Q \; N_{D,w,Q_0} \; k_{Q,Q_0}$$

- M_Q is the chamber reading in beam of quality Q and corrected for influence quantities to the reference conditions used in the standards laboratory.
- N_{D,w,Q_0} is the water dose calibration coefficient provided by the standards laboratory for reference beam quality Q_0.
- k_{Q,Q_0} is a factor correcting for the differences between the reference beam quality Q_0 and the actual user quality Q.

9.4 USE OF CALIBRATED IONIZATION CHAMBERS
9.4.2 Absorbed dose to water based protocols

- The beam quality correction factor k_{Q,Q_o} is defined as the ratio, at beam qualities Q and Q_o, of the calibration coefficients in terms of absorbed dose to water of the ionization chamber:

$$k_{Q,Q_o} = \frac{N_{D,w,Q}}{N_{D,w,Q_o}}$$

- Currently, the common reference quality Q_o used for the calibration of ionization chambers is the cobalt-60 gamma radiation and the symbol k_Q is normally used to designate the beam quality correction factor:

$$k_{Q,Q_o} = k_{Q,Co} = k_Q$$

9.4 USE OF CALIBRATED IONIZATION CHAMBERS
9.4.2 Absorbed dose to water based protocols

- The beam quality correction factor k_{Q,Q_o} is difficult to measure, so it is usually calculated theoretically by k_{Q,Q_o} comparing the dose to water expressed with:
  - The air kerma in air formalism: $D_{w,Q} = M_Q \; N_{D,air} \; (\bar{s}_{w,air})_Q \; p_Q$
  - The dose to water formalism: $D_{w,Q} = M_Q \; N_{D,w,Q_o} \; k_{Q,Q_o}$
- The beam quality correction factor k_{Q,Q_o} can be written as:

$$k_{Q,Q_o} = \frac{N_{D,w,Q}}{N_{D,w,Q_o}} = \frac{(s_{w,air})_Q}{(s_{w,air})_{Q_o}} \frac{p_Q}{p_{Q_o}}$$

9.4 USE OF CALIBRATED IONIZATION CHAMBERS
9.4.2 Absorbed dose to water based protocols

- Exposure calibration coefficient N_X is still frequently used in calibration of photon and electron beams.
- The exposure calibration coefficient N_X is related to the air kerma in air calibration coefficient as follows:

$$N_K = N_X \frac{\overline{W}_{air}}{e} \frac{1}{1-\bar{g}}$$

  - $(\overline{W}_{air}/e)$ is the average energy required to produce an ion pair in air (33.97 J/C)
  - $\bar{g}$ is the radiation fraction, i.e., fraction of energy loss in air expended in radiative interactions.

  $\bar{g}$(Co-60 in air) = 0.003, $\bar{g}$(superficial x rays in air) = 0.0002

9.4 USE OF CALIBRATED IONIZATION CHAMBERS
9.4.2 Absorbed dose to water based protocols

- Calibration beam at standards laboratory (cobalt-60)

Air kerma in air based protocol $(K_{air}(Co))_{air}$

Calibration coefficient: $N_{K,Co}$

$\times(1-\bar{g})k_m k_{att} k_{cel}$

$N_{D,air}$

$\times M_Q (s_{w,air})_Q p_Q$

$D_{w,Q} = M_Q N_{D,air} (s_{w,air})_Q p_Q$

Dose in water based protocol $D_{w,Co}$

Calibration coefficient: $N_{D,w,Co}$

$\times \dfrac{1}{(s_{w,air})_{Co} p_{Co}}$

$\times M_Q k_{Q,Co}$

$D_{w,Q} = M_Q N_{D,w,Co} k_{Q,Co}$

- Absorbed dose to water in user's beam of quality Q

9.4 USE OF CALIBRATED IONIZATION CHAMBERS

9.4.2 Absorbed dose to water based protocols

- The air kerma in air based formalism and the absorbed dose to water based formalism for the determination of absorbed dose to water in reference conditions include:
  - Stopping power ratios (essentially independent of the detector).
  - Correction factors for perturbation effects that are detector dependent and may include mass-energy absorption coefficient ratios.
- Ideally, the formalism in terms of absorbed dose to water is based on experimentally determined quantities, however, the beam quality factors k_{Q,Q_o} are currently determined theoretically.

9.5 STOPPING POWER RATIOS

- The determination of absorbed dose in a medium using an ionization chamber is based on the Bragg-Gray principle:
  - Relating the absorbed dose at a point in the medium (water) D_w
  - To the mean absorbed dose in the detector (air) $\bar{D}_{air}$.
  - Through a proportionality factor that classically has been identified as the ratio of mass collision stopping powers water to air.
- The key Bragg-Gray assumption is that the electron fluence present in the detector is identical to that in the undisturbed medium at the point of interest in the water phantom.

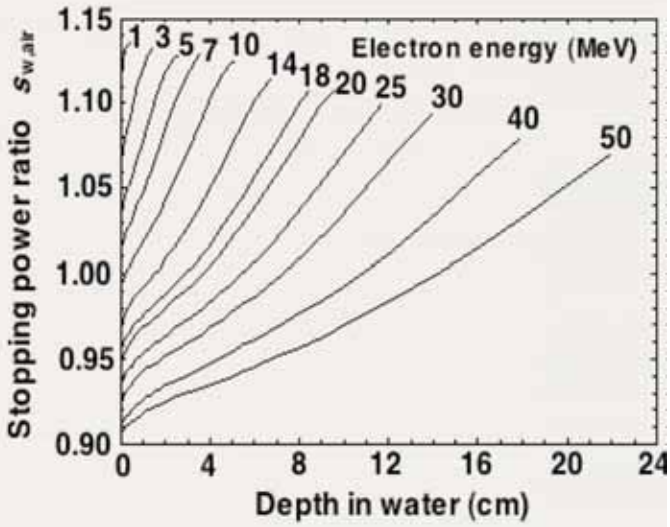
9.5 STOPPING POWER RATIOS

- The gas filled ionization chamber in a megavoltage photon or electron beam behaves to a good approximation as a Bragg-Gray detector.
- Any deviations from the Bragg-Gray behaviour are accounted for by perturbation factors.
- The fulfillment of the two Bragg-Gray conditions depends on the cavity size compared to the range of electrons in the cavity medium.

9.5 STOPPING POWER RATIOS

9.5.1 Stopping power ratios for electron beams

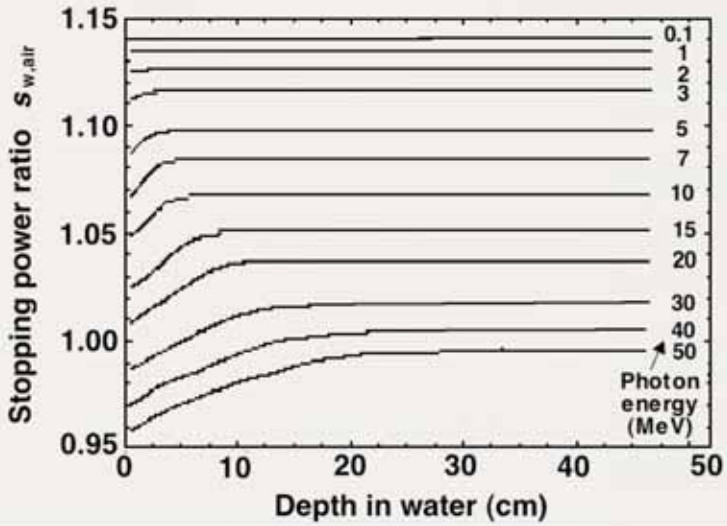
- The most important characteristic of the water/air restricted mass collision stopping power ratios for mono-energetic electrons is their strong dependence on energy and depth, resulting mainly from the variation in electron energy spectra at various depths in water.



9.5 STOPPING POWER RATIOS

9.5.2 Stopping power ratios for photon beams

- The water/air restricted average collision stopping power ratios for mono-energetic photons are almost constant with depth at depths exceeding the depth of dose maximum (in the region of the transient electronic equilibrium).



9.6 MASS-ENERGY ABSORPTION COEFFICIENT RATIOS

- Mass-energy absorption coefficient ratios, medium to air, are of historical importance, since they were used for defining the roentgen to cGy (rad) conversion factors:

$$f_{med} = 0.876 \frac{cGy}{R} \left[\frac{\mu_{ab}}{\rho} \right]_{air}^{med}$$

- Mass-energy absorption coefficient ratios are also used for defining the dose to small mass of medium D'_{med} :

$$D'_{med} = f_{med} X \; k(r_{med}) \qquad k(r_{med}) \approx e^{-\left(\frac{\mu_{ab}}{\rho}\right)_{med} \rho r_{med}}$$

  - $k(r_{med})$ is a correction factor accounting for the photon beam attenuation in the small mass of medium of density ρ_{med}

9.6 MASS-ENERGY ABSORPTION COEFFICIENT RATIOS

- The role of spectrum averaged mass-energy absorption coefficient ratios in modern dosimetry protocols is mainly restricted to their use in calculating perturbation and other correction factors for ionization chambers in cobalt-60 and high energy photon beams.
- In general mass-energy absorption coefficient ratios are associated with the fraction of energy deposited within a detector due to electrons generated by photon interactions in the detector material.

9.7 PERTURBATION CORRECTION FACTORS

- For a detector to behave as a Bragg-Gray cavity, the electron fluence in the sensitive medium of the detector must be identical to that at a specified point in a uniform medium.
- The only possible true Bragg-Gray detector would be an exceedingly small air bubble; all protocols for absolute dose determination are based on air filled ionization chambers.

9.7 PERTURBATION CORRECTION FACTORS

- For megavoltage photon radiation the Bragg-Gray conditions are adequately fulfilled for air cavity sizes encountered in practical ionization chambers with:
  - Volumes of 0.01 cm^3 to 0.6 cm^3 in cylindrical chambers
  - Electrode separations of the order of 1 mm in parallel-plate chambers
- In cylindrical ionization chambers neither the wall nor the central electrode are medium (water) equivalent, and this introduces deviations from perfect Bragg-Gray behaviour.

9.7 PERTURBATION CORRECTION FACTORS

- The deviations from Bragg-Gray behaviour are generally dealt by introducing appropriate correction (perturbation) factors into the expression for the absorbed dose:

$$D_{w,Q} = M_Q \; N_{D,air} \; (\bar{s}_{w,air})_Q \; p_Q$$

- The perturbation factor p_Q is often written as a product of four perturbation factors, each one accounting for a different effect, valid for beam quality Q and assumed to be independent of the others:

$$p_Q = (p_{dis} \; p_{wall} \; p_{cel} \; p_{cav})_Q$$

9.7 PERTURBATION CORRECTION FACTORS

- The perturbation correction factor p_Q corrects for four effects that cause deviations from Bragg-Gray behaviour:

$$p_Q = (p_{dis}\ p_{wall}\ p_{cel}\ p_{cav})_Q$$

- p_{dis} accounts for the effect of replacing a volume of water with the chamber air cavity in cylindrical chambers.
- p_{wall} accounts for the non-water equivalence of the chamber wall and any waterproofing material.
- p_{cel} accounts for the effect of the central electrode during in-phantom measurements.
- p_{dis} accounts for the effects of the air cavity on the in-scattering of electrons making the electrons fluence different from that in water in absence of the cavity.

9.7 PERTURBATION CORRECTION FACTORS
9.7.1 Displacement perturbation factor p_{dis}

- An ionization chamber placed into a phantom will displace a certain volume of the phantom medium and replace it with a wall (possibly medium equivalent) and air.
- The chamber reading will be affected by the “missing” medium in two ways:
  - Reduced attenuation
  - Reduced scatter.
- The net result of reduced attenuation and reduced scatter generally is an increase in the chamber signal. The increase in the signal is corrected for by the displacement perturbation factor p_{dis} which is less than unity.

9.7 PERTURBATION CORRECTION FACTORS

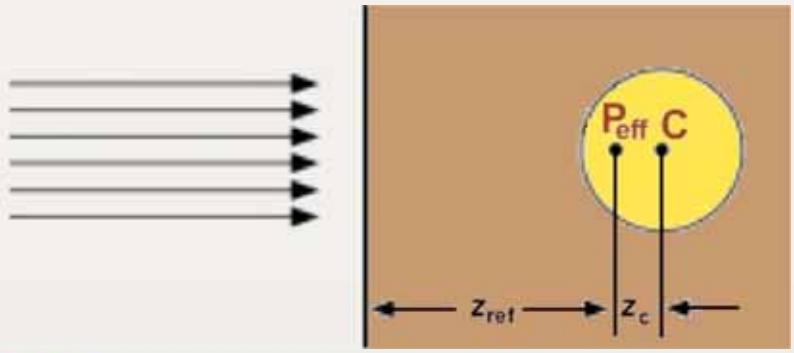
9.7.1 Displacement perturbation factor p_{dis}

- The displacement perturbation factor p_{dis} depends upon:
  - Radiation quality Q.
  - Physical dimensions of the air cavity in the direction of the beam.
  - Depth of measurement.
- In photon beams
  - p_{dis} is essentially constant for depths beyond z_{max}.
  - p_{dis} varies in a complicated fashion with depth in the buildup region.
- For a cobalt beam p_{dis} = 0.988 for a Farmer chamber with internal radius of 3 mm.

9.7 PERTURBATION CORRECTION FACTORS

9.7.1 Effective point of measurement P_{eff}

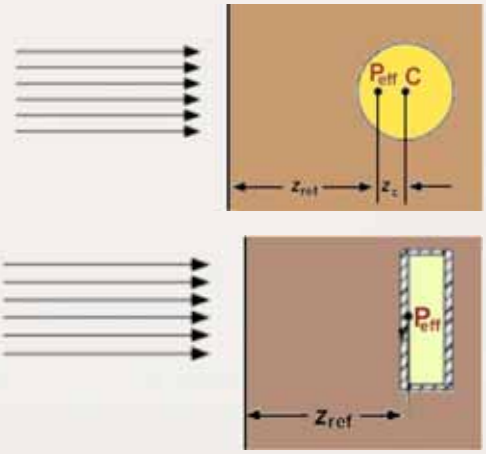
- Rather than correcting the chamber reading using p_{dis} with the chamber centre C positioned at the point of interest, one can correct for the displacement effect by introducing the concept of effective measurement point P_{eff} which is shifted toward the radiation source from the chamber centre by a distance z_c.



9.7 PERTURBATION CORRECTION FACTORS
9.7.1 Effective point of measurement P_{eff}

Absorbed dose to water based dosimetry protocols use:

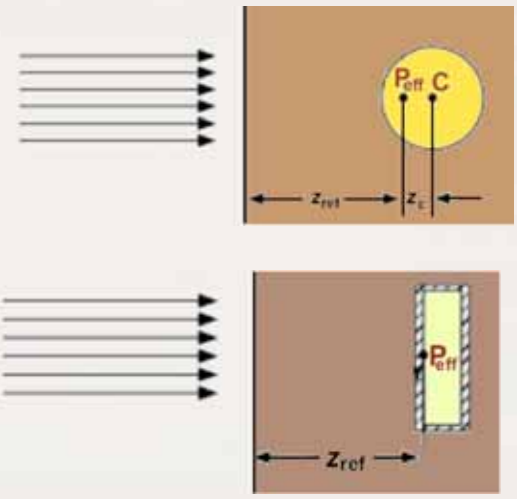
- Displacement perturbation factor p_{dis} approach for photon beams.
- Effective point of measurement P_{eff} approach for electron beams.
  - For cylindrical chambers with radius *r* the shift z_c is 0.5*r*.
  - For parallel-plate chambers P_{eff} is situated at the centre of the inside face of the front wall of the chamber.



9.7 PERTURBATION CORRECTION FACTORS
9.7.1 Effective point of measurement P_{eff}

Air kerma in air based protocols use the effective point of measurement P_{eff} approach for photon and electron beams.

- For cylindrical chambers with radius *r,* the shift z_c is 0.6*r*.
- For parallel-plate chambers, P_{eff} is situated at the centre of the inside face of the front wall of the chamber.



9.7 PERTURBATION CORRECTION FACTORS

9.7.2 Chamber wall perturbation factor p_{wall}

- Compliance with the Bragg-Gray conditions implies that the electron fluence in the sensitive volume of the detector is identical in magnitude, energy and angular distribution to that present in the undisturbed medium at the position of interest.
- The wall of the ionization chamber is in general not made of phantom medium equivalent material. Thus, in general, some of the electrons contributing to the electron fluence in the air cavity originate in the surrounding medium and others originate in the chamber wall.

9.7 PERTURBATION CORRECTION FACTORS

9.7.2 Chamber wall perturbation factor p_{wall}

- For chambers with walls of intermediate thickness p_{wall} is expressed by the following empirical expression:

$$p_{wall} = \frac{\alpha s_{wall,air} (\mu_{ab}/\rho)_{w,wall} + (1-\alpha) s_{w,air}}{s_{w,air}}$$

  - α is the fraction of the dose to the air in the chamber cavity due to electrons generated in the chamber wall.
  - $(1-\alpha)$ is the fraction of the dose to air in the chamber cavity due to electrons generated in the chamber medium and passing through the chamber wall.
  - $p_{wall}(\alpha = 0) = 1$ $\qquad$ $p_{wall}(\alpha = 1) = s_{wall,air} (\mu_{ab}/\rho)_{w,wall}$

9.7 PERTURBATION CORRECTION FACTORS
9.7.2 Chamber wall perturbation factor p_{wall}

- When a waterproofing sleeve is used with an ionization chamber in a water phantom, p_{wall} is expressed as:

$$p_{wall} = \frac{\alpha s_{wall,air} (\mu_{ab}/\rho)_{w,wall} + \tau s_{sleeve,air} (\mu_{ab}/\rho)_{w,sleeve} + (1-\alpha-\tau) s_{w,air}}{s_{w,air}}$$

  - α is the fraction of the dose to the air in the chamber cavity due to electrons generated in the chamber wall.
  - τ is the fraction of the dose to the air in the chamber cavity due to electrons generated in the sleeve.
  - $(1-\alpha-\tau)$ is the fraction of the dose to air in the chamber cavity due to electrons generated in the chamber medium and passing through the chamber wall and the sleeve.

9.7 PERTURBATION CORRECTION FACTORS
9.7.2 Chamber wall perturbation factor p_{wall}

- For cobalt-60 beams the two parameters α and τ are estimated from known chamber wall thickness t_{wall} (in g/cm^2) and sleeve thickness t_{sleeve} (in g/cm^2) using:

$$\alpha = 1 - e^{-11.88 t_{wall}} \qquad \tau = e^{-11.88 t_{wall}} - e^{-11.88 (t_{wall} + t_{sleeve})}$$

- For high energy megavoltage x-ray beams, the fractional ionizations α and τ are derived from the data given in the IAEA TRS 398 protocol.
- For megavoltage electron beams, the effect of the chamber wall is assumed negligible.

9.7 PERTURBATION CORRECTION FACTORS

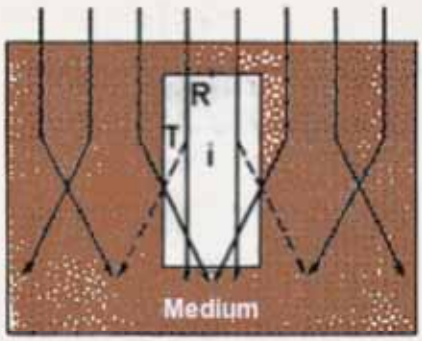
9.7.3 Central electrode perturbation factor p_{cel}

- Cylindrical ionization chambers have a central electrode, usually made of aluminum or graphite.
- The central electrode produces an increase in the chamber signal compared with the signal that would be obtained in a Bragg-Gray air bubble. The central electrode correction factor p_{cel} is introduced to correct for this effect.
  - In photon beams a graphite electrode produces essentially no effect; the effect of a 1 mm diameter aluminum electrode decreases with beam energy from 1.008 to 1.004.
  - In electron beams the effect is negligible for graphite; the effect is smaller than 0.2% for 1 mm diameter aluminum electrode.

9.7 PERTURBATION CORRECTION FACTORS

9.7.4 Cavity or fluence perturbation factor p_{cav}

- An ionization chamber introduces a low density heterogeneity (gas cavity) into a medium and this causes a perturbation of the electron fluence.
- According to Harder, in the unperturbed medium the angular distribution of electrons broadens in the cavity with depth; a low density cavity will scatter out fewer electrons than are scattered in. This results in an increase in the electron fluence toward the downstream end of the cavity in comparison with the fluence in a uniform medium at same depth.



Electron beams and the cavity perturbation factor p_{cav}.

- For cylindrical chambers the electron fluence is significantly perturbed. The cavity perturbation factor p_{cav} is:

$$p_{cav}(\bar{E}_o, r) = 1 - 0.02155re^{-0.1224\bar{E}(z)}$$

  - r is the inner radius of the air cavity in millimetres.
  - $\bar{E}_o$ is the average electron energy on the phantom surface (z = 0).
  - $\bar{E}(z)$ is the average electron energy at depth z (Harder expression).
  - R_p is the practical electron range.

$$\bar{E}(z) = \bar{E}_o \left\{ 1 - \frac{z}{R_p} \right\}$$

9.7 PERTURBATION CORRECTION FACTORS
9.7.4 Cavity or fluence perturbation factor p_{cav}

- For parallel-plate chambers the plate separation is usually much smaller (typically 2 mm) than the electrode radius.
  - The electron fluence in the sensitive chamber volume is equal to that existing in the uniform, unperturbed medium at the depth of the inside face of the front window (same as the effective point P_{eff}).
  - The cavity perturbation factor p_{cav} for parallel-plate chambers in electron beams is 1.
- In photon beams, beyond the depth of dose maximum the cavity correction factor p_{cav} is equal to 1 for all types of chambers, since the electron fluence perturbation is negligible.

9.8 BEAM QUALITY SPECIFICATION

- To obtain the absorbed dose to water at a reference point in water the signal (current or charge) that is produced by an ionization chamber and measured by an electrometer must be multiplied by various factors correcting for:
  - Influence quantities (air temperature, pressure, humidity, polarity effects, collections efficiency, stem effects, etc.).
  - Various dosimetric physical quantities related to deviations from Bragg-Gray conditions.
- Some of these quantities depend upon photon or electron beam energy, thus the beam quality must be specified for these calculations.

9.8 BEAM QUALITY SPECIFICATION

- The most straightforward means to characterize the quality of clinical radiation beam is to state its spectral distribution.
- Since beam spectra are difficult to measure directly and cumbersome to determine with Monte Carlo simulations, other, more practical, approaches to beam quality specification have been developed, specific to three distinct ionizing radiation beam categories:
  - Kilovoltage (superficial and orthovoltage) x-ray beams.
  - Megavoltage x -ray beams.
  - Megavoltage electron beams.

9.8 BEAM QUALITY SPECIFICATION

9.8.1 Beam quality specification for kilovoltage photon beams

- For low energy photon beams the quality of the beam is most conveniently expressed in terms of the half-value layer (HVL) of the beam.
- The HVL represents the thickness of an attenuator that decreases the measured air kerma rate in air to half of its original value.
  - For superficial x-ray beams (10 - 100 kVp) HVLs are usually given in millimetres of pure aluminum (0.01 to 10 mm).
  - For orthovoltage x-ray beams (above 100 kVp) HVLs are usually given in millimetres of pure copper (0.5 to 4 mm).

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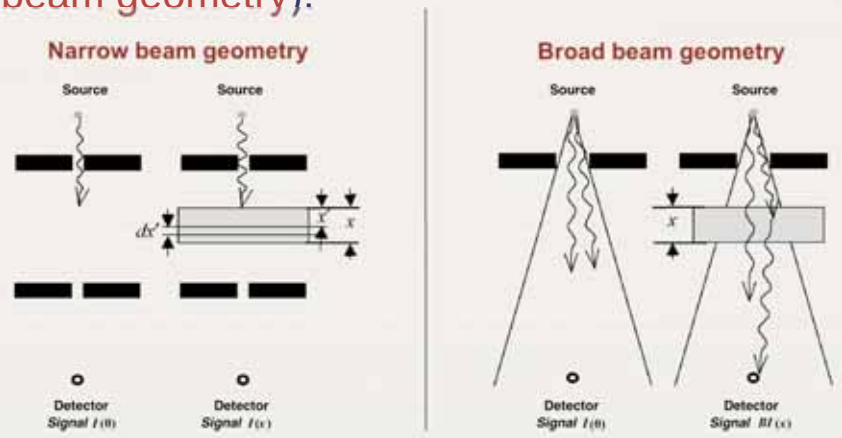
9.8 BEAM QUALITY SPECIFICATION

9.8.1 Beam quality specification for kilovoltage photon beams

- To minimize the effects of radiation scattered in the attenuator the HVL must be measured under "good geometry" conditions that imply a narrowly collimated source of photons and a narrowly collimated detector (narrow beam geometry).



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9.8 BEAM QUALITY SPECIFICATION

9.8.1 Beam quality specification for kilovoltage photon beams

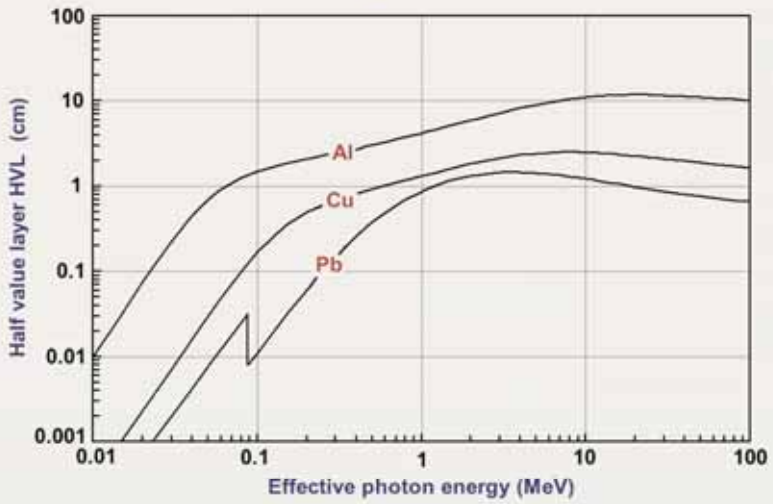
- The specification of beam quality in terms of the HVL is a very crude beam specification, since it tells little about the energy distribution of the photons present in the beam.
- Yet, beam specification with the HVL provides a general idea of the effective energy of the photon beam used for:
  - Assessing the radiation beam penetration into tissue
  - Determining appropriate values of the quantities used in dosimetry protocols.

IAEA

9.8 BEAM QUALITY SPECIFICATION

9.8.1 Beam quality specification for kilovoltage photon beams

- Effective energy of a heterogeneous beam is defined as that energy of a monoenergetic photon beam that yields the same HVL as does the heterogeneous beam.



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9.8 BEAM QUALITY SPECIFICATION

9.8.1 Beam quality specification for kilovoltage photon beams

- Since two photon beams with widely differing potentials can have similar HVLs, due to a marked effect of different filtrations, it is customary to state, in addition to the HVL, the x-ray potential and total filtration used in generating a given x-ray beam.
- Often low energy x-ray beams are also characterized by stating their homogeneity coefficient κ, which is defined as the ratio between the first and second HVL.

$$\kappa = \frac{HVL_1}{HVL_2}$$

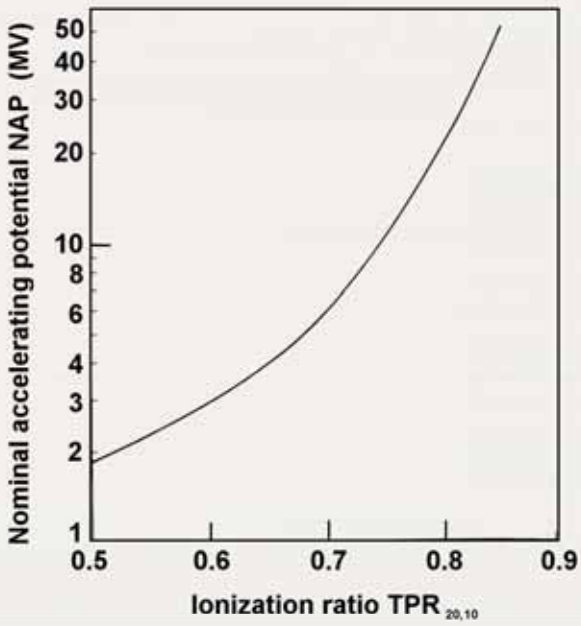
  - For heterogeneous low energy x-ray beams $HVL_2 > HVL_1$, resulting in $\kappa < 1$.
  - For monochromatic beams HVL2 = HVL1 and $\kappa = 1$.

9.8 BEAM QUALITY SPECIFICATION

9.8.2 Beam quality specification for megavoltage photon beams

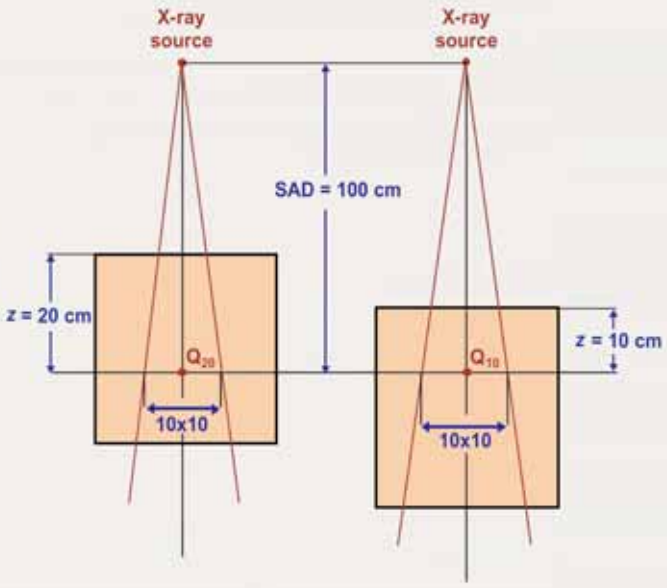
- In the megavoltage photon energy range, HVLs vary little with photon energy, making HVLs unsuitable for beam quality specification.
- Indices used for megavoltage photon beam specification are based upon:
  - Energy of the electron beam as it strikes the target (nominal accelerating potential - NAP)
  - Radiation beam attenuation as the beam penetrates into water or tissue, such as the tissue-phantom ratio (TPR) or percentage depth dose (PDD).

- Nominal accelerating potential (NAP)
  - NAP was introduced in the AAPM-TG 21 dosimetry protocol (1983) as a matter of convenience and is related to the energy of the electrons striking the target.
  - NAP is defined in terms of the ionization ratio measured in water on central beam axis at a fixed SAD of 100 cm and a field size of 10x10 cm^2 for depths z of 20 cm and 10 cm.



9.8 BEAM QUALITY SPECIFICATION
9.8.2 Beam quality specification for megavoltage photon beams

- Tissue-phantom ratio $TPR_{20,10}$ is defined as the ratio of doses on the beam central axis at depths of z = 20 cm and z = 10 cm in water obtained at an SAD of 100 cm and a field size of 10x10 cm^2.



9.8 BEAM QUALITY SPECIFICATION

9.8.2 Beam quality specification for megavoltage photon beams

- Tissue-phantom ratio $TPR_{20,10}$:
  - $TPR_{20,10}$ is independent of electron contamination of the incident photon beam.
  - $TPR_{20,10}$ is used as megavoltage beam quality specifier in the IAEA-TRS 398 dosimetry protocol.
  - $TPR_{20,10}$ is related to measured $PDD_{20,10}$ as:

$$TPR_{20,10} = 1.2661\, PDD_{20,10} - 0.0595$$

9.8 BEAM QUALITY SPECIFICATION

9.8.2 Beam quality specification for megavoltage photon beams

Percentage depth dose PDD(10) as beam specifier:

- PDD(10) is defined as the percentage depth dose measured in water on the beam central axis for a 10x10 cm^2 field and an SSD of 100 cm.
- The problem of electron beam contamination of the megavoltage photon beam is circumvented by placing a 1 mm thick lead foil into the beam to remove the unknown electron contamination.

9.8 BEAM QUALITY SPECIFICATION

9.8.2 Beam quality specification for megavoltage photon beams

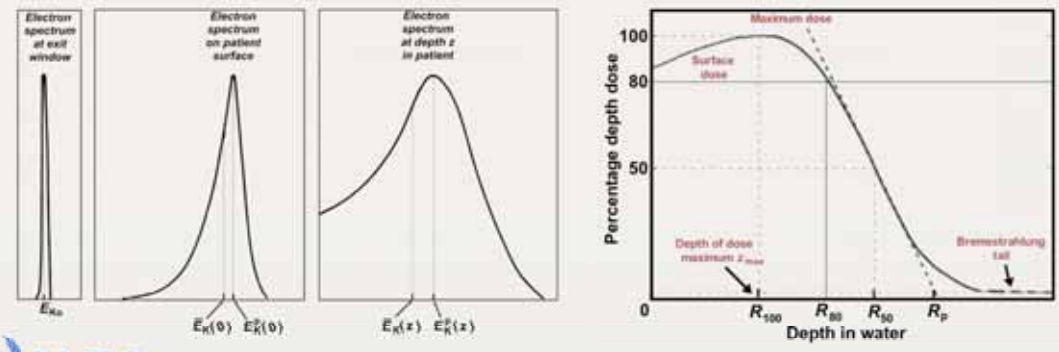
Percentage depth dose PDD(10) as beam specifier:

- The electron contamination contributed by the 1 mm thick lead foil can be assumed known and is determined with Monte Carlo calculations.
- $PDD(10)_x$ is the photon component of the PDD at 10 cm depth for a field of 10x10 cm^2 on phantom surface at source-surface distance SSD of 100 cm.
- $PDD(10)_x$ for the pure photon beam can be calculated from $PDD(10)_{Pb}$ using a correction formula.

9.8 BEAM QUALITY SPECIFICATION

9.8.3 Beam quality specification for megavoltage electron beams

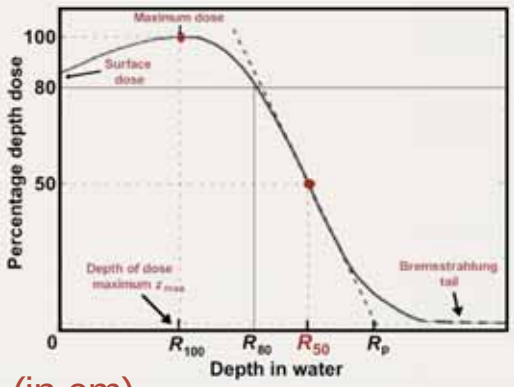
- Electron beams are essentially monoenergetic when they exit the accelerator waveguide.
- The electron beam striking the phantom or patient surface at a nominal SSD exhibits a spectrum that results from the energy spread caused by interactions between electrons and atoms of air and linac components.



9.8 BEAM QUALITY SPECIFICATION

9.8.3 Beam quality specification for megavoltage electron beams

- Until lately, the quality of clinical electron beams has been specified in dosimetry protocols by $\bar{E}_o$, the mean (average) electron energy of the incident spectrum striking the phantom surface.
- The beam quality index $\bar{E}_o$ is derived from measurement of R_{50} defined as the depth at which the electron beam depth dose decreases to 50% of its maximum value.



$$\bar{E}_o = CR_{50} = (2.33 \text{ MeV/cm}) \times R_{50}(\text{in cm})$$

9.8 BEAM QUALITY SPECIFICATION

9.8.3 Beam quality specification for megavoltage electron beams

- Equation $\bar{E}_o = CR_{50}$ has limited validity and is only valid for:
  - Large field sizes (broad electron beams)
    - Fields exceeding 12x12 cm^2 for electron beam energies below 15 MeV.
    - Fields exceeding 20x20 cm^2 for electron beams larger than 15 MeV.
  - Electron energies $\bar{E}_o$ between 5 MeV and 30 MeV.
  - R_{50} determined from depth dose distributions measured in water with a constant source-surface distance.

9.8 BEAM QUALITY SPECIFICATION

9.8.3 Beam quality specification for megavoltage electron beams

- Percentage depth dose distributions for clinical electron beams are most commonly determined from ionization measurements carried out in water or water equivalent phantoms using ionization chambers or diodes.
  - Percentage depth ionization curves measured with a diode represent the PDD curve directly, since the mass collision stopping power ratios silicon to water are essentially constant with depth in a phantom (i.e., with electron beam energy).
  - Percentage depth ionization curves measured with an ionization chamber must be corrected for gradient effects as well as for variations in mass collision stopping power ratios water to air with electron beam energy when determining the PDDs from ionization measurements.

9.8 BEAM QUALITY SPECIFICATION

9.8.3 Beam quality specification for megavoltage electron beams

- R_{50} may be determined from I_{50} (in centimeters), the 50% value on the percentage depth ionization (PDI) curve, measured with an ionization chamber in water as:

$$R_{50} = 1.029 I_{50} - 0.06 \text{ cm} \quad \text{for } 2 \text{ cm} \leq I_{50} \leq 10 \text{ cm}$$

$$R_{50} = 1.059 I_{50} - 0.37 \text{ cm} \quad \text{for } I_{50} > 10 \text{ cm}$$

- The recent dosimetry protocols use R_{50} directly as a beam quality index for selecting stopping power ratios and reference depths.

9.8 BEAM QUALITY SPECIFICATION

9.8.3 Beam quality specification for megavoltage electron beams

- The recent dosimetry protocols based on in-water calibration by the IAEA (TRS 398) and the AAPM (TG 51) have endorsed the choice of R_{50} as the quality index, and all data are expressed in terms of R_{50}.
- The reference depth z_{ref} for electron beam calibration in water is expressed in terms of R_{50} (in centimetres) as:

$$z_{ref} = 0.6R_{50} - 0.1\ \text{cm}$$

  - The reference depth z_{ref} in water is close to the depth of dose maximum z_{max} for beams with $R_{50} < 4$ cm ($\bar{E}_o < 10$ MeV).
  - $z_{ref} > z_{max}$ for beams with $R_{50} \geq 4$ cm.

9.9 CALIBRATION OF MEGAVOLTAGE BEAMS: PRACTICAL ASPECT

9.9.1 MV photon beams: Air kerma in air calibration coefficient $N_{K,Co}$

- A cylindrical ionization chamber is used at a given depth z in a water phantom (typically z is 5 cm or 10 cm).
- The calibration is based on an air kerma in air calibration coefficient $N_{K,Co}$ obtained in a cobalt-60 beam at a standards laboratory.
- The beam quality is specified with $\bar{E}_o$, the mean electron energy on a phantom surface obtained from

$$\bar{E}_o = CR_{50} = (2.33\ \text{MeV/cm}) \times R_{50}(\text{in cm})$$

9.9.1 MV photon beams: Air kerma in air calibration coefficient $N_{K,Co}$

- The Bragg-Gray or Spencer-Attix cavity theory is used to determine the dose $D_w(z)$ at the point of interest at depth z in a water phantom from the signal M_Q (charge) measured at beam quality Q and corrected for influence quantities :

$$D_w(z) = M_Q \; N_{D,air} \; s_{w,air} \; p_Q = M_Q \; N_{D,air} \; s_{w,air} \; p_{wall} \; p_{cel}$$

  - $N_{D,air}$ is the cavity air calibration coefficient.
  - $s_{w,air}$ is the restricted stopping power ratio water to air averaged over the electron slowing down spectrum resulting from the photon spectrum.
  - p_Q is the perturbation correction factor accounting for the perturbations caused by the chamber inserted into the water phantom.

9.9 CALIBRATION OF MEGAVOLTAGE BEAMS: PRACTICAL ASPECTS

9.9.1 MV photon beams: Air kerma in air calibration coefficient $N_{K,Co}$

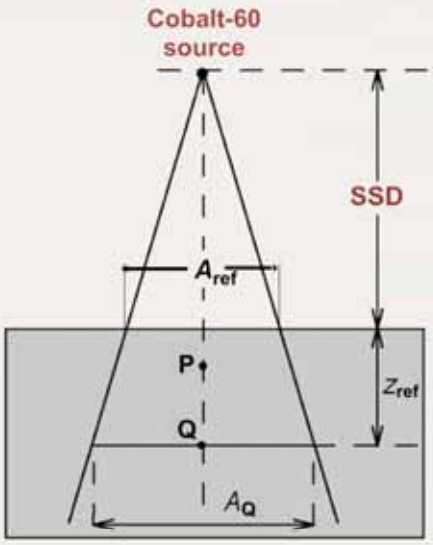
- Generally, the chamber correction factor p_Q is a product of four perturbation factors: displacement, wall, central electrode, and fluence:

$$p_Q = (p_{dis} \; p_{wall} \; p_{cel} \; p_{cav})_Q \qquad D_w(z) = M_Q \; N_{D,air} \; s_{w,air} \; p_{wall} \; p_{cel}$$

- Of the four perturbation factors, only p_{wall} and p_{cell} apply for air kerma in air based protocols and MV photon beams:
  - The displacement effect resulting from insertion of an air cavity into a phantom is accounted for by defining an effective point of measurement P_{eff}, thus $p_{dis} = 1$.
  - The cavity fluence perturbation correction factor p_{cav} is unity in high energy photon beams.

9.9.2 MV photon beams: Dose to water calibration coefficient $N_{D,w,Co}$

- A cylindrical ionization chamber is used at a given depth z in a water phantom (typically z is 10 cm).
- The calibration is based on a dose to water calibration coefficient $N_{D,w,Co}$ obtained from a standards laboratory with the chamber irradiated with a cobalt-60 beam at a reference depth z_{ref} in a water phantom.

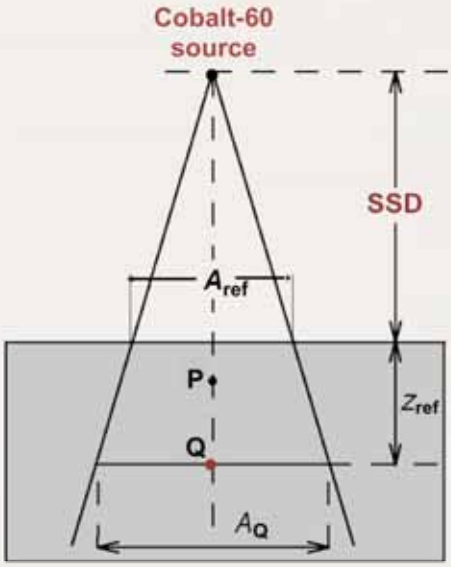


9.9.2 MV photon beams: Dose to water calibration coefficient $N_{D,w,Co}$

- The absorbed dose to water $D_{w,Co}$ at a given depth z_{ref} in a water phantom in a cobalt beam in the absence of the ionization chamber is:

$$D_{w,Co} = M_{Co}\ N_{D,w,Co}$$

  - M_{co} is the chamber signal (charge) corrected for influence quantities.
  - $N_{D,w,Co}$ is the dose to water chamber calibration coefficient.



9.9 CALIBRATION OF MEGAVOLTAGE BEAMS: PRACTICAL ASPECTS

9.9.2 MV photon beams: Dose to water calibration coefficient $N_{D,w,Co}$

- When the chamber is irradiated in a water phantom with a beam of quality Q that is different from the cobalt-60 beam quality used in chamber calibration, the absorbed dose to water is:

$$D_{w,Co} = M_{Co}\ N_{D,w,Co}\ k_{Q,Co}$$

  - M_Q is the chamber reading at point of interest in the water phantom, corrected for influence quantities.
  - $N_{D,w,Co}$ is the dose to water cobalt-60 chamber calibration coefficient.
  - $k_{Q,Co}$ is a correction factor correcting for the effects of the difference between the reference cobalt-60 beam quality and the actual beam quality Q.

9.9 CALIBRATION OF MEGAVOLTAGE BEAMS: PRACTICAL ASPECTS

9.9.2 MV photon beams: Dose to water calibration coefficient $N_{D,w,Co}$

- The beam quality Q of megavoltage photon beams is specified either with a ratio of TPRs [TPR20,10(Q)] or with the PDD [PDD(10,10x10,SSD,$Q)_x$].
- The IAEA TRS 398 dosimetry protocol recommends the use of the ratio of TPRs, while the AAPM TG 51 protocol recommends the use of the PDD$(10)_x$.
- Despite considerable polemics on the merits of each of the two approaches, in practice they both give essentially the same result for the megavoltage photon beams currently used in the clinical practice.

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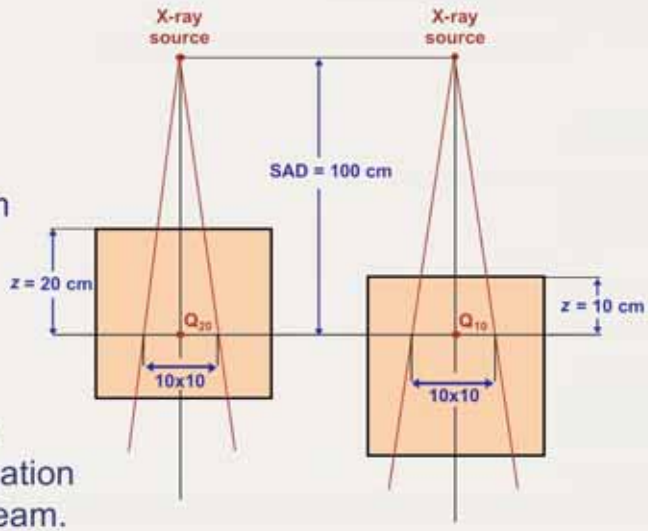
- The tissue-phantom ratio $TPR_{20,10}$ method for beam quality specification:
  - $TPR_{20,10}$ is defined as the ratio of doses on the beam central axis at depths of z = 20 cm and z = 10 cm in water obtained at an SAD of 100 cm and a field size of 10x10 cm^2.
  - $TPR_{20,10}$ is independent of the electron contamination of the incident photon beam.

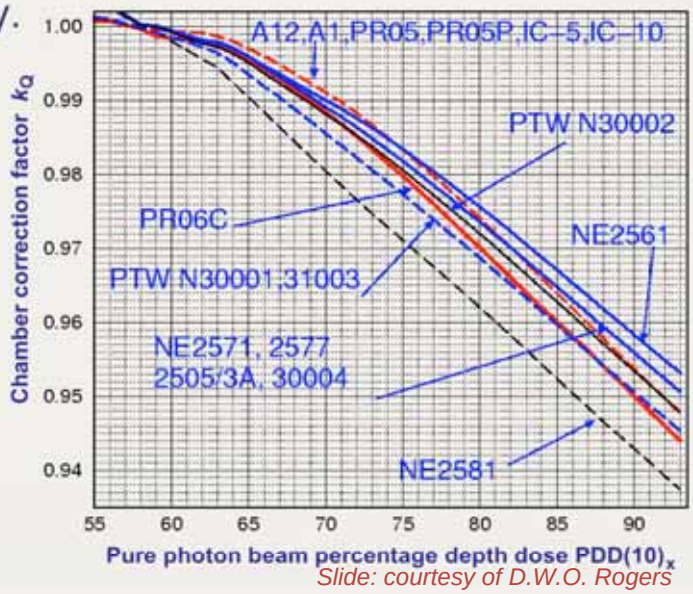


9.9 CALIBRATION OF MEGAVOLTAGE BEAMS: PRACTICAL ASPECTS
9.9.2 MV photon beams: Dose to water calibration coefficient $N_{D,w,Co}$

- The percentage depth dose $PDD(10)_x$ method for beam quality specification:
  - PDD(10) is defined as the percentage depth dose measured in water on the central axis for a 10x10 cm^2 field and an SSD of 100 cm.
  - The problem of electron beam contamination of the megavoltage photon beam is circumvented by placing a 1 mm thick lead foil into the beam to remove the unknown electron contamination.
  - The electron contamination contributed by the lead foil can be assumed known and is determined with Monte Carlo calculations.
  - $PDD(10)_x$ for the pure photon beam can be calculated from $PDD(10)_{Pb}$ using a correction formula.

9.9.2 MV photon beams: Dose to water calibration coefficient $N_{D,w,Co}$

- Chamber correction factor k_Q against PDD(10)$_x$ for cylindrical ionization chambers commonly used for clinical reference dosimetry.
  - For cobalt-60 beams: $k_Q = k_{Co} = 1$
  - For megavolage x-ray beams: $k_Q < 1$.



Slide: courtesy of D.W.O. Rogers

9.9.3 MV electron beams: Air kerma in air calibration coefficient $N_{K,Co}$

- Megavoltage electron beams are calibrated at appropriate reference depth z_{ref} (close to z_{max}) in a water phantom.
  - For electron energies equal to or above 10 MeV a cylindrical or a parallel-plate ionization chamber can be used.
  - For electron energies below 10 MeV a parallel-plate ionization chamber must be used.
- The air kerma based calibration is based on air kerma in air calibration coefficient $N_{K,Co}$ obtained in a cobalt-60 beam at the standards laboratory.

9.9.3 MV electron beams: Air kerma in air calibration coefficient $N_{K,Co}$

- The Spencer-Attix cavity relationship is used to determine the absorbed dose at the reference point in water:

$$D_{w,Q}(z_{ref}) = M_Q \; N_{D,air} \; [s_{w,air}]_Q \; p_Q = \; M_Q \; N_{D,air} \; [s_{w,air} \; p_{cav} \; p_{cel}]_Q$$

  - M_Q is the charge measured in a water phantom at the reference point and corrected for influence quantities.
  - $N_{D,air}$ is the cavity air calibration coefficient
    $N_{D,air} = N_{K,Co}(1-\bar{g})k_m \, k_{att} \, k_{cel}$
  - $s_{w,air}$ is the restricted stopping power ratio water to air.
  - p_Q is a perturbation correction factor accounting for perturbations caused by the chamber inserted into the water.

9.9.3 MV electron beams: Air kerma in air calibration coefficient $N_{K,Co}$

- In electron beams, the restricted stopping power ratio water to air $s_{w,air}$ varies significantly as a function of depth z in phantom.

- For clinical beams, the stopping power ratio water to air $s_{w,air}$ against the depth z in phantom, parametrized by R_{50}, is given by a fit established by Burns et al.:

$$s_{w,air}(z,R_{50}) = \frac{a + b\ln R_{50} + c(\ln R_{50})^2 + d(z/R_{50})}{1 + e\ln R_{50} + f(\ln R_{50})^2 + g(\ln R_{50})^3 + h(z/R_{50})}$$

a = 1.0752	b = -0.50867	c = 0.08867	d = -0.08402
e = -0.42806	f = 0.064627	g = 0.003085	h = -0.12460

Burns, Ding, Rogers: Med. Phys. 23, 383 (1996)

- Generally, the chamber perturbation correction factor p_Q is a product of four perturbation factors: displacement, wall, central electrode, and fluence:

$$p_Q = (p_{dis}\ p_{wall}\ p_{cel}\ p_{cav})_Q \qquad D_{w,Q}(z_{ref}) = M_Q\ N_{D,air}\ [s_{w,air}\ p_{cel}\ p_{cav}]_Q$$

- Of the four perturbation factors, only p_{cav} and p_{cel} apply for air kerma in air based protocols and MV electron beams:
  - p_{cav} is the cavity fluence perturbation correction factor accounting for the electron in-scattering effect.
  - p_{cel} is the central electrode perturbation correction factor that accounts for scatter and absorption of radiation on the central electrode of a cylindrical chamber.

9.9 CALIBRATION OF MEGAVOLTAGE BEAMS: PRACTICAL ASPECTS
9.9.3 MV electron beams: Air kerma in air calibration coefficient $N_{K,Co}$

- In electron beams the use of the displacement perturbation factor p_{dis} is impractical, since the depth dose curve is very irregular in shape in contrast to the quasi-exponential decrease in photon beams beyond the buildup region.
- Since p_{dis} would vary rapidly and in an irregular fashion with depth in an electron beam, the effective point of measurement P_{eff} concept is used in electron beams.

9.9.3 MV electron beams: Air kerma in air calibration coefficient $N_{K,Co}$

- The wall correction factor p_{wall} is considered unity in electron beam dosimetry.
- Instead of p_{dis}, the effective point of measurement P_{eff} concept is universally employed in electron beams:
  - For parallel-plate chambers the effective point of measurement is located on the inner surface of the window and no gradient correction is required.
  - For cylindrical ionization chambers the effective point of measurement is located 0.5r upstream from the chamber centre with r the chamber inner radius.

9.9.4 MV electron beams: Dose to water calibration coefficient $N_{D,w,Co}$

- Megavoltage electron beams are calibrated in a water phantom at appropriate reference depth z_{ref} with a field of 10x10 cm^2.
  - For electron energies equal to or above 10 MeV a cylindrical or a parallel-plate ionization chamber can be used.
  - For electron energies below 10 MeV a parallel-plate ionization chamber must be used.
- Water is recommended as the reference medium. For electron energies below 10 MeV a plastic phantom may be used but all depths must be scaled appropriately.

- R_{50} (in g/cm^2), defined as the depth of the 50% dose level, i.e., the half-value depth in water, is the beam quality index for electron beams. It is measured with a field size of:
  - At least 10x10 cm^2 for $R_{50} \leq 7$ g/cm^2.
  - At least 20x20 cm^2 for $R_{50} > 7$ g/cm^2.
- The preferred choice of detector for the measurement of R_{50} is a well guarded parallel-plate ionization chamber, the preferred choice of phantom medium is water.

9.9 CALIBRATION OF MEGAVOLTAGE BEAMS: PRACTICAL ASPECTS
9.9.4 MV electron beams: Dose to water calibration coefficient $N_{D,w,Co}$

- The reference depth z_{ref} for electron beam output measurement with R_{50} in g/cm^2 is given as:

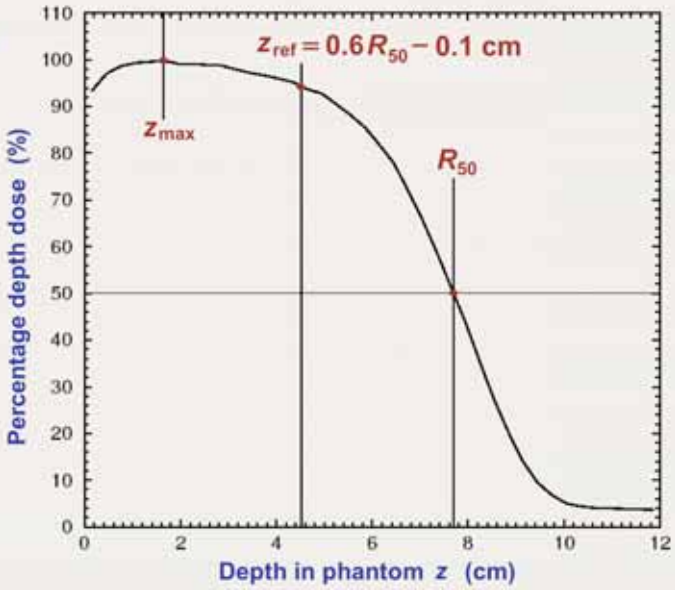
$$z_{ref} = 0.6R_{50} - 0.1 \text{ g/cm}^2$$

  - $z_{ref} \approx z_{max}$ for $R_{50} < 4$ g/cm^2 ($\bar{E}_o \leq 10$ MeV).
  - $z_{ref} > z_{max}$ for $R_{50} > 4$ g/cm^2 ($\bar{E}_o > 10$ MeV).
- The choice of this reference depth is inconvenient; however, it reduces significantly the machine to machine variations in chamber calibration coefficients, and the gained accuracy justifies its use.

9.9 CALIBRATION OF MEGAVOLTAGE BEAMS: PRACTICAL ASPECTS

9.9.4 MV electron beams: Dose to water calibration coefficient $N_{D,w,Co}$

- The reference depth z_{ref}
  - For low energy electron beams, $z_{ref} \approx z_{max}$.
  - For high energy electron beams, $z_{ref} > z_{max}$.
  - In general, $z_{ref} = 0.6R_{50} - 0.1\ g/cm^2$



9.9 CALIBRATION OF MEGAVOLTAGE BEAMS: PRACTICAL ASPECTS

9.9.4 MV electron beams: Dose to water calibration coefficient $N_{D,w,Co}$

- The absorbed dose to water at a reference depth z_{ref} in electron beam of quality Q, in the absence of the chamber, is:

$$D_{w,Q} = M_Q \; N_{D,w,Co} \; k_{Q,Co}$$

  - M_Q is the chamber signal measured at the reference depth z_{ref} in a water phantom and corrected for influence quantities.
  - $N_{D,w,Co}$ is the chamber calibration coefficient in terms of absorbed dose to water for the chamber irradiated in a cobalt-60 beam at a standards laboratory.
  - $k_{Q,Co}$ is a chamber correction factor accounting for the differences between the reference beam quality (cobalt-60) and the electron beam quality Q.

9.9.4 MV electron beams: Dose to water calibration coefficient $N_{D,w,Co}$

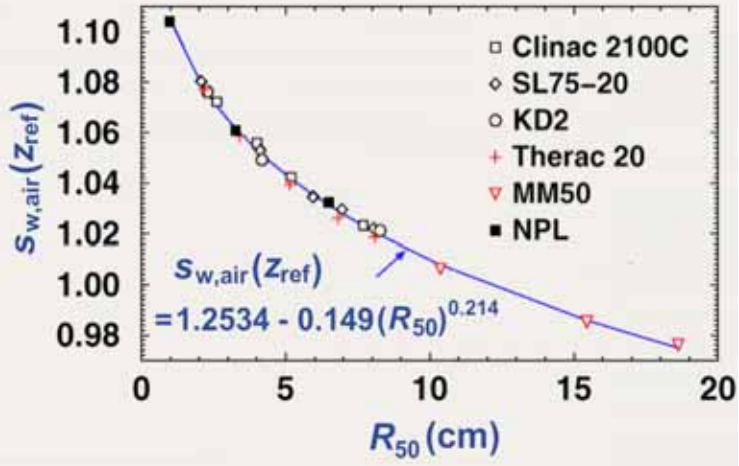
- Electron beam output calibration based on dose to water cobalt-60 calibration coefficient $N_{D,w,Co}$:

$$D_{w,Q} = M_Q \; N_{D,w,Co} \; k_{Q,Co}$$

- Calculated values of $k_{Q,Co}$ against R_{50} are available in dosimetry protocol documents for a wide variety of parallel-plate chambers and cylindrical chambers:
  - In the IAEA TRS protocol $k_{Q,Co}$ is tabulated directly.
  - In the AAPM TG 51 protocol $k_{Q,Co}$ is determined as a product of conversion and correction factors termed k_{ecal}, P_{gr}, and $k'_{R_{50}}$.

9.9.4 MV electron beams: Dose to water calibration coefficient $N_{D,w,Co}$

- In electron beams, the restricted stopping power ratio water to air $s_{w,air}$ at the reference depth z_{ref} varies significantly as a function of R_{50}.



Slide: courtesy of D.W.O. Rogers

9.9 CALIBRATION OF MEGAVOLTAGE BEAMS: SUMMARY

Megavoltage photon beams

Calibration coefficient	Reference point in water	Dose to water at reference point
$N_{K,Co}$	z = 5 cm or 10 cm	$D_{w,Q} = M_Q \; N_{D,air} \; [s_{w,air} \; p_{wall} \; p_{cel}]_Q$
$N_{D,w,Co}$	z = 10 cm	$D_{w,Co} = M_{Co} \; N_{D,w,Co} \; k_{Q,Co}$

$$N_{D,air} = N_{K,Co}(1-\bar{g}) \; k_m \; k_{att} \; k_{cel}$$

9.9 CALIBRATION OF MEGAVOLTAGE BEAMS: SUMMARY

Megavoltage electron beams

Calibration coefficient	Reference point in water	Dose to water at reference point
$N_{K,Co}$	z_{max}	$D_{w,Q} = M_Q \; N_{D,air} \; [s_{w,air} \; p_{cav} \; p_{cel}]_Q$
$N_{D,w,Co}$	$z_{ref} = 0.6R_{50} - 0.1$ cm	$D_{w,Co} = M_{Co} \; N_{D,w,Co} \; k_{Q,Co}$

$$N_{D,air} = N_{K,Co}(1-\bar{g}) \; k_m \; k_{att} \; k_{cel}$$

9.10 KILOVOLTAGE DOSIMETRY

9.10.1. Specific features of kilovoltage beams

- Despite the advent of megavoltage photon and electron beams, kilovoltage beams are still in widespread use in treatment of superficial lesions.
- When kilovoltage x rays interact with a medium, the secondary electrons produced through photoelectric and Compton interactions have very short ranges due to their low initial energy coupled with the increase in the collision stopping power at low kinetic energies.

9.10 KILOVOLTAGE DOSIMETRY

9.10.1. Specific features of kilovoltage beams

- There are several notable differences between kilovoltage and megavoltage beams:
  - The Bragg-Gray principle no longer applies because the electron fluence in the air cavity of the ionization chamber is not exclusively determined by electron interactions in the surrounding medium.
  - Absorbed dose can be equated to collision kerma to a very good approximation owing to the short electron ranges.
  - Absorbed dose and kerma are essentially equivalent, since radiative losses can be ignored in low atomic number materials.

9.10 KILOVOLTAGE DOSIMETRY

9.10.1. Specific features of kilovoltage beams

- Calibration coefficient for kilovoltage radiation dosimetry is determined with reference to a free air standard ionization chamber at a set of kilovoltage radiation quantities in contrast to a single air kerma in air calibration coefficient at cobalt-60 for all megavoltage beams.
- Since the wall thickness of a typical cylindrical ionization chamber is larger than the range of secondary electrons released in the wall, the chamber acts as a kerma detector even when used in a phantom.

9.10 KILOVOLTAGE DOSIMETRY

9.10.1. Specific features of kilovoltage beams

- Kilovoltage beam quality Q is specified in terms of half-value layer HVL, generally expressed:
  - In millimetres of aluminum for superficial x-ray beams.
  - In millimetres of copper for orthovoltage x-ray beams.
- Beams with widely differing tube potentials may have similar HVLs, due to a marked effect of different filtrations. The user determines the HVL of the beams of interest and then chooses the air kerma calibration coefficient N_K values for the calibrated chamber for the beam using the calibration curve supplied by the standards laboratory.

9.10 KILOVOLTAGE DOSIMETRY

9.10.2. Air kerma in air based in-phantom calibration method

- For medium energy (orthovoltage) x-ray beams, typically above 100 kV, various dosimetry protocols recommend that the dose be determined at a reference depth z_{ref} in a water phantom.
- The reference depth z_{ref} varies from one protocol to another:
  - The IAEA TRS 277 protocol recommends z_{ref} = 5 cm of water.
  - The UK protocol (IPEMB, 1996) recommends z_{ref} = 2 cm of water.

9.10 KILOVOLTAGE DOSIMETRY

9.10.2. Air kerma in air based in-phantom calibration method

- The formalism for determination of the absorbed dose is:

$$D_{w,Q} = M_Q \, N_{K,Q} \left[\left(\frac{\mu_{ab}}{\rho} \right)_{w,air} \right]_Q p_Q$$

  - M_Q is the chamber reading corrected for influence quantities
  - $N_{K,Q}$ is the air kerma in air chamber calibration coefficient for beam quality Q (specified with HVL).
  - $\left[\left(\frac{\mu_{ab}}{\rho} \right)_{w,air} \right]_Q$ is the mass-energy absorption coefficient ratio water to air for the photon spectrum at the reference depth in water and for the field size of the user's beam.
  - p_Q is an overall correction factor (different from the p_Q perturbation factor used in megavoltage beams).

9.10 KILOVOLTAGE DOSIMETRY

9.10.3. Air kerma in air based backscatter method

- Clinically, the dose for low energy (superficial) x rays is most often prescribed for the skin surface (just below skin surface where CPE is established).
- The calibration process is as follows:
  - A calibrated chamber is positioned free in air (no phantom) at the position corresponding to the centre of the field on the patient's skin surface.
  - The chamber reading yields the air kerma in air $(K_{air})_{air}$.
  - $(K_{air})_{air}$ is converted into dose to water at the surface of the phantom at the field size of interest.

9.10 KILOVOLTAGE DOSIMETRY

9.10.3. Air kerma in air based backscatter method

- The theoretical route is as follows:
  - The air kerma in air $(K_{air})_{air}$ is converted into water kerma in air $(K_w)_{air}$ through the mass-energy absorption coefficient ratio water to air $(\mu_{ab}/\rho)_{w,air}$, but still under free in air conditions (i.e., for the primary spectrum). This has the advantage that $(\mu_{ab}/\rho)_{w,air}$ is independent of field size.
  - The water kerma in air $(K_w)_{air}$ is then converted into water kerma in water $(K_w)_w$ at the surface of the water phantom by multiplying $(K_w)_{air}$ with the backscatter factor BSF for the given field size, HVL and SSD used.

9.10 KILOVOLTAGE DOSIMETRY

9.10.3. Air kerma in air based backscatter method

- The formalism for this procedure is:

$$D_{w,Q} = M_{\text{free air}} N_{K,Q} \ \text{BSF} \left[\left(\frac{\mu_{ab}}{\rho} \right)_{w,air} \right]_{\text{free air, Q}}$$

  - $M_{\text{free air, Q}}$ is the chamber reading corrected for influence quantities.
  - $N_{K,Q}$ is the air kerma in air chamber calibration coefficient for beam quality Q described with a specific HVL.
  - BSF is the backscatter factor for the specific field size, HVL and SSD used.
  - $\left[\left(\frac{\mu_{ab}}{\rho} \right)_{w,air} \right]_{\text{free air, Q}}$ mass-energy absorption coefficient ratio water to air for the free in air primary photon spectrum.

9.10 KILOVOLTAGE DOSIMETRY

9.10.4 Air kerma in air based calibration for very low energies

- In the very low superficial x-ray energy range (10 - 50 kV) a thin window parallel-plate ionization chamber is the recommended instrument for beam output calibration.
- The parallel-plate chamber is placed at the surface of a water equivalent phantom and the dose at the surface is determined:

$$D_{w,Q} = M_Q \ N_{K,Q} \left[\left(\frac{\mu_{ab}}{\rho} \right)_{w,air} \right]_Q k_{ch}$$

  - k_{ch} is a chamber correction factor referring to the specific parallel-plate chamber and pertaining to the surface dose.

9.10 KILOVOLTAGE DOSIMETRY

9.10.5. Absorbed dose to water based calibration method

- Standards of absorbed dose to water in the kilovoltage x-ray range are not generally available.
- However, it is possible to derive calibration coefficients in terms of absorbed dose to water from air kerma in air calibration coefficients using one of the accepted dosimetry protocols.
- Thus, any calibration laboratory with standards of air kerma in air can in this way derive calibration coefficients in terms of absorbed dose to water thereby unifying and standardizing the methodology.

9.11 ERROR AND UNCERTAINTY ANALYSIS

9.11.1. Errors and uncertainties

- A measurement error is defined as the difference between the measured value of a measurand and the true value.
- An error carries a sign and a correction factor may be associated with it.
- When the error is known, the true value of the measurand can be calculated from the measured value.

9.11 ERROR AND UNCERTAINTY ANALYSIS
9.11.1. Errors and uncertainties

- An uncertainty associated with a measurement is a parameter that characterizes the dispersion of the values that can be attributed to a measurand.
- The value of the uncertainty:
  - Is usually an estimated standard deviation
  - Has no sign
  - Is assumed to be symmetrical with respect to the estimated value of the quantity.
- The uncertainty is a measure of our lack of exact knowledge after all recognized systematic effects have been eliminated by applying appropriate corrections.

9.11 ERROR AND UNCERTAINTY ANALYSIS
9.11.2. Classification of uncertainties

- Uncertainties of measurements are expressed as relative standard uncertainties, and the evaluation of standard uncertainties is classified into two types: A and B.
  - Type A uncertainties are inherently random and are obtained by a statistical analysis of a series of observations. A1σ type A uncertainty corresponds to the standard error on the mean of a set of observations at the 68% confidence level.
  - Type B uncertainties are determined through other than statistical, often subjective, methods and account for systematic effects in the determination of a quantity.

9.11 ERROR AND UNCERTAINTY ANALYSIS
9.11.3. Uncertainties in the calibration chain

- An analysis of uncertainties on the calculated values of the beam quality conversion factors k_Q for photon and electron beams has shown the following estimated relative standard uncertainties:
  - For photon beams and cobalt-60 calibration technique: 1%
  - For electron beams and cobalt-60 calibration technique: 1.2% for cylindrical chambers and 1.7% for parallel-plate chambers.
  - For electron beams and cross-calibration technique in an electron beam: 0.9% for cylindrical chambers and 0.6% for parallel-plate chambers.

9.11 ERROR AND UNCERTAINTY ANALYSIS
9.11.3. Uncertainties in the calibration chain

- To obtain the total uncertainty on beam output calibration, the uncertainty on k_Q must be combined with uncertainties on other quantities, such as:
- The absorbed dose calibration coefficient at cobalt-60 or in a high energy electron beam, if a cross calibration technique is used.
- In-phantom measurement of absorbed dose in the clinic.

- Some of the issues related to in-phantom measurement of absorbed dose in the clinic comprise type A and type B uncertainties:
  - Positioning of the chamber in the water phantom.
  - Positioning of the water phantom into the radiation beam.
  - Temperature measurement.
  - Pressure measurement.
  - Determination of ion recombination.
  - Determination of polarity effect.
  - Electrometer correction factor (if present).
  - Linac stability during the calibration process.