ICTP SCHOOL ON MEDICAL PHYSICS FOR RADIATION THERAPY: DOSIMETRY AND TREATMENT PLANNING FOR BASIC AND ADVANCED APPLICATIONS
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Dosimetry: Electron Beams

G. Hartmann
EFOMP & German Cancer Research Center (DKFZ)
g.hartmann@dkfz.de
Content:

1. Dosimetry equipment
2. Calibration procedure
3. Correction factors
4. The radiation quality correction factor $k_Q$: Determination & Calculation
5. Depth of measurement: at reference depth & at depth of maximum dose
6. Cross calibration
1. Dosimetry Equipment

Ionization chambers

Types of chambers used:

- **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
1. Dosimetry Equipment
Ionization chambers

Types of chambers used:

- Parallel-plate (also called end window or plane-parallel) chambers are used:
  - for the calibration of superficial x-ray beams
  - for the calibration of electron beams with energies below 10 MeV
  - for dose measurements in photon beams in the buildup region and surface dose
1. Dosimetry Equipment

Ionization chambers

Cylindrical Chambers

Plane Parallel Chambers

Farmer-Chamber

Roos-Chamber
1. Dosimetry Equipment
1. Dosimetry Equipment
Electrometer, ionization camber and radioactive check source
1. Dosimetry Equipment

Electrometer plus connectors

From the PTW Catalogue:

"Ionizing Radiation Detectors"

"The following overview of connecting systems facilitates the identification of a variety of adequate connectors"
1. Dosimetry Equipment
Phantoms

Water Phantoms

Solid Phantoms
1. Dosimetry Equipment

Phantoms

Pease note:

- **Water** is always recommended in the IAEA Codes of Practice as the phantom material for the **calibration** of megavoltage photon and electron beams.
- The phantom should extend to at least 5 cm beyond all four sides of the largest field size employed at the depth of measurement.
- There should also be a margin of at least 5 g/cm² beyond the maximum depth of measurement except for medium energy X rays in which case it should extend to at least 10 g/cm².
1. Dosimetry Equipment

Phantoms for measurements

Solid (plastic) phantom:

Please note:
In spite of their increasing popularity, the use of plastic phantoms is strongly discouraged for reference measurements.

In general such measurements are responsible for the largest discrepancies in the determination of absorbed dose for most beam types.
1. Dosimetry Equipment

Phantoms for measurements

Solid (plastic) phantom:

Several disadvantages because a plastic phantom requires:

- scaling of depth: \[ Z_w = Z_{pl} \ c_{pl} \]
  where \( c_{pl} \) is a depth scaling factor

- scaling of dosimeter reading \( M_{Q,pl} \):
  \[ M_Q = M_{Q,pl} \ h_{pl} \]
  \( h_{pl} \) is a fluence scaling factor
1. Dosimetry Equipment
Phantoms for measurements

Values from TRS 398 for $c_{pl}$ and $h_{pl}$

<table>
<thead>
<tr>
<th>Plastic phantom</th>
<th>$c_{pl}$</th>
<th>$h_{pl}$</th>
<th>$\rho_{pl} ,(g ,cm^{-3})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid water (WT1)</td>
<td>0.949</td>
<td>1.011</td>
<td>1.020</td>
</tr>
<tr>
<td>Solid water (RMI-457)</td>
<td>0.949</td>
<td>1.008</td>
<td>1.030</td>
</tr>
<tr>
<td>Plastic water</td>
<td>0.982</td>
<td>0.998</td>
<td>1.013</td>
</tr>
<tr>
<td>Virtual water</td>
<td>0.946</td>
<td>-</td>
<td>1.030</td>
</tr>
<tr>
<td>PMMA</td>
<td>0.941</td>
<td>1.009</td>
<td>1.190</td>
</tr>
<tr>
<td>Clear polystyrene</td>
<td>0.922</td>
<td>1.026</td>
<td>1.060</td>
</tr>
<tr>
<td>White polystyrene</td>
<td>0.922</td>
<td>1.019</td>
<td>1.060</td>
</tr>
<tr>
<td>A-150</td>
<td>0.948</td>
<td>-</td>
<td>1.127</td>
</tr>
</tbody>
</table>

*a Average of the values given in Ref. [95] below 10 MeV.

*b Average of the values given in Ref. [64] below 10 MeV.

*c Data not available.

*d Also referred to as high-impact polystyrene.

Note:
The high uncertainty associated with $h_{pl}$ is the main reason for avoiding the use of plastic phantoms.
2. Calibration procedure

General formula

\[ D_{w,Q} = M_Q \cdot N_{D,w,Q_o} \cdot k_{Q,Q_o} \]

\( M_{Q_o} \) is the **chamber reading in beam of quality** \( Q \) and corrected for influence quantities to the reference conditions used in the standards laboratory.

\( N_{D,w,Q_o} \) is the **water dose calibration coefficient** provided by the standards laboratory for reference beam quality \( Q_o \).

\( k_{Q,Q_o} \) is a **factor correcting for the differences between the reference beam quality** \( Q_o \) and the **actual user quality** \( Q \).
2. Calibration procedure
Positioning of the ionization chamber in water

Positioning can be defined as the adjustment of the reference point of a chamber with respect to the measuring depth.

Positioning of the reference point of a cylindrical chamber according to the International Code of Practice of the IAEA, TRS 398:

<table>
<thead>
<tr>
<th>Source</th>
<th>Beam calibration</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co-60</td>
<td>at measuring depth</td>
<td>0.6 ( r ) deeper than measuring depth</td>
</tr>
<tr>
<td>HE photons</td>
<td>at measuring depth</td>
<td>0.6 ( r ) deeper than measuring depth</td>
</tr>
<tr>
<td>HE electrons</td>
<td>0.5 ( r ) deeper than measuring depth</td>
<td>0.5 ( r ) deeper than measuring depth</td>
</tr>
</tbody>
</table>
2. Calibration procedure

Positioning of the ionization chamber in water

Positioning of the reference point of a **plane parallel chamber** according to the International Code of Practice of the IAEA, TRS 398:

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Beam calibration</th>
<th>Depth dose measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co-60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HE photons</td>
<td></td>
<td>always at measuring depth</td>
</tr>
<tr>
<td>HE electrons</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Positioning for **high energy electrons**

- **depth of measurement**
- plane-parallel chamber
- cylindrical chamber
3. Correction factors

- If the chamber is used under conditions that differ from the reference conditions, then the measured charge must be corrected for the influence quantities by so-called influence correction factors $k$.

- The three most important correction factors are:
  - $k_{T,P}$ for air density
  - $k_{pol}$ for polarity effects
  - $k_{sat}$ for missing saturation effects
4. The beam quality correction factor

- Frequently, the reference quality \( Q_o \) used for the calibration of ionization chambers is the cobalt-60 gamma radiation and the symbol \( k_Q \) is then normally used to designate the beam quality correction factor:

\[
\frac{k_{Q,Q_0}}{k_{Q,\text{Co-60}}} = k_Q
\]
# Determination of radiation quality correction factor $k_Q$

TABLE 18. CALCULATED VALUES FOR $k_Q$ FOR ELECTRON BEAMS, FOR VARIOUS CHAMBER TYPES CALIBRATED IN $^{60}$Co GAMMA RADIATION, AS A FUNCTION OF BEAM QUALITY $R_{50}$

(*the data are derived using values for stopping-power ratios and perturbation factors, as given in Appendix II*)

<table>
<thead>
<tr>
<th>Ionization chamber type$^3$</th>
<th>1.0</th>
<th>1.4</th>
<th>2.0</th>
<th>2.5</th>
<th>3.0</th>
<th>3.5</th>
<th>4.0</th>
<th>4.5</th>
<th>5.0</th>
<th>5.5</th>
<th>6.0</th>
<th>7.0</th>
<th>8.0</th>
<th>10.0</th>
<th>13.0</th>
<th>16.0</th>
<th>20.0</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Plane-parallel chambers</strong></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Attix RMI 449</td>
<td>0.953</td>
<td>0.943</td>
<td>0.932</td>
<td>0.925</td>
<td>0.919</td>
<td>0.913</td>
<td>0.908</td>
<td>0.904</td>
<td>0.900</td>
<td>0.896</td>
<td>0.893</td>
<td>0.886</td>
<td>0.881</td>
<td>0.871</td>
<td>0.859</td>
<td>0.849</td>
<td>0.837</td>
</tr>
<tr>
<td>Capintec PS-033</td>
<td>—</td>
<td>—</td>
<td>0.921</td>
<td>0.920</td>
<td>0.919</td>
<td>0.918</td>
<td>0.917</td>
<td>0.916</td>
<td>0.915</td>
<td>0.913</td>
<td>0.912</td>
<td>0.908</td>
<td>0.905</td>
<td>0.898</td>
<td>0.887</td>
<td>0.877</td>
<td>0.866</td>
</tr>
<tr>
<td>Exradin P11</td>
<td>0.958</td>
<td>0.948</td>
<td>0.937</td>
<td>0.930</td>
<td>0.923</td>
<td>0.918</td>
<td>0.913</td>
<td>0.908</td>
<td>0.904</td>
<td>0.901</td>
<td>0.897</td>
<td>0.891</td>
<td>0.885</td>
<td>0.875</td>
<td>0.863</td>
<td>0.853</td>
<td>0.841</td>
</tr>
<tr>
<td>Holt (Memorial)</td>
<td>0.971</td>
<td>0.961</td>
<td>0.950</td>
<td>0.942</td>
<td>0.936</td>
<td>0.931</td>
<td>0.926</td>
<td>0.921</td>
<td>0.917</td>
<td>0.913</td>
<td>0.910</td>
<td>0.903</td>
<td>0.897</td>
<td>0.887</td>
<td>0.875</td>
<td>0.865</td>
<td>0.853</td>
</tr>
<tr>
<td>NACP / Calcam</td>
<td>0.952</td>
<td>0.942</td>
<td>0.931</td>
<td>0.924</td>
<td>0.918</td>
<td>0.912</td>
<td>0.908</td>
<td>0.903</td>
<td>0.899</td>
<td>0.895</td>
<td>0.892</td>
<td>0.886</td>
<td>0.880</td>
<td>0.870</td>
<td>0.858</td>
<td>0.848</td>
<td>0.836</td>
</tr>
<tr>
<td>Markus</td>
<td>—</td>
<td>—</td>
<td>0.925</td>
<td>0.920</td>
<td>0.916</td>
<td>0.913</td>
<td>0.910</td>
<td>0.907</td>
<td>0.904</td>
<td>0.901</td>
<td>0.899</td>
<td>0.894</td>
<td>0.889</td>
<td>0.881</td>
<td>0.870</td>
<td>0.860</td>
<td>0.849</td>
</tr>
<tr>
<td>Roos</td>
<td>0.965</td>
<td>0.955</td>
<td>0.944</td>
<td>0.937</td>
<td>0.931</td>
<td>0.925</td>
<td>0.920</td>
<td>0.916</td>
<td>0.912</td>
<td>0.908</td>
<td>0.904</td>
<td>0.898</td>
<td>0.892</td>
<td>0.882</td>
<td>0.870</td>
<td>0.860</td>
<td>0.848</td>
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<tr>
<td><strong>Cylindrical chambers</strong></td>
<td></td>
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<tr>
<td>Capintec PR06C (Farmer)</td>
<td>—</td>
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<td>—</td>
<td>—</td>
<td>—</td>
<td>0.916</td>
<td>0.914</td>
<td>0.912</td>
<td>0.911</td>
<td>0.909</td>
<td>0.906</td>
<td>0.904</td>
<td>0.899</td>
<td>0.891</td>
</tr>
<tr>
<td>Exradin A2 (Spokas)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.914</td>
<td>0.913</td>
<td>0.913</td>
<td>0.913</td>
<td>0.912</td>
<td>0.911</td>
<td>0.910</td>
<td>0.908</td>
<td>0.903</td>
</tr>
<tr>
<td>Exradin T2 (Spokas)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.882</td>
<td>0.881</td>
<td>0.881</td>
<td>0.881</td>
<td>0.880</td>
<td>0.879</td>
<td>0.878</td>
<td>0.876</td>
<td>0.871</td>
</tr>
<tr>
<td>Exradin A12</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.921</td>
<td>0.919</td>
<td>0.918</td>
<td>0.916</td>
<td>0.914</td>
<td>0.911</td>
<td>0.909</td>
<td>0.903</td>
<td>0.896</td>
</tr>
</tbody>
</table>
Determination of the quality index for HE electrons

Definition of the quality parameter $Q$ for HE photons

• The quality parameter used for megavoltage electron beam specification is commonly based upon the half-value depth in water, $R_{50}$

The unit of $R_{50}$ is gcm$^{-2}$
Determination of the quality index for HE electrons

Definition of the quality parameter $Q$ for HE electrons according TRS 398:

- $R_{50}$ is measured with
  - a constant SSD of 100 cm
  - a field size at the phantom surface of
    - at least 10 cm x 10 cm for $R_{50} \leq 7 \text{ g cm}^{-2}$ ($E_0 < 16 \text{ MeV}$)
    - at least 20 cm x 20 cm for $R_{50} > 7 \text{ g cm}^{-2}$ ($E_0 \leq 16 \text{ MeV}$).
Determination of the quality index for HE electrons

Measurement of $R_{50}$:

- **Problem:**
  The measurement with an ionization chamber yields an ionization-depth curve (dose in air), not a dose-depth curve (dose in water).

- $D_w(P) = D_{air} \cdot \bar{s}_{w,air} \cdot p$

  $s_{w,air}$ however, is dependent on energy, and hence on the depth
Determination of the quality index for HE electrons

Solution of this problem:

• The half-value of the depth-dose distribution in water $R_{50}$ can be obtained directly from measured depth ionization curves using:

$$R_{50} = 1.029 \ R_{50,\text{ion}} - 0.06 \ \text{g cm}^{-2} \quad (R_{50,\text{ion}} \leq 10 \ \text{g cm}^{-2})$$

$$R_{50} = 1.059 \ R_{50,\text{ion}} - 0.37 \ \text{g cm}^{-2} \quad (R_{50,\text{ion}} > 10 \ \text{g cm}^{-2})$$

• As an alternative to the use of an ionization chamber, other detectors (for example diode, diamond, etc.) may be used to determine $R_{50}$.

• In this case the user must verify that the detector is suitable for depth-dose measurements by test comparisons with an ionization chamber at a set of representative beam qualities.
Calculation of $k_Q$

The values $k_Q$ tabulated in TRS 398 have been obtained by calculation.

$$k_Q = \frac{\left(\frac{W}{e}\right)^Q \cdot s^Q_{W,\text{air}} \cdot p_Q}{\left(\frac{W}{e}\right)^{Q_0} \cdot s^{Q_0}_{W,\text{air}} \cdot p_{Q_0}}$$
5. **Reference depth for HE electrons**

A further reference condition for HE electrons:

- The values of $k_Q$ are valid only if the calibration measurement is performed at **the reference depth** $z_{\text{ref}}$.

- $z_{\text{ref}}$ is **energy dependent**, and obtained by:

  $$z_{\text{ref}} = 0.6 \ R_{50} - 0.1 \ \text{g cm}^{-2} \quad (R_{50} \ \text{in g cm}^{-2})$$

- This depth is close to the depth of the absorbed-dose maximum $z_{\text{max}}$ at beam qualities $R_{50} < 4 \ \text{g cm}^{-2} (E_0 < 10 \ \text{MeV})$, but at higher beam qualities is deeper than $z_{\text{max}}$. 
Absorbed dose at $z_{\text{max}}$ for HE electrons

Frequently, the basic output for an electron beam is wanted to be obtained at $z_{\text{max}}$.

- This again requires the determination of a depth dose curve.

- A depth dose curve has to be converted from a measured depth ionization curve.

- The conversion is performed by multiplying the depth ionization curve with the depth dependent water to air stopping power ratio adjusted to the beam quality of the electron beam.
Absorbed dose at $z_{\text{max}}$ for HE electrons

This is the depth dependent water to air stopping power ratio adjusted to the beam quality of the electron beam:

$$S_{w,a}^\Delta (z) = \frac{a + bx + cx^2 + dy}{1 + ex + fx^2 + gx^3 + hy}$$

- with $x = \ln(R_{50}/\text{cm})$, and $y = z / R_{50}$

$a = 1.0752 \quad b = -0.50867 \quad c = 0.08867 \quad d = -0.08402$

$e = -0.42806 \quad f = 0.06463 \quad g = 0.003085 \quad h = -0.1246$
6. Cross calibration in electron beams

**Concept**

- What is a cross-calibration of an ionization chamber?
  - Cross-calibration refers to the calibration of a **user chamber** by direct comparison in a **reference chamber** that has previously been calibrated.
  - A particular example is the cross-calibration of a **plane-parallel chamber** for use in electron beams against a **reference cylindrical chamber** calibrated in $^{60}$Co gamma radiation.
  - Despite the additional step, such a cross-calibration generally results in a determination of absorbed dose to water using the plane-parallel chamber **that is more reliable** than that achieved by the use of a plane-parallel chamber calibrated directly in $^{60}$Co.
  - The main reason is: problems associated with the $p_{\text{wall}}$ correction for plane-parallel chambers in $^{60}$Co, entering into the determination of $k_Q$, are avoided.
# Uncertainty of Calibration for High Energy Electrons

(from the International Code of Practice TRS 398)

<table>
<thead>
<tr>
<th>Physical quantity or procedure</th>
<th>Relative standard uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>User chamber type:</td>
</tr>
<tr>
<td></td>
<td>Beam quality range:</td>
</tr>
<tr>
<td><strong>Step 1: Standards laboratory</strong></td>
<td>0.5</td>
</tr>
<tr>
<td>$N_{D,\text{w}}$ calibration of secondary standard at PSDL</td>
<td>0.1</td>
</tr>
<tr>
<td>Long-term stability of secondary standard</td>
<td>0.4</td>
</tr>
<tr>
<td>$N_{D,\text{w}}$ calibration of user dosimeter at SSDL</td>
<td>0.6</td>
</tr>
<tr>
<td>Combined uncertainty of Step 1</td>
<td><strong>b</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step 2: User electron beam</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Long-term stability of user dosimeter</td>
<td>0.3</td>
</tr>
<tr>
<td>Establishment of reference conditions</td>
<td>0.4</td>
</tr>
<tr>
<td>Dosimeter reading $M_Q$ relative to beam monitor</td>
<td>0.6</td>
</tr>
<tr>
<td>Correction for influence quantities $k_i$</td>
<td>0.4</td>
</tr>
<tr>
<td>Beam quality correction $k_O$ (calculated values)</td>
<td><strong>1.2</strong></td>
</tr>
<tr>
<td>Combined uncertainty of Step 2</td>
<td><strong>1.5</strong></td>
</tr>
</tbody>
</table>

Combined standard uncertainty of $D_{w,Q}$ (Steps 1+2) | **1.6** | **2.1** |
6. Cross calibration in electron beams

Cross-calibration procedure

- The highest-energy electron beam available should be used; $E_o > 16$ MeV is recommended. Note: This is now the calibration quality!

- The reference chamber and the chamber to be calibrated are compared by alternately positioning each at the reference depth $z_{ref}$ in water.

- The calibration factor $N_{D,w,Q_{cross}}^x$ in terms of absorbed dose to water for the chamber under calibration, at the cross-calibration quality $Q_{cross}$, is then given by:

$$N_{D,w,Q_{cross}}^x = \frac{M_{Q_{cross}}^{ref}}{M_{Q_{cross}}^x} N_{D,w,Q_o}^{ref} k_{Q_{cross},Q_o}^{ref}$$
6. Cross calibration in electron beams

Cross-calibration procedure

Such equations require some exercise for reading.

\[
N^x_{D,w,Q_{cross}} = \frac{M_{Q_{cross}}^{ref}}{M^x_{Q_{cross}}} N_{D,w,Q_o}^{ref} k_{Q_{cross},Q_o}^{ref}
\]

However, when applied to an example, they can be “translated”

Example:
chamber to be cross calibrated: plane-parallel Roos chamber
cross calibrated against: cylindrical Farmer chamber
cross calibration performed at an electron energy of 18 MeV

\[
N_{Roos,18MeV}^{D,w} = \frac{M_{Farmer,18MeV}}{M_{Roos,18MeV}} N_{D,w}^{Farmer} k_{18MeV}^{Farmer}
\]
6. Cross calibration in electron beams

Cross-calibration procedure

- Subsequent use of a cross-calibrated chamber
  - The cross-calibrated chamber with calibration factor $N_{D,w,Q_{\text{cross}}}^x$ may be used subsequently for the determination of absorbed dose in a user beam of quality $Q$ using the basic equation:

$$D_{w,Q} = M_Q^x \cdot N_{D,w,Q_{\text{cross}}}^x \cdot k_{Q,Q_{\text{cross}}}^x$$

- The values for $k_{Q,Q_{\text{cross}}}^x$ are derived using the procedure:

$$k_{Q,Q_{\text{cross}}}^x = \frac{k_{Q,Q_{\text{int}}}^x}{k_{Q_{\text{cross}},Q_{\text{int}}}^x}$$

where $k_{Q,Q_{\text{int}}}^x$ and $k_{Q_{\text{cross}},Q_{\text{int}}}^x$ are given in TRS 398, Table 19.
1) Cylindrical chambers are used in the calibration of electron beams at energies of 10 MeV and above; Parallel-plate chambers are used below 10 MeV

2) The “mother” of any calibration equation is:

\[ D_{w,Q} = M_Q \cdot N_{D,w,Q_0} \cdot k_{Q,Q_0} \]

3) The most important correction factors to be applied to the measured charge are:
   - \( k_{T,P} \) for air density
   - \( k_{pol} \) for polarity effects
   - \( k_{sat} \) for missing saturation effects
4) Quality correction factors are tabulated in TRS 398. $k_Q$ can be calculated as:

$$k_Q = \left( \frac{W^Q}{e^Q} \right) \cdot s_{w,air}^{Q} \cdot p_{Q}$$

5) Measurement have to be performed at energy dependent reference depths:

$$z_{ref} = 0.6 \ R_{50} - 0.1 \ \text{g cm}^{-2} \quad (R_{50} \ \text{in g cm}^{-2})$$

6) Cross calibration is used for plane-parallel chambers in electron dosimetry to reduce the uncertainty of the resultant absorbed dose to water.