ICTP SChool On MEdical PHysics For RAdiation THerapy: DOsimetry And TReatment PLanning For BAsic And ADvanced APplications

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Dosimetry: Photon Beams

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In the following, “**dosimetry**" means the determination of absorbed dose to water under reference conditions in the clinical beam of a radiation delivery unit (accelerator), using calibrated ionization chambers.

This is also frequently referred to as **beam calibration**.

Content:

1. Principles of a calibration procedure
2. Performance of a calibration procedure
3. Correction factors
4. Determination of radiation quality Q

1. Principles of the calibration procedure: Need for a Protocol

- **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** can be left to individual radiotherapy departments or jurisdictions of individual countries
- Dosimetry protocols are generally issued by national, regional, or international organizations.

1. Principles of the calibration procedure
Protocol

Examples of dosimetry protocols

- **National:**
  - UK: Institution of Physics and Engineering in Medicine and Biology (IPEMB)
  - Germany: DIN 6800-2, Deutsches Institut für Normung
- **Regional:**
  - American Association of Physicists in Medicine (AAPM) for North America: TG-51
  - Nederlandse Commissie voor Stralingsdosimetrie (NCS) for Netherlands and Belgium
  - Nordic Association of Clinical Physics (NACP) for Scandinavia
- **International:**
  - International Atomic Energy Agency (IAEA): TRS 398

1. Principles of the calibration procedure
Protocol

- A dosimetry protocol provides three essentials:

  - **the formalism**
  - **the procedure**
  - **and, all the data, tables, etc required**

  to use a calibrated ionization chamber traceable to a standards laboratory for "dosimetry".

1. Principles of the calibration procedure
Protocol

- Two types of dosimetry protocol are currently in use:
    - **Not addressd in this course !!!**
    - Protocols based on **calibration factors in absorbed dose to water.**

IAEA Code of Practice TRS 398 (2000)

- 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.

1. Principles of the calibration procedure

Calibration and calibration coefficient (factor)

Suppose the dose D_w is well known at 5 cm depth in a water phantom under so-called calibration conditions:

beam quality	^{60}Co gamma radiation
field size:	10 cm x 10 cm
SSD:	100 cm
phantom:	water phantom
measurement depth in water:	5 cm
positioning of a cyl. chamber:	central electrode at measuring depth

1. Principles of the calibration procedure

Calibration under reference conditions

- The cylindrical user chamber is then placed with its center at a depth of 5 cm in a water phantom
- Its calibration factor (or calibration coefficient) $N_{D,w}$ is obtained from

$$N_{D,w,Co} = \frac{D_w}{M}$$

where M is the dosimeter reading.

Unit: Gray per reading, or Gray per Coulomb

1. Principles of the calibration procedure

Measurement at ^{60}Co gamma radiation beams

- The absorbed dose to water at the reference depth z_{ref} in water for the **reference beam of quality Q_0 = Co** and in the absence of the chamber is then given by

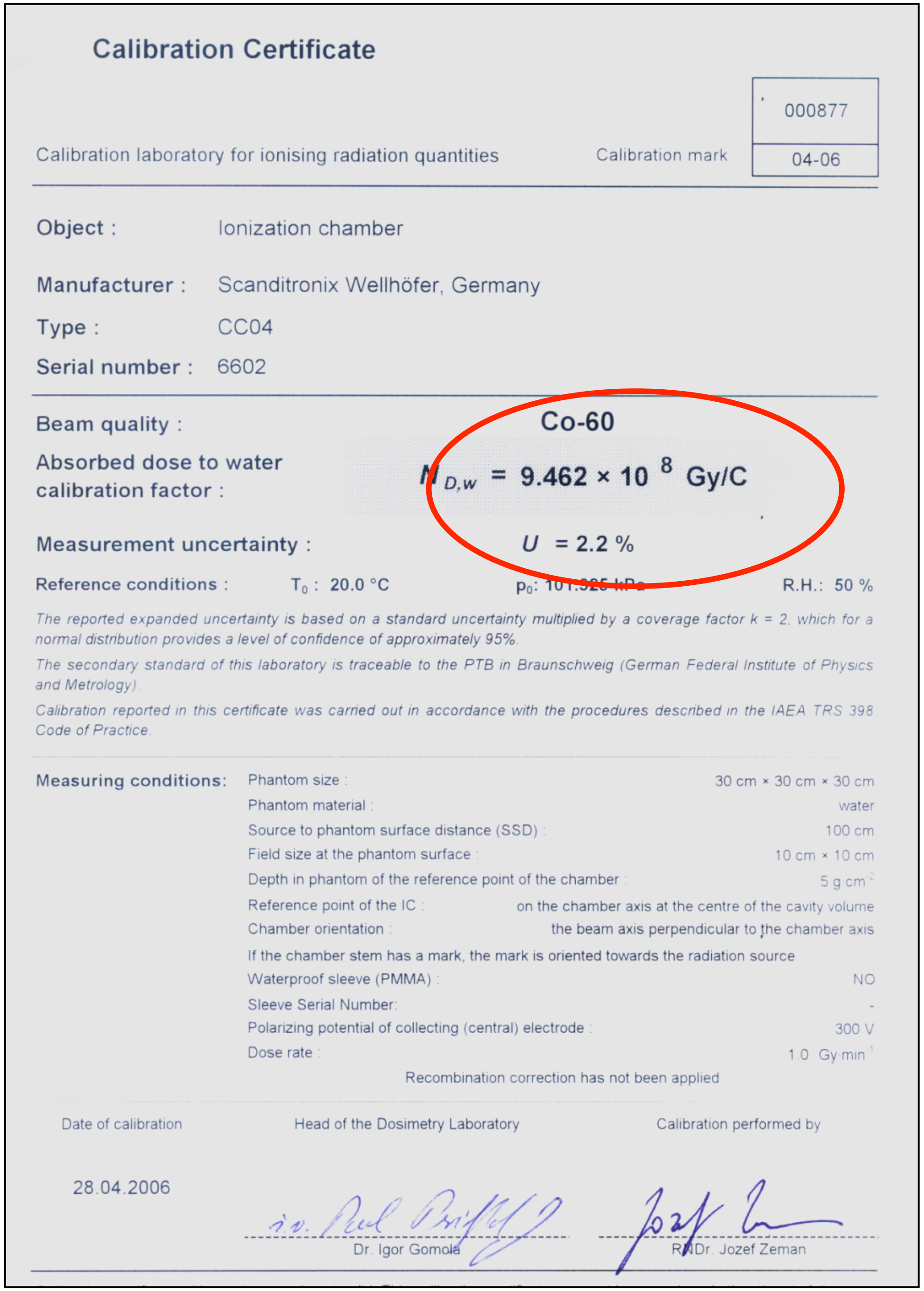
$$D_{w,Q_o} = M_{Q_o} \; N_{D,w,Q_o}$$

where

M_{Q_o} is the reading of the dosimeter corrected for influence quantities to the **reference conditions** as used at calibration

N_{D,w,Q_o} is the calibration factor in terms of absorbed dose to water of the dosimeter obtained from a standards laboratory.

Example of an Calibration Certificate



Calibration Certificate

Calibration laboratory for ionising radiation quantities

Calibration mark: 000877 / 04-06

Object :	Ionization chamber
Manufacturer :	Scanditronix Wellhöfer, Germany
Type :	CC04
Serial number :	6602

Beam quality : Co-60

Absorbed dose to water calibration factor : $N_{D,w} = 9.462 \times 10^{8}$ Gy/C

Measurement uncertainty : $U = 2.2$ %

Reference conditions : T_0 : 20.0 °C p_0: 101.325 kPa R.H.: 50 %

The reported expanded uncertainty is based on a standard uncertainty multiplied by a coverage factor k = 2, which for a normal distribution provides a level of confidence of approximately 95%.

The secondary standard of this laboratory is traceable to the PTB in Braunschweig (German Federal Institute of Physics and Metrology).

Calibration reported in this certificate was carried out in accordance with the procedures described in the IAEA TRS 398 Code of Practice.

Measuring conditions:

Phantom size :	30 cm × 30 cm × 30 cm
Phantom material :	water
Source to phantom surface distance (SSD) :	100 cm
Field size at the phantom surface :	10 cm × 10 cm
Depth in phantom of the reference point of the chamber :	5 g cm^{-2}
Reference point of the IC :	on the chamber axis at the centre of the cavity volume
Chamber orientation :	the beam axis perpendicular to the chamber axis

If the chamber stem has a mark, the mark is oriented towards the radiation source

Waterproof sleeve (PMMA) :	NO
Sleeve Serial Number:	-
Polarizing potential of collecting (central) electrode :	300 V
Dose rate :	1.0 Gy min^{-1}

Recombination correction has not been applied

Date of calibration	Head of the Dosimetry Laboratory	Calibration performed by
28.04.2006	Dr. Igor Gomola	RNDr. Jozef Zeman

1. Principles of the calibration procedure

Measurement at other qualities

- The chamber is now to be used in a beam with a another quality Q such as
  - **high energy photons**
  - **high energy electrons**

  that differs from the ^{60}Co quality used in the chamber calibration at the standards laboratory

- Then the formula for the determination of **absorbed dose to water** is changed

Beam quality correction factor

from

$$D_{w,Q_o} = M_{Q_o} \; N_{D,w,Q_o}$$

to

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

1. Principles of the calibration procedure

Beam quality correction factor

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

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.**

1. Principles of the calibration procedure

Beam quality correction factor

- Frequently, 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:

$$k_{Q,Qo} = k_{Q,Co\text{-}60} = k_Q$$

1. Principles of the calibration procedure
Beam quality correction factor

How to get the beam quality correction factor k_Q???

- First choice:
  An experimentally obtained k_Q is available from the calibration laboratory.

- Second choice:
  When no experimental data are available, or it is difficult to measure k_Q directly for realistic clinical beams, **calculated correction factors** can be used.
- Such **calculated correction factors** are normally provided in dosimetry protocols.

1. Principles of the calibration procedure

Beam quality correction factor

- General properties of k_Q:

  - Values for k_Q are dependent on the quality of radiation (type, energy, machine).

  - Each **type** of ionization chamber needs a particular k_Q

  - Values for k_Q are given in protocol tables for a large variety of beam qualities and chambers (e.g.in TRS 398)

1. Principles of the calibration procedure

Beam quality correction factor

TABLE 14. CALCULATED VALUES OF k_Q FOR HIGH ENERGY PHOTON BEAMS FOR VARIOUS CYLINDRICAL IONIZATION CHAMBERS AS A FUNCTION OF BEAM QUALITY $TPR_{20,10}$ *(adapted from Andreo [20])*

Beam quality

Ionization chamber type[a]	0.50	0.53	0.56	0.59	0.62	0.65	0.68	0.70	0.72	0.74	0.76	0.78	0.80	0.82	0.84
Capintec PR-05P mini															
Capintec PR-05 mini															
Capintec PR-06C/G Farmer															
Exradin A2 Spokas															
Exradin T2 Spokas															
Exradin A1 mini Shonka															
Exradin T1 mini Shonka															
Exradin A12 Farmer															
Far West Tech. IC-18															
FZH TK 01															
Nuclear Assoc. 30-750															
Nuclear Assoc. 30-749															
Nuclear Assoc. 30-744															
Nuclear Assoc. 30-716															
Nuclear Assoc. 30-753 Farmer shortened															
Nuclear Assoc. 30-751 Farmer															
Nuclear Assoc. 30-752 Farmer															

2. Performance of a calibration procedure
Positioning of the ionization chamber in water

- The absorbed dose to water is to be determined in a point P in water **at the reference depth $z_{ref.}$**

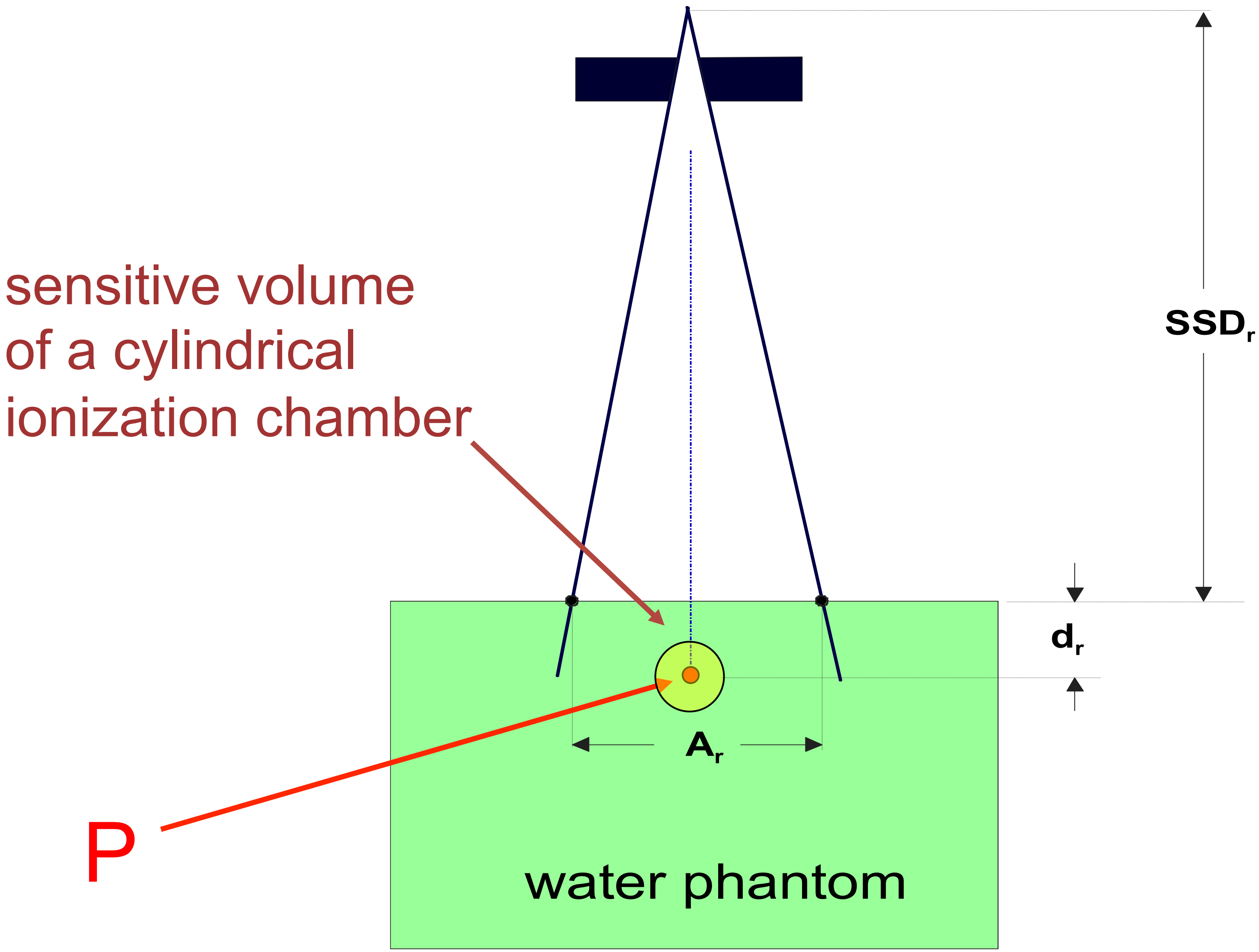
- In the absence of the chamber the dose is given by

$$D_{w,Q}(P=z_{ref})$$

- Using the chamber, the dose is given by

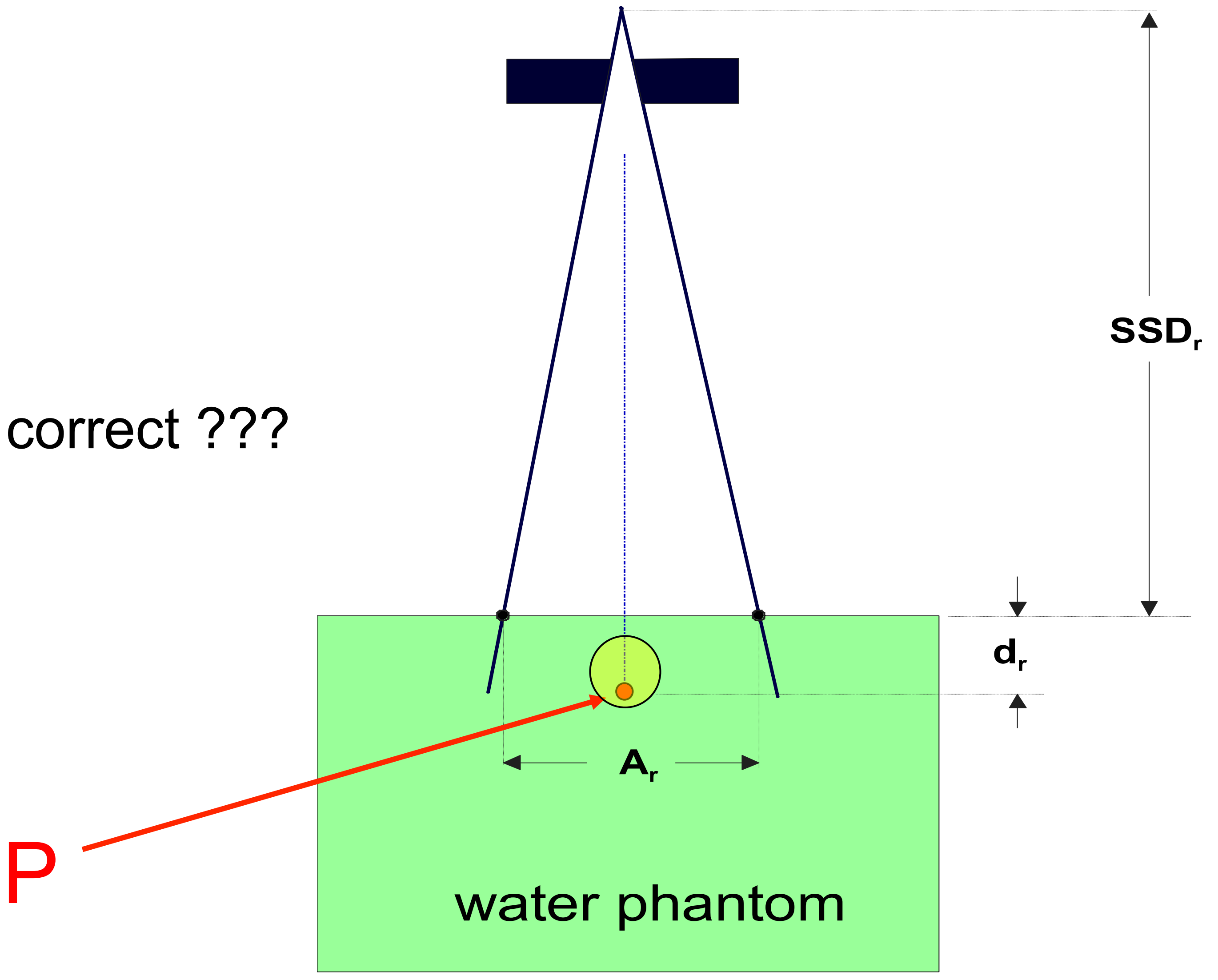
$$D_{w,Q}(P) = M_Q \; N_{D,w,Q_o} \; k_Q$$

- How the chamber must be positioned??

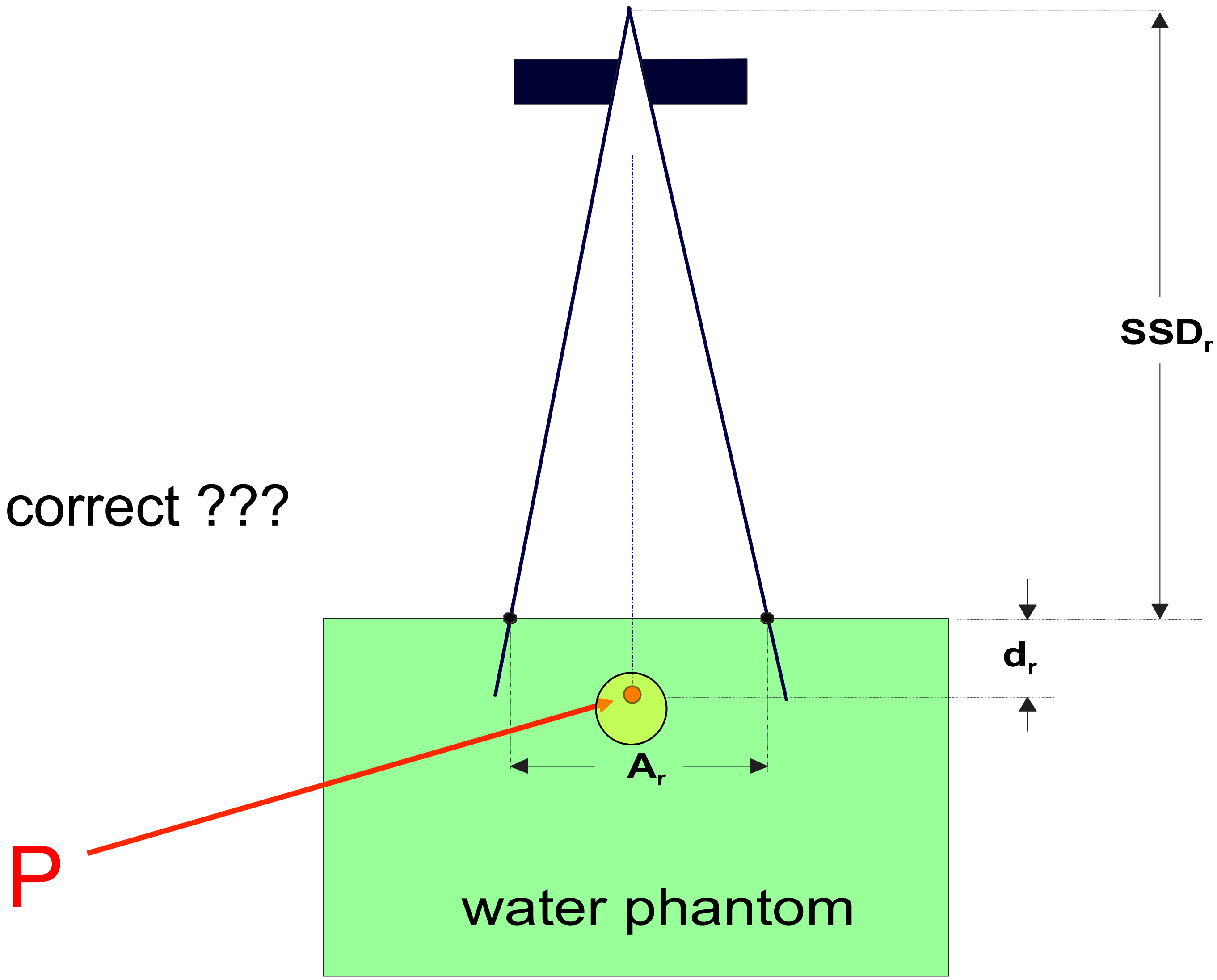


SSD$_r$
sensitive volume
of a cylindrical
ionization chamber
d$_r$
A$_r$
P
water phantom

correct ???



correct ???

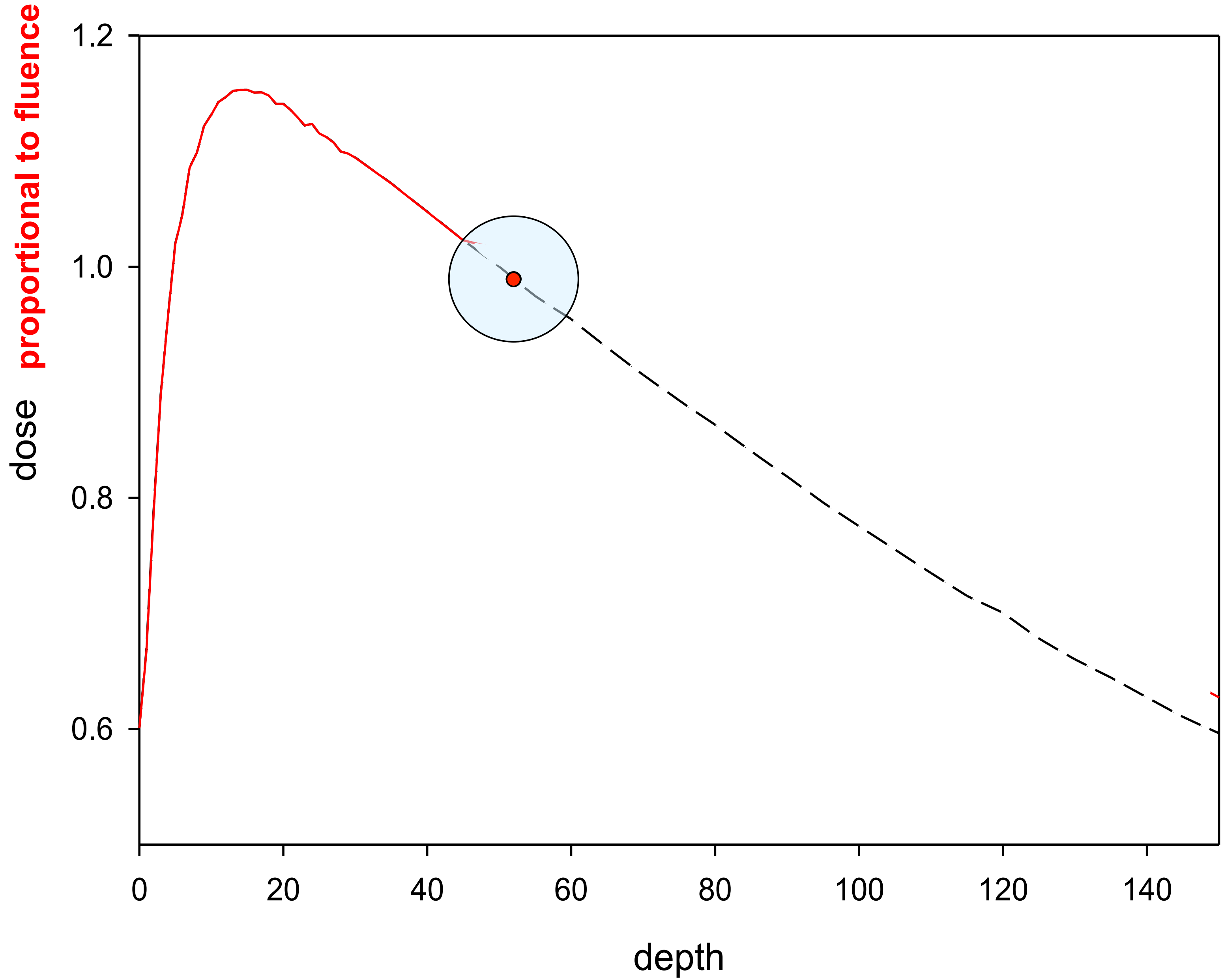


2. Performance of a calibration procedure
Positioning of the ionization chamber in water

- Remember the **Bragg-Gray Condition (1):**

  The cavity must be small when compared with the range of charged particles, so that its **presence does not perturb the fluence** of charged particles in the water.

- However:
  A chamber positioned with its cavity center at the point P does not sample the same electron fluence which is present at P in the undisturbed phantom, i.e. without the chamber.

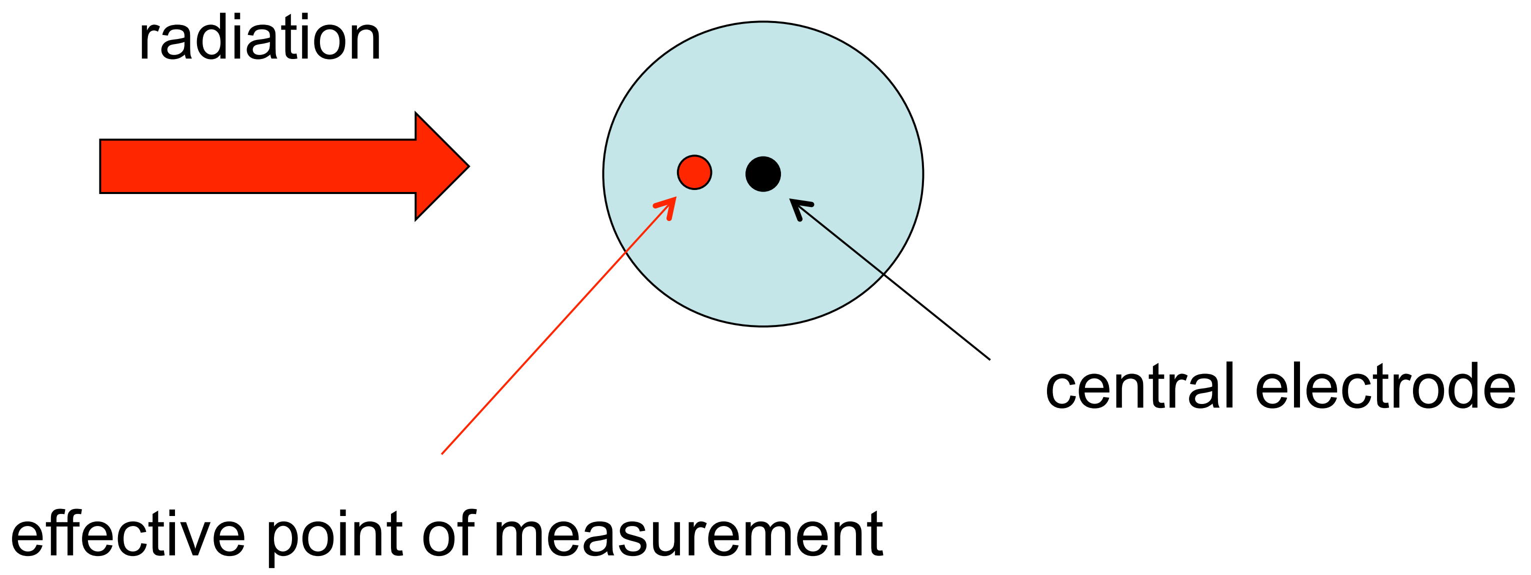


proportional to fluence
dose
1.2
1.0
0.8
0.6
0
20
40
60
80
100
120
140
depth

2. Performance of a calibration procedure
Positioning of the ionization chamber in water

- Which positioning is correct?

- One may think that the correct way is the positioning of the chamber at its effective point of measurement.



2. Performance of a calibration procedure
Positioning of the ionization chamber in water

- However:
  It does not matter as long as the **positioning** is well defined, and any deviation of the "correct" positioning is taken into account in the calibration factor N_{D,w,Q_o} , or in the quality correction factor k_Q

- How can the positioning be well defined?

2. Performance of a calibration procedure
Positioning of the ionization chamber in water

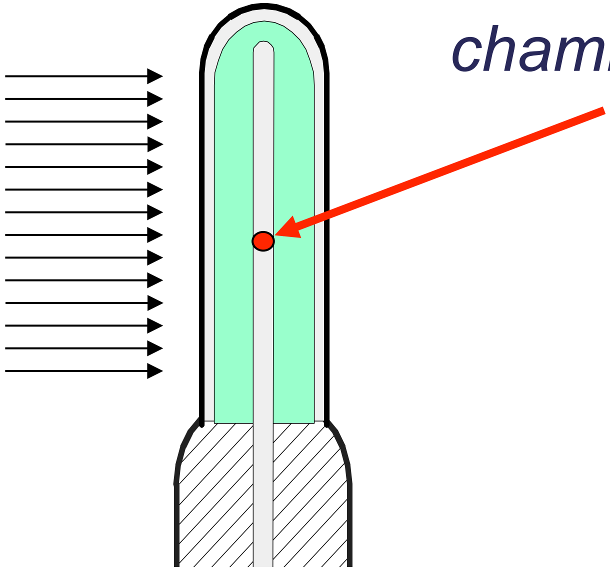
- Positioning for the calibration geometry setup:

  - Positioning must refer to a well defined point within the chamber.

  - This well defined point is the so-called **reference point of the chamber**.

2. Performance of a calibration procedure
Positioning of the ionization chamber in water

cylindrical chamber

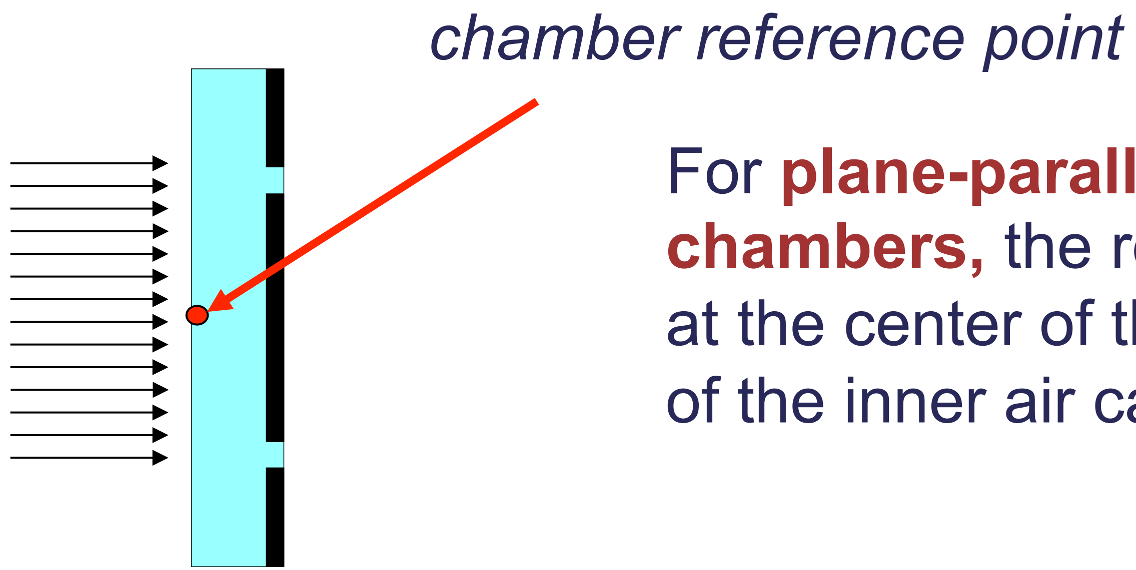


chamber reference point

For **cylindrical chambers** the reference point is at the centre of the cavity volume of the chamber on the chamber axis.

2. Performance of a calibration procedure
Positioning of the ionization chamber in water

plane-parallel chamber



For **plane-parallel ionization chambers,** the reference point is at the center of the front surface of the inner air cavity

2. Performance of a calibration procedure
Positioning of the ionization chamber in water

Positioning can now 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:

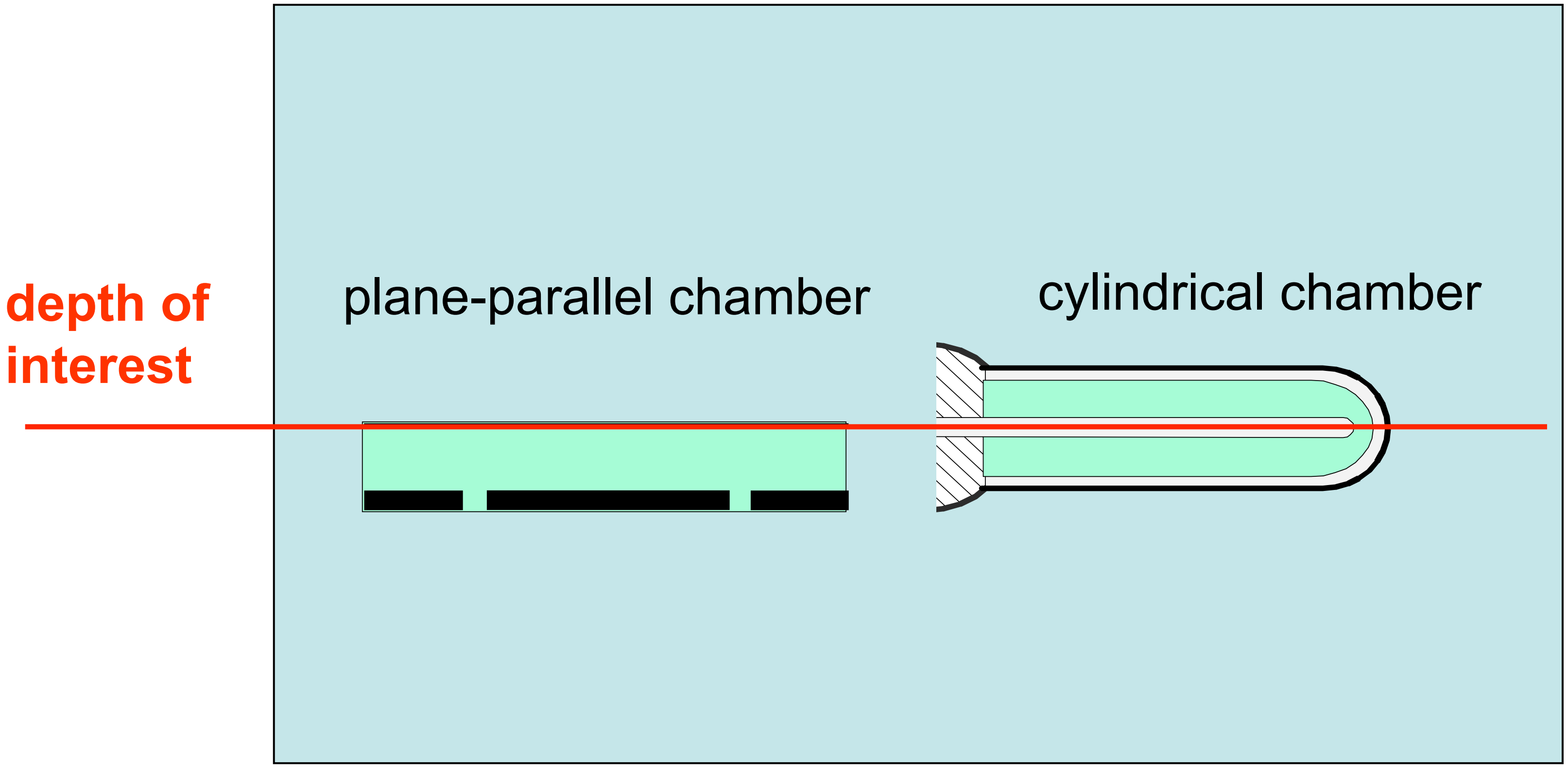
	Purpose
	Beam calibration
Co-60	at measuring depth
HE photons	at measuring depth
HE electrons	0.5 *r* deeper than measuring depth

2. Performance of a 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:

	Purpose	
	Beam calibration	**Depth dose measurement**
Co-60	always at measuring depth	always at measuring depth
HE photons	always at measuring depth	always at measuring depth
HE electrons	always at measuring depth	always at measuring depth

Positioning for ^{60}Co radiation and high energy photons



2. Performance of a calibration procedure
Main procedure

- The procedure of a calibration measurement now appears to be quite simple:
  - Take an ionization chamber for which a calibration factor from a certificate is available
  - Adjust the chamber in the water phantom following the positioning prescription in the protocol
  - Obtain charge under reference conditions
  - Obtain k_Q from an appropriate look-up table (e.g. protocol)
  - Multiply charge, calibration factor and quality correction factor to get the absorbed dose to water

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

2. Performance of a calibration procedure
Main procedure

- There are only two points left:

  (1) What exactly means “Obtain charge under reference conditions"?

  (2) We have a lookup table for k_Q , but how we get a **quantitative** value for the quality Q ?

  We need a procedure to determine a quantitative measure for the beam quality

2. Performance of a calibration procedure

(1) Measurement of charge under reference conditions

- The numerical value of the calibration factor N_{D,w,Q_O} and that of the quality correction factor k_Q are applicable only if the **reference conditions** are fulfilled.
- Reference conditions are described by a set of values of influence quantities.

(1) Measurement of charge under reference conditions

Reference conditions for the calibration of ionization chambers

Influence quantity	Reference value or reference characteristic
Phantom material	water
Phantom size	30 cm x 30 cm x 30 cm (approximately)
Source-chamber distance (SCD)	100 cm
Air temperature	T_0 = 20 °C [c]
Air pressure	P_0 = 101.3 kPa
Reference point of the ionization chamber	for cylindrical chambers, on the chamber axis for plane-parallel chambers on the inner surface of the entrance window,
Depth in phantom of the reference point of the chamber	5 g cm^{-2}
Field size at the position of the reference point of the chamber	10 cm x 10 cm
Relative humidity	50%
Polarizing voltage and polarity	as in the calibration certificate
Dose rate	no reference values are recommended but the dose rate used should always be stated in the calibration certificate. It should also be stated whether a recombination correction has or has not been applied and if so, the value should be stated

3. Correction factors

(1) Measurement of charge under reference conditions

- In calibrating an ionization chamber or a dosimeter, as many influence quantities as practicable are kept under control.
- However, some influence quantities cannot be controlled, for example air pressure and humidity, and dose rate in ^{60}Co gamma radiation.
- If those influence quantities cannot be adjusted to the reference conditions, their departure can be taken into account by applying appropriate correction factors.
- Assuming that influence quantities act independently from each other, a product of correction factors can be applied:

$$M_Q = M_Q^{raw} \cdot \prod k_i$$

where k_i refers to different influence quantities

3. Correction factors

(1) Measurement of charge under reference conditions

Air temperature and air pressure

- T_0 and P_0 are the reference conditions for chamber air temperature (in °C) and pressure.
- T and P are the actual air temperature (in °C) and pressure.
- Then in the user's beam, the correction factor for air temperature and air pressure $k_{T,P}$ is:

$$k_{T,P} = \frac{(273.2 + T)}{(273.2 + T_0)} \frac{P_0}{P}$$

3. Correction factors

(1) Measurement of charge under reference conditions

❑ Polarity effect

- 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.**
- If the used polarity differs from that at calibration, the following correction factor must be applied:

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

- 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).

3. Correction factors

(1) Measurement of charge under reference conditions

- Polarity effect: Has the calibration laboratory really corrected for the polarity effect ??

Reference conditions : T_0 : 20.0 °C p_0: 101.325 kPa R.H.: 50 %

The reported expanded uncertainty is based on a standard uncertainty multiplied by a coverage factor k = 2, which for a normal distribution provides a level of confidence of approximately 95%.

The secondary standard of this laboratory is traceable to the PTB in Braunschweig (German Federal Institute of Physics and Metrology).

Calibration reported in this certificate was carried out in accordance with the procedures described in the IAEA TRS 398 Code of Practice.

Measuring conditions:

Phantom size :	30 cm × 30 cm × 30 cm
Phantom material :	water
Source to phantom surface distance (SSD) :	100 cm
Field size at the phantom surface :	10 cm × 10 cm
Depth in phantom of the reference point of the chamber :	5 g·cm^{-2}
Reference point of the IC :	on the chamber axis at the centre of the cavity volume
Chamber orientation :	the beam axis perpendicular to the chamber axis

If the chamber stem has a mark, the mark is oriented towards the radiation source

Waterproof sleeve (PMMA) :	NO
Sleeve Serial Number:	-
Polarizing potential of collecting (central) electrode :	300 V
Dose rate :	1.0 Gy·min^{-1}

Recombination correction has not been applied

- If not then do the following:

3. Correction factors

(1) Measurement of charge under reference conditions

- If **no polarity correction is performed** during calibration, it is included in N :
- It follows: If the
  - user beam quality is the same as the calibration quality (normally Co-60)
  - and the chamber is used at the *same polarizing potential and polarity* as used during the calibration,

then k_{pol} will be the same at **calibration laboratory** and at the **user beam**

Therefore the user must *not* apply a polarity correction for that particular beam.

3. Correction factors

(1) Measurement of charge under reference conditions

If the user beam quality **is not the same as the calibration quality**, one should:

1) reproduce the calibration quality

2) estimate the polarity correction $[k_{pol}]_{Qo}$ that was not applied at the time of calibration using the **same polarizing potential and polarity** as was used at the calibration laboratory.

$$\left[k_{pol}\right]_{Qo} = \frac{\left|M_{+}\right| + \left|M_{-}\right|}{2M}$$

3) In the same way, the polarity effect at the user beam quality, k_{pol} must be determined.

3. Correction factors

Polarity correction factor

The correct polarity correction then is :

$$k_{pol} = \frac{k_{pol}}{[k_{pol}]_{Q_o}}$$

3. Correction factors

(1) Measurement of charge under reference conditions

- **There is always a difference between the charge produced by the radiation and actually measured**
  - Most important is an incomplete collection of charge in an ionization chamber cavity owing to the **recombination of ions.**

  - Two main separate effects take place:
    (i) the recombination of ions formed by separate ionizing particle tracks, termed **general** (or volume) **recombination**, which is dependent on the density of ionizing particles and therefore on the dose rate;

    (ii) the recombination of ions formed by a single ionizing particle track, referred to as **initial recombination**, which is independent of the dose rate.

3. Correction factors

(1) Measurement of charge under reference conditions

- Recombination effect
  - In **pulsed radiation** (i.e. at any linear accelerator!), the dose rate during a pulse is relatively high and general recombination is often significant.
  - In the IAEA Code of Practice it is recommended, that the correction factor k_s for pulsed beams be derived using the two voltage method:

$$k_s = a_o + a_1\left(\frac{M_1}{M_2}\right) + a_2\left(\frac{M_1}{M_2}\right)^2$$

    - where the values of the collected charges ***M*1** and ***M*2** are measured at the polarizing voltages *V*1 and *V*2, respectively.
    - *V*1 is the normal operating voltage and *V*2 a lower voltage.
    - The ratio *V*1/*V*2 should ideally be equal to or larger than 3.
    - the constants $\boldsymbol{a_0}$, $\boldsymbol{a_1}$, and $\boldsymbol{a_2}$ are given in the following slide.

3. Correction factors

(1) Measurement of charge under reference conditions

Fit coefficients $\boldsymbol{a_i}$, for the calculation of k_s by the "TWO-VOLTAGE" technique in pulsed radiation, as a function of the voltage ratio V_1/V_2

V_1/V_2	a_o	a_1	a_2
2.0	2.337	–3.636	2.299
2.5	1.474	–1.587	1.114
3.0	1.198	–0.875	0.677
3.5	1.080	–0.542	0.463
4.0	1.022	–0.363	0.341
5.0	0.975	–0.188	0.214

3. Correction factors

(1) **Measurement of charge under reference conditions**

- Recombination effect
  - In continuous radiation, notably ^{60}Co gamma rays, the two voltage method may also be used and a correction factor derived using the relation:

$$k_s = \frac{(V_1/V_2)^2 - 1}{(V_1/V_2)^2 - (M_1/M_2)}$$

3. Correction factors

Summary:

- 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 import correction factors are:
  - $k_{T,P}$ for air density
  - k_{pol} for polarity effects
  - k_{sat} for missing saturation effects

4. Determination of radiation quality

- Radiation quality may refer to:
  - a) **Low energy X rays** with generating potentials up to 100 kV and HVL of 3 mm Al (the lower limit is determined by the availability of standards);
  - b) **Medium energy X rays** with generating potentials above 80 kV and HVL of 2 mm Al;
  - c) **^{60}Co gamma radiation**;
  - d) **High energy photons** generated by electrons with energies in the interval 1–50 MeV;
  - e) **Electrons** in the energy interval 3–50 MeV;
  - f) **Protons** in the energy interval 50–250 MeV, with a practical range, R_p, between 0.25 and 25 g/cm^2;
  - g) **Heavy ions** with Z between 2 (He) and 18 (Ar) having a practical range in water, R_p, of 2 to 30 g/cm^2

4. Determination of radiation quality Q

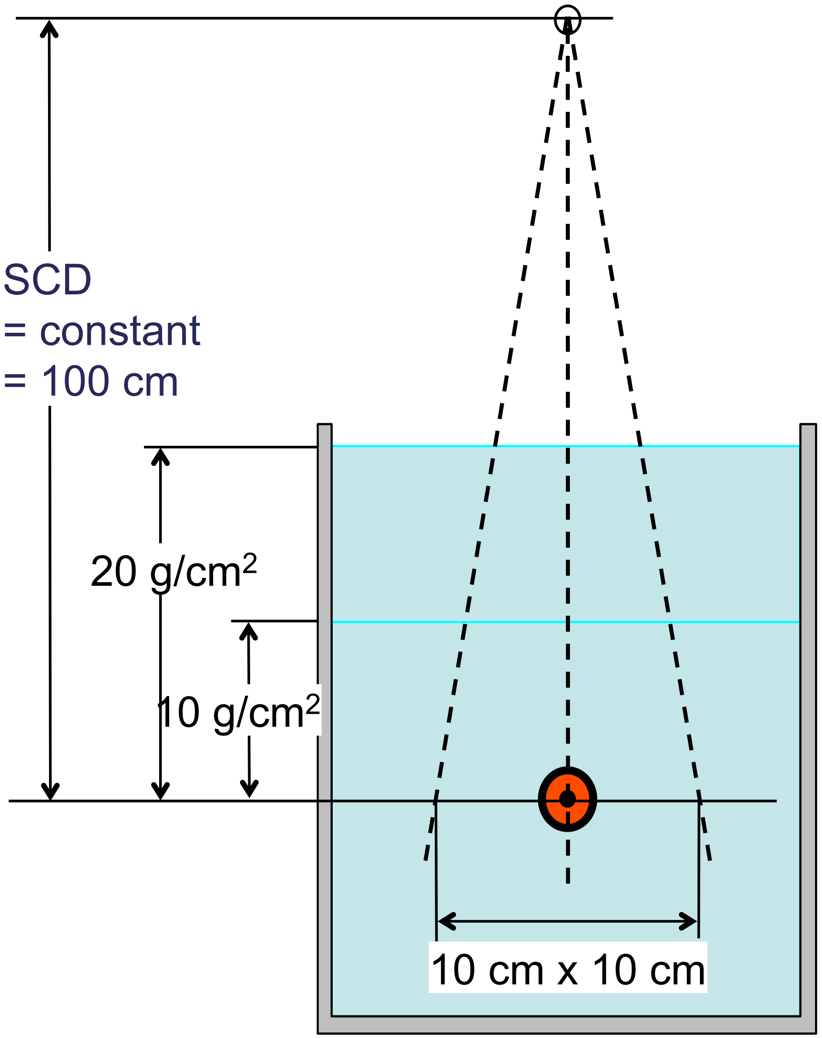
- Within each category of radiation type, a particular quantitative parameter, the so-called **quality parameter** is defined.
- Values of k_Q are tabulated as a function of this quality parameter.
- The selection of the correct value of k_Q therefore requires the determination of the quality parameter.
- The method to determine the quality parameter differs from one radiation type to another.

4. Determination of radiation quality Q

Definition of the quality index *Q* for HE photons

- For high energy photons produced by clinical accelerators the beam quality *Q* is specified by the **tissue phantom ratio $TPR_{20,10}$**.
- This is the **ratio** of the absorbed doses at depths of 20 and 10 cm in a water phantom, measured with a constant SCD of 100 cm and a field size of 10 cm × 10 cm **at the plane of the chamber**.
- The most important characteristic of the beam quality index **$TPR_{20,10}$** is its independence of the electron contamination in the incident beam.

4. Determination of radiation quality Q



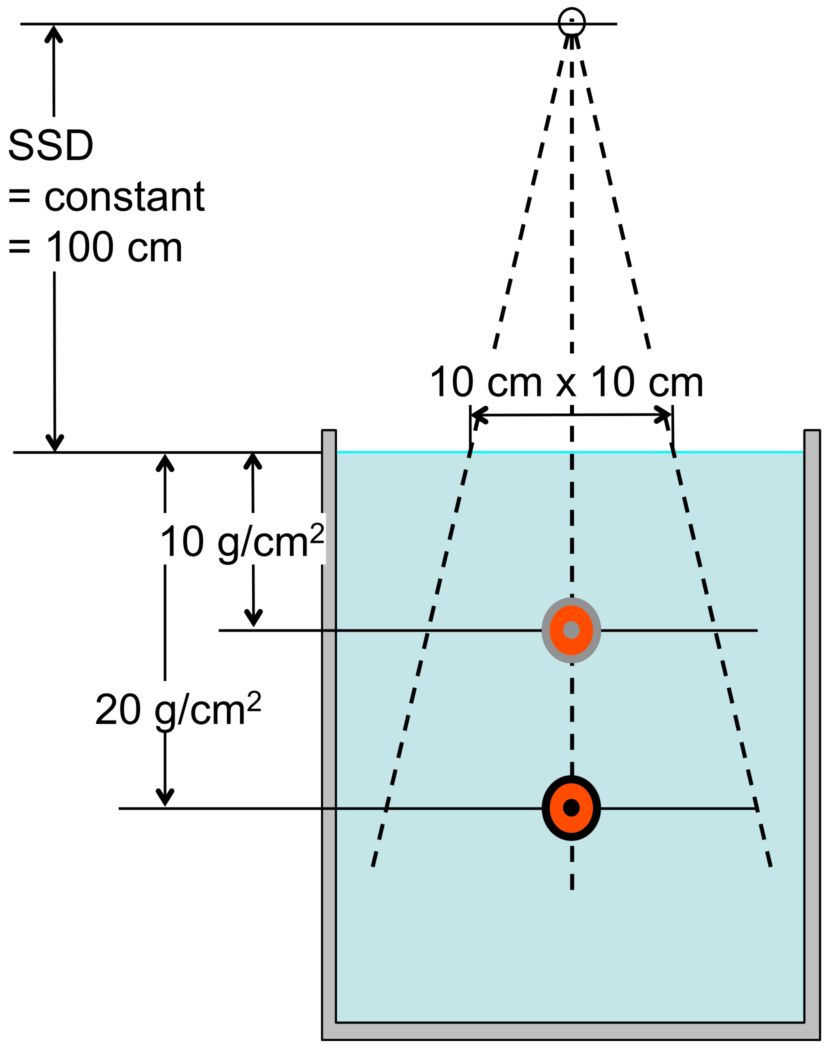
$\Rightarrow M_{10}$

$\Rightarrow M_{20}$

$$TPR_{20,10} = \frac{D_{20}}{D_{10}} \approx \frac{M_{20}}{M_{10}}$$

4. Determination of radiation quality Q

Alternative method and easier to perform: the PDD method



$$\Rightarrow M_{10}$$

$$\Rightarrow M_{20}$$

$$PDD_{20,10} = \frac{M_{20}}{M_{10}}$$

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

4. Determination of radiation quality Q

TABLE 14. CALCULATED VALUES OF k_Q FOR HIGH ENERGY PHOTON BEAMS FOR VARIOUS CYLINDRICAL IONIZATION CHAMBERS AS A FUNCTION OF BEAM QUALITY $TPR_{20,10}$ *(adapted from Andreo [20])*

Ionization chamber type[a]	Beam Quality $TPR_{20,10}$														
	0.50	0.53	0.56	0.59	0.62	0.65	0.68	0.70	0.72	0.74	0.76	0.78	0.80	0.82	0.84
Capintec PR-05P mini	1.004	1.003	1.002	1.001	1.000	0.998	0.996	0.994	0.991	0.987	0.983	0.975	0.968	0.960	0.949
Capintec PR-05 mini	1.004	1.003	1.002	1.001	1.000	0.998	0.996	0.994	0.991	0.987	0.983	0.975	0.968	0.960	0.949
Capintec PR-06C/G Farmer	1.001	1.001	1.000	0.998	0.998	0.995	0.992	0.990	0.988	0.984	0.980	0.972	0.965	0.956	0.944
Exradin A2 Spokas	1.001	1.001	1.001	1.000	0.999	0.997	0.996	0.994	0.992	0.989	0.986	0.979	0.971	0.962	0.949
Exradin T2 Spokas	1.002	1.001	0.999	0.996	0.993	0.988	0.984	0.980	0.977	0.973	0.969	0.962	0.954	0.946	0.934
Exradin A1 mini Shonka	1.002	1.002	1.001	1.000	1.000	0.998	0.996	0.994	0.991	0.986	0.982	0.974	0.966	0.957	0.945
Exradin T1 mini Shonka	1.003	1.001	0.999	0.996	0.993	0.988	0.984	0.980	0.975	0.970	0.965	0.957	0.949	0.942	0.930
Exradin A12 Farmer	1.001	1.001	1.000	1.000	0.999	0.997	0.994	0.992	0.990	0.986	0.981	0.974	0.966	0.957	0.944
Far West Tech. IC-18	1.005	1.003	1.000	0.997	0.993	0.988	0.983	0.979	0.976	0.971	0.966	0.959	0.953	0.945	0.934
FZH TK 01	1.002	1.001	1.000	0.998	0.996	0.993	0.990	0.987	0.984	0.980	0.975	0.968	0.960	0.952	0.939
Nuclear Assoc. 30-750	1.001	1.001	1.000	0.999	0.998	0.996	0.994	0.991	0.988	0.984	0.979	0.971	0.963	0.954	0.941
Nuclear Assoc. 30-749	1.001	1.000	1.000	0.999	0.998	0.996	0.994	0.992	0.989	0.984	0.980	0.972	0.964	0.956	0.942
Nuclear Assoc. 30-744	1.001	1.000	1.000	0.999	0.998	0.996	0.994	0.992	0.989	0.984	0.980	0.972	0.964	0.956	0.942
Nuclear Assoc. 30-716	1.001	1.000	1.000	0.999	0.998	0.996	0.994	0.992	0.989	0.984	0.980	0.972	0.964	0.956	0.942
Nuclear Assoc. 30-753 Farmer shortened	1.001	1.000	1.000	0.999	0.998	0.996	0.994	0.992	0.989	0.985	0.980	0.973	0.965	0.956	0.943
Nuclear Assoc. 30-751 Farmer	1.002	1.002	1.000	0.999	0.997	0.994	0.991	0.989	0.985	0.981	0.977	0.969	0.961	0.953	0.940
Nuclear Assoc. 30-752 Farmer	1.004	1.003	1.001	1.000	0.998	0.996	0.993	0.991	0.989	0.985	0.981	0.974	0.967	0.959	0.947

Summary: Beam Calibration of Photon Beams TRS 398

1) Calibration formula: $D_{w,Q} = M_Q \; N_{D,w,Q_o} \; k_{Q,Q_o}$

2) Follow the positioning instruction of the protocol:

   For depth dose measurements:

   Position the effective point of the chamber at the measuring depth

   For beam calibration measurements:

   Position the reference point of the chamber at measuring depth

3) The most important correction factors required to meet the reference conditions are:
   - $k_{T,P}$ for air density
   - k_{pol} for polarity effects
   - k_{sat} for missing saturation effects

Summary: Beam Calibration of Photon Beams TRS 398

4) The quality correction factor ***k_Q*** is given in tables provided in the TRS document, Chapter 6.

5) For high energy photons produced by clinical accelerators, the beam quality *Q* is specified by the **tissue phantom ratio $TPR_{20,10}$** photons produced This parameter can be measured directly or determined by the depth dose methods