SIF
International School of Physics "Enrico Fermi"
Metrology and Physical Constants
Varenna, 17 - 27 July 2012

1- Ionizing radiation metrology for radiation protection

2- Metrological requirements for ionizing radiation measurement in radiotherapy and radiodiagnostics

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Metrological needs for ionizing radiation measurement in radiation protection and radiotherapy

Part 2

Metrological traceability and specific needs in:

- IR measurement for radiation protection (RP)
- IR measurement for radiotherapy (RT)

Accuracy in IR measurement in RP and RT

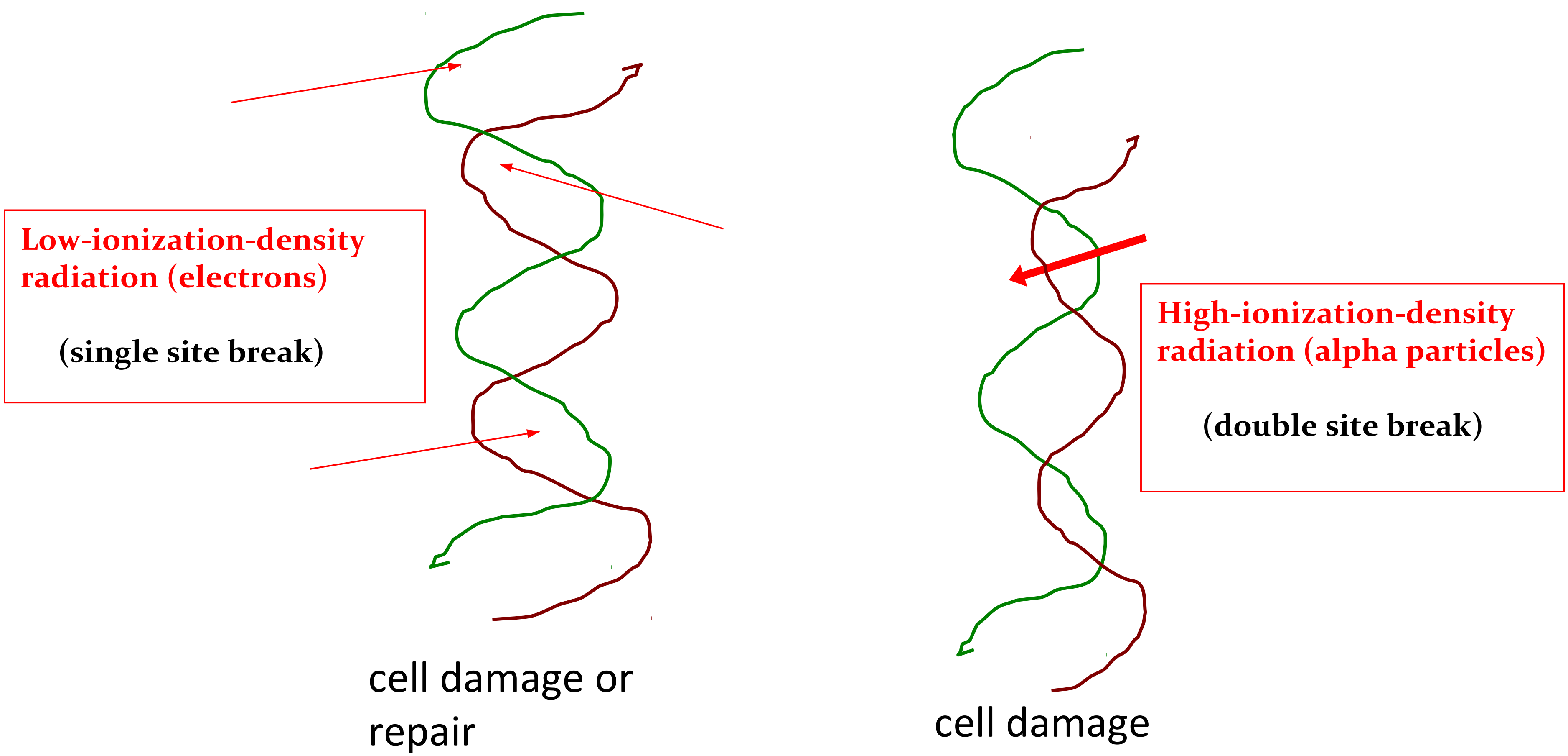
Need for a further quantity for measurements in radiation protection

For some types of radiations the absorbed dose (*D*) has not a bijective correspondence to radiation effects in living organisms

Radiation effects may depend on both the energy deposited by radiation and its spatial distribution in biological matter.

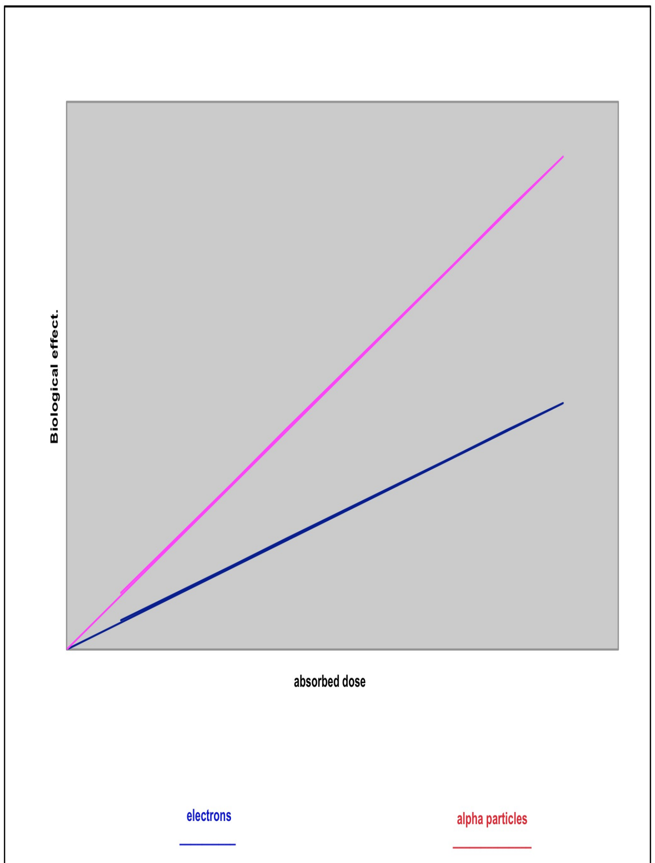
This dependence is particularly evident with densely ionizing radiation (e.g., α, *n*) at low values of *D*, as in exposures due to ionizing radiation in the environment

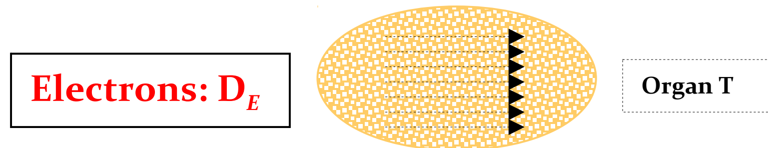
Biological effects in living organisms exposed to low doses of ionizing radiation



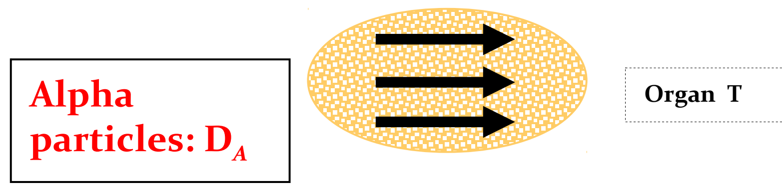
Relative biological effectiveness (RBE) of ionizing radiation

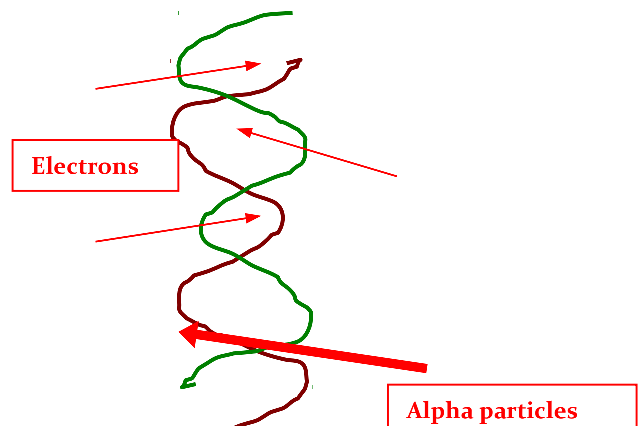
Equal values of absorbed dose imparted to the same biological organ, T, by densely or sparsely ionizing radiation, respectively, result in different biological effects in that organ.





$$D_E = D_A \quad (J/kg)$$





The "dose equivalent": a quantity introduced to account for the RBE of different types of ionizing radiation

Dose equivalent: $H = D \cdot Q$ **[J kg^{-1}] (Sievert, Sv)**

where:

D is the absorbed dose referred to a material with composition similar to the biological tissue,

Q is an adimensional factor, the "quality factor", depending on the RBE of ionizing radiation.

The higher the RBE of a radiation the greater the ionization density produced by that radiation

An apparent metrological inconsistency caused by the identical SI derived units for the quantities *D* and *H*

SI unit of dose equivalent (*H=DQ):* J kg^{-1} (sievert, Sv)

SI unit of absorbed dose (D): J kg^{-1} (gray, Gy)

The statement:

"in neutron irradiation, an absorbed dose (D) of 10 Jkg^{-1} may correspond to a dose equivalent (H) of 100 Jkg^{-1}"

sounds somewhat ambiguous. The ambiguity is no longer apparent if D and H are always expressed by the respective special name units, gray (Gy) and sievert (Sv), instead of Jkg^{-1}.

Traceability to the primary standards for measurements of the quantity *H*

- Instrument calibrations for measurement of *H* are made, at NMIs, by primary standards of quantities other than the dose equivalent *H.*

- *H* is indirectly determined as a function of other radiation quantities by using conversion coefficients obtained by calculation.

Determination of *H* as a function of:

- Kerma, *K*, for photon radiatiation

$$H = C_K(E)\,K, \quad C_K(E) = (\mathrm{Sv/Gy})$$

- Absorbed dose, *D*, for electrons (beta rays)

$$H = C_D(E)\,D, \quad C_D(E) = (\mathrm{Sv/Gy})$$

- Particle fluence, *Φ*, for neutrons

$$H = C_\Phi(E)\,D, \quad C_D(E) = (\mathrm{Sv/Gy})$$

The conversion coefficients $C_i(E)$ are calculated in stated conditions of irradiation (geometry, energy and direction of incident radiation, etc.)

A remarkable problem in gamma-ray dosimetry for radiation protection purposes

1- Instrument energy response, *$R_H(E)$*, not constant with energy,

2- Energy spectrum of the environmental gamma rays often not known.

$$R_H(E) = \frac{M(E)}{H(E)} = \frac{1}{N_H(E)} = f(E)$$

$M(E) = \textit{detector indication}$

$N_H(E) = \textit{instrument calibration coefficient in terms of } H$

Energy dependence of the response, $R_H(E)$, for gamma-ray detectors

$$R_H(E) = \frac{M(E)}{H(E)} = f(E)$$

$$M(E) = f(E, \Omega, Z_{det}, \rho_{det}, P_o)$$

$$H(E) = f(E, \Omega, Z_{tissue}, \rho_{tissue}, P_{ref})$$

M(E) and H(E) do not have the same dependence on energy and direction of incident radiation

Examples of energy dependence $R_H(E)$ for gamma-ray detectors with atomic number $Z_{det} \neq Zt_{issue}$

curve a:

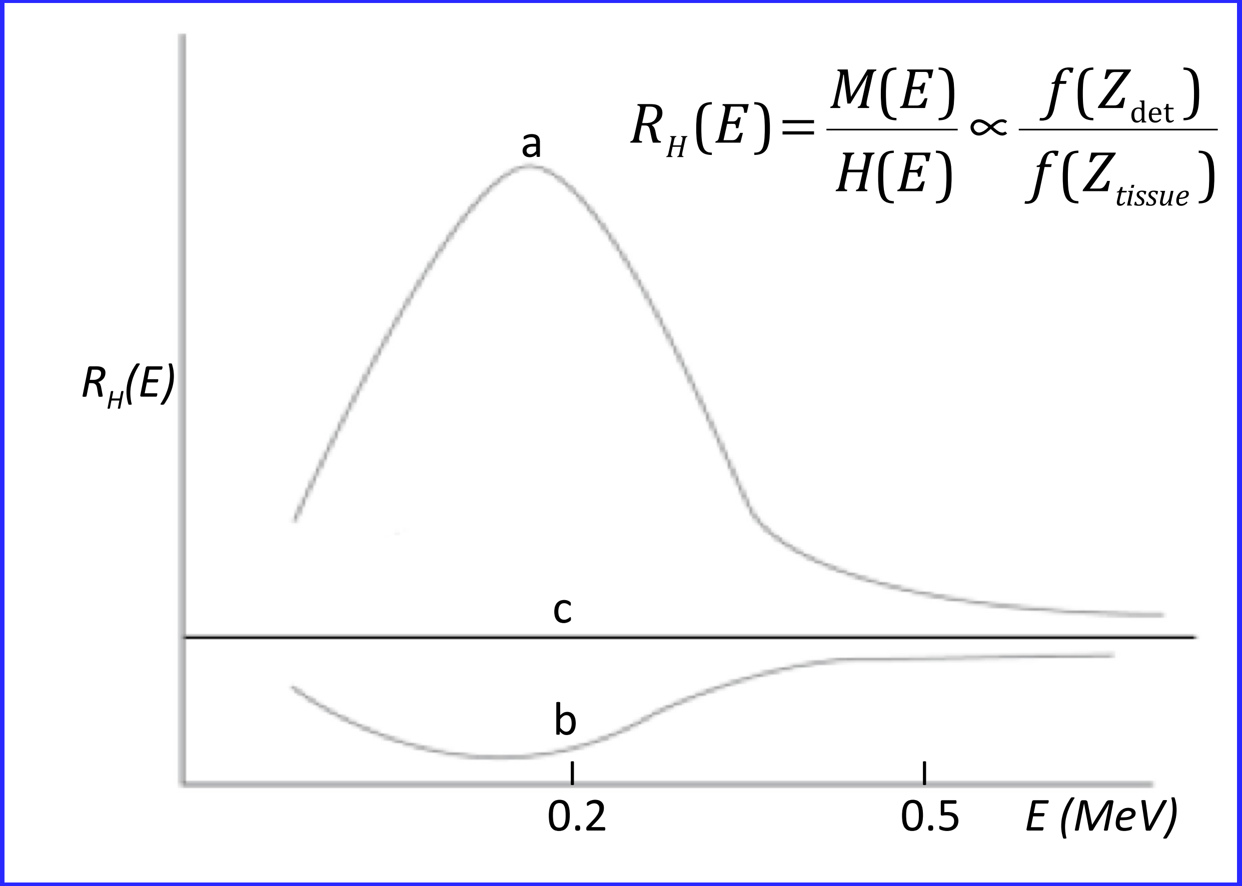
$Z_{det} >> Z_{tissue}$

curve b:

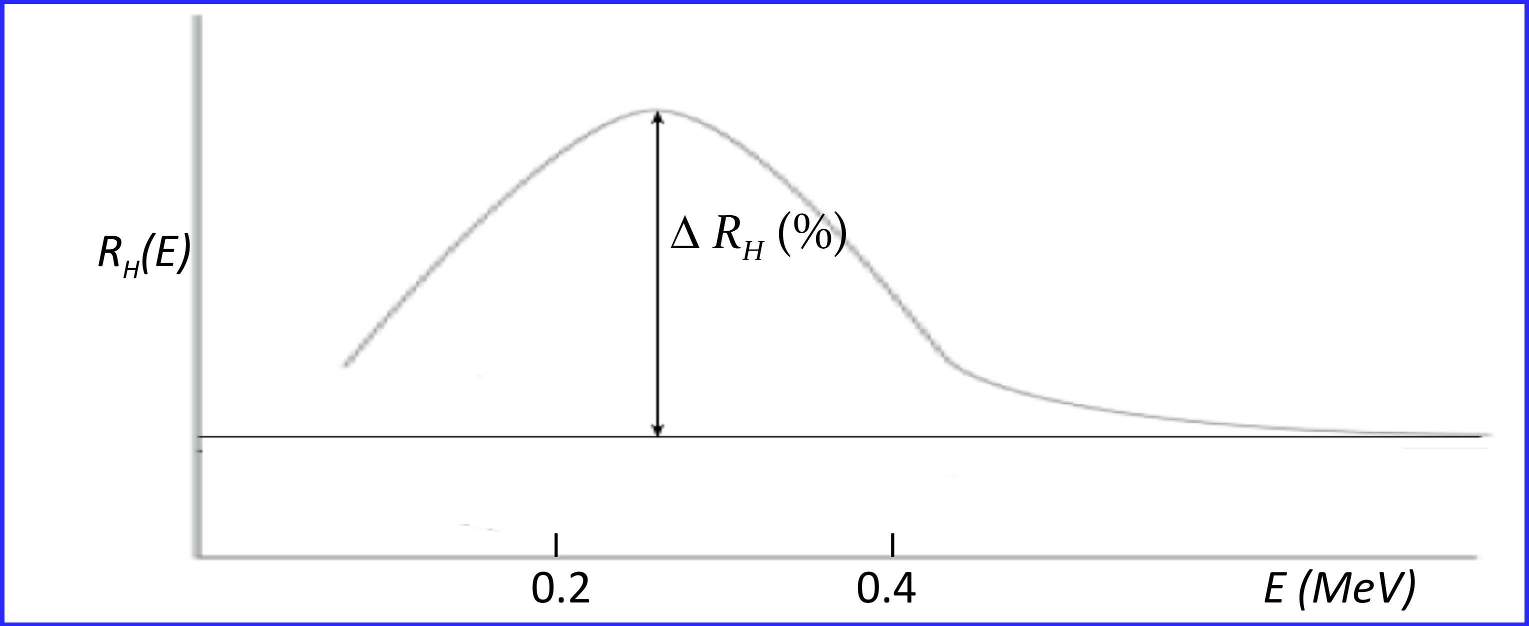
$Z_{det} < Z_{tissue}$

curve c:

$Z_{det} \cong Z_{tissue}$

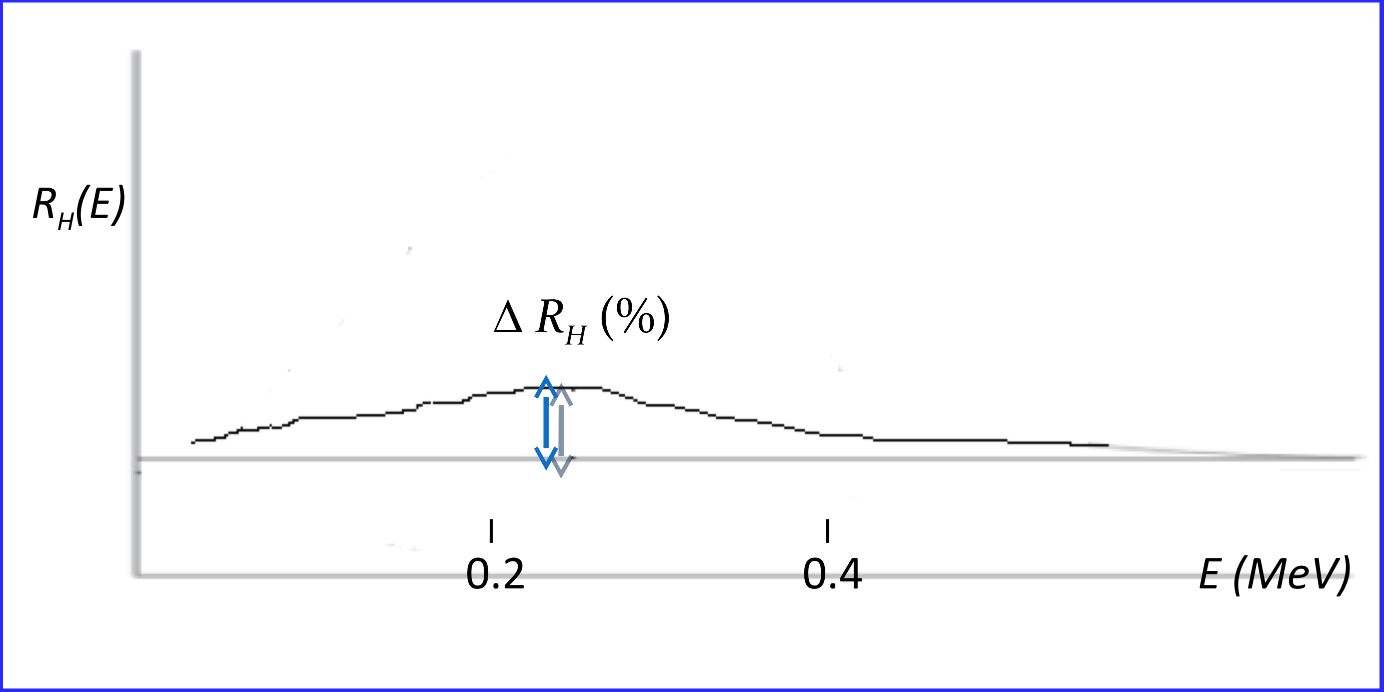


Uncertainty due to the energy dependence of detector response in environmental gamma-ray dosimetry



Measuring *H(E)* in a gamma-ray field with unknown energy, may result in an uncertainty U(%) ≈ $\Delta\, R_H$ (%)

Detector characteristics to account for the photon energy dependence of its response, $R_H(E)$



To minimize the detector energy response variation, the detector material should have density and atomic number close to those of the biological tissue ($\rho \approx 1$, $Z \approx 7$)

Typical uncertainty range for dosimetry of the environmental ionizing radiation

Measurement of dose equivalent, *H*

- Uncertainty range in typical experimental conditions:

10% to 50% (relative expanded uncertainty, $k = 2$).

- Even the upper limit of 50% may be difficult to fulfill in many practical situations because of the uncertain energy and direction of environmental radiation.

Radiation protection dosimetry: typical uncertainties in the measurement chain traceable to an air-kerma standard

Measurement steps	*Relative standard uncertainty*
Realization of the air kerma unit at PSL [(1)]	0.2 - 0.3
Instrument calibration coefficient (N_H) [(2)]	0.5 - 2
Field measurement of *H (ambient γ rays)* [(3)]	5 - 50

(1) depending on NMI and primary standard
(2) depending on instrument detector type
(3) depending essentially on direction and energy spectrum of radiation

Ionizing radiation measurement in radiotherapy

- Reference quantity: absorbed dose to water (D_w)

- Instrument calibration in terms of D_w or K_{air}

- Basic instrument detector: ionization chamber

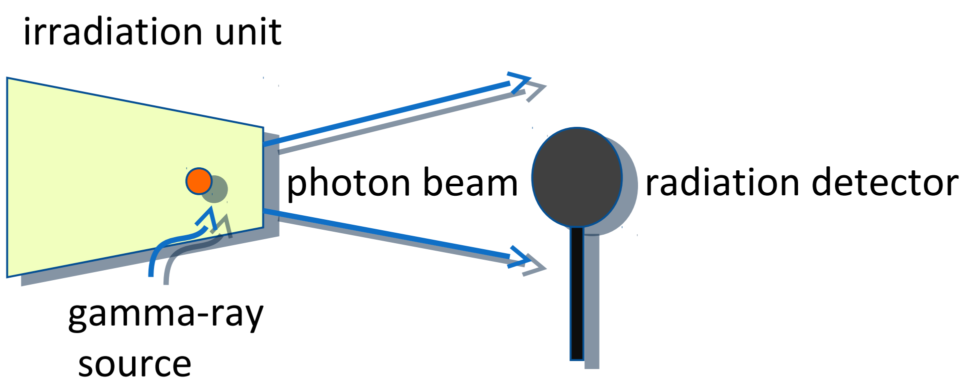
Detector calibration in a reference radiation beam at a metrological laboratory

Typical calibration radiation: gamma rays emitted by a ^{60}Co radioactive source.

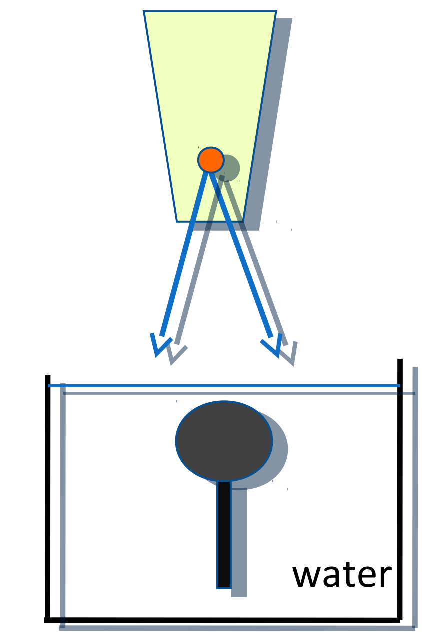
Calibration conditions: detector irradiated at a point *P* in air (a) or in water (b) according to the type of calibration.

Value of the calibration quantity (*K* or D_w) in *P* previously determined by the appropriate primary standard.

→ $N = K/M$ or D_w/M



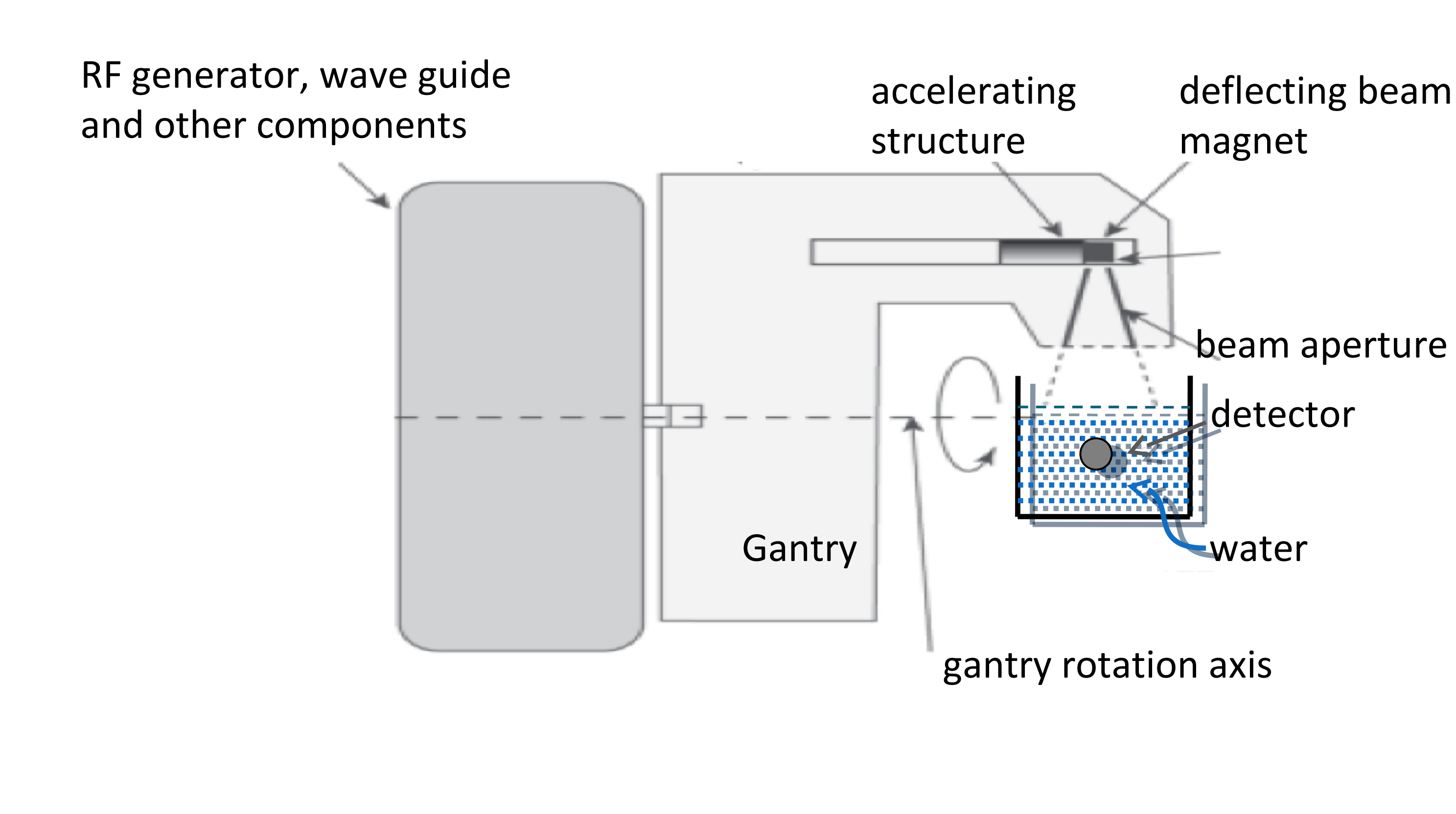
a) in-air calibration



b) in-water calibration

Measurement of D_w in the user's radiation beam by calibrated detectors

Radiation: photon or charged particle beams
Basic detector: cavity ionization chamber
- measurements in water -



A model of linear accelerator (linac) for radiotherapy. Typical energy range: 4 – 25 MeV (electron and photon beams)

Characteristics of the user's beam that are almost always different from those relevant to the conditions of detector calibration

1- Mean energy and energy distribution

2- Area of the beam impinging on the detector

3- Dose rate and dose per pulse

4- Direction of incidence

↓

The detector calibration coefficient, N, may have to be changed if the conditions in the user's beam are different from the calibration conditions.

Calibration procedures to account for the energy dependence of the detector calibration coefficient, *N*

(1)

Determining a value of N for each radiation quality Q (type and energy) that is intended to use:

$$(D_w)_Q = M_Q N_Q$$

- this procedure needs more than one radiation source at NMI and is not available in most NMIs

Calibration procedures to account for the energy dependence of the detector calibration coefficient, *N*

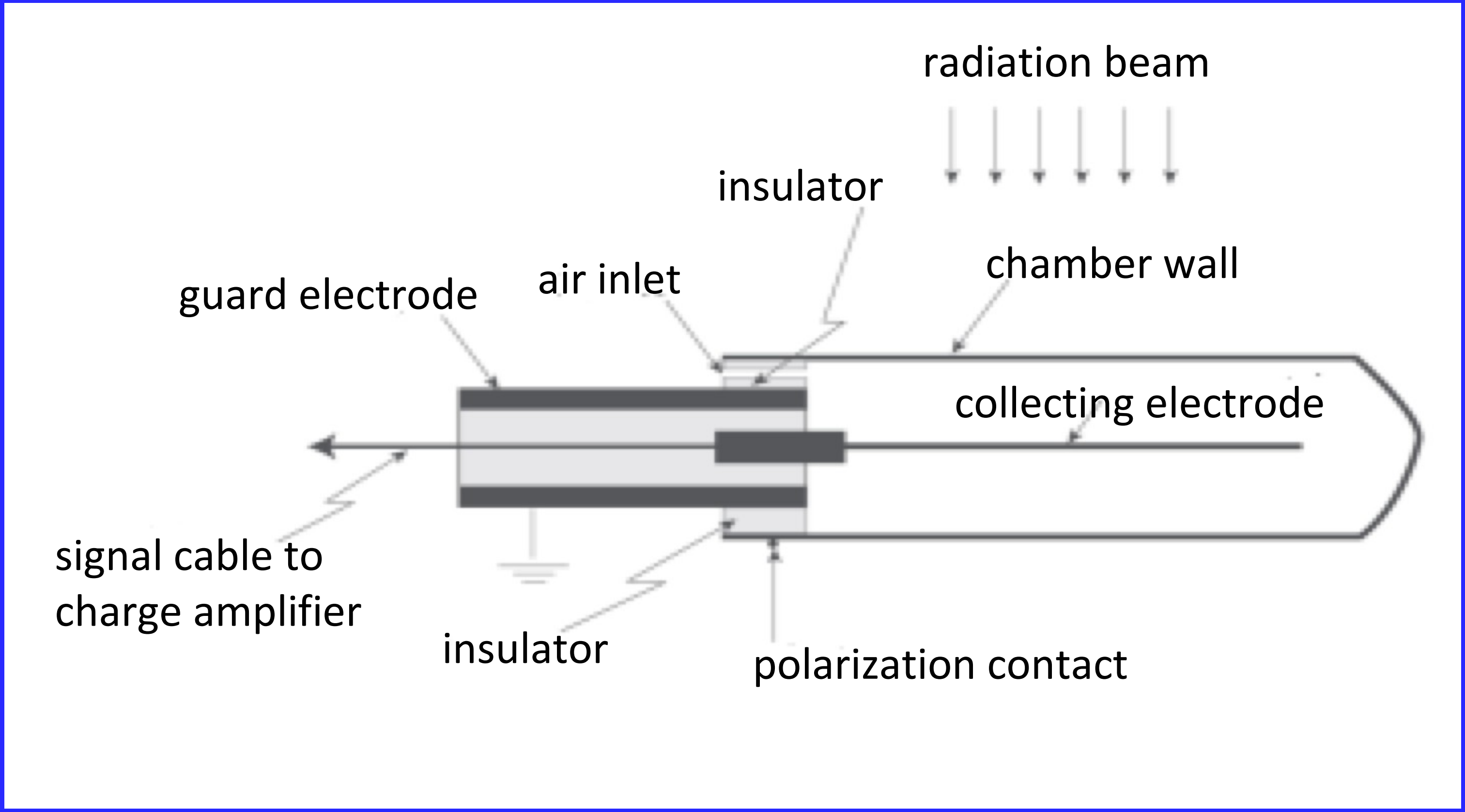
(2)

Determining one value of N at a reference radiation quality Q_0 and apply a correction factor, $f(Q,Q_0)$ to account for the energy dependence of N:

$$(D_w)_Q = M_Q \, N_{Q_0} \, f(Q,Q_0)$$

- ***this procedure needs a cavity ionization chamber, as detector, to be able to determine the factor $f(Q,Q_0)$. Procedure available in almost all NMIs.***

Typical cavity ionization chamber



A cavity chamber is an ionization chamber with a small air-filled cavity. Chamber size and materials are such to minimize the radiation field perturbation when the detector is exposed to radiation in water.

Calibration alternatives for the quantity to use in detector calibration

- Two calibration quantities are commonly used: kerma and absorbed dose.

- ***Calibrations based on a kerma primary standard can be made only at one reference radiation, Q_0,and are based on cavity chambers.***

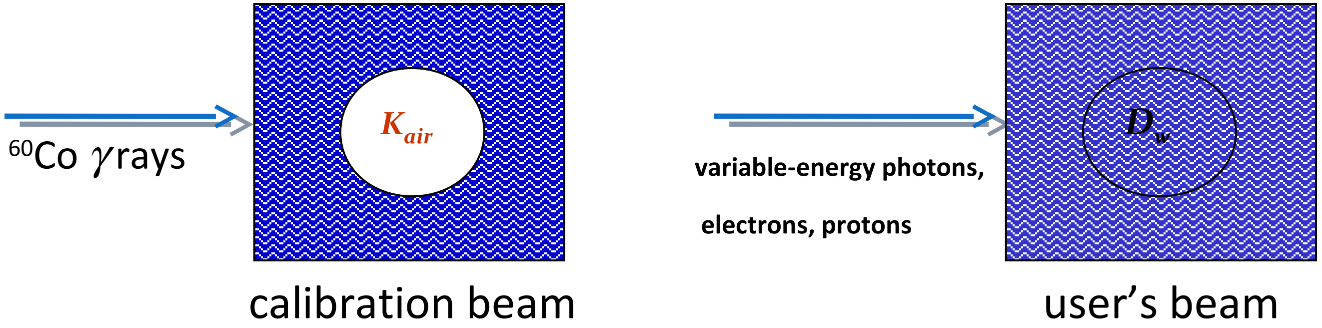
- ***Calibrations based on an absorbed dose primary standard (calorimetry) are also usually made at a reference radiation Q_0, even if on principle might be made at any radiation, Q.***

Measurement of D_w by a cavity chamber calibrated by a K_{air} primary standard at a reference radiation, Q_0, (^{60}Co γ-rays)

(K_{air}- standard-based approach)

$$D_{w,Q} = M_Q (N_K)_{Qo} f(Q,Q_0)$$

The user's radiation, *Q*, (high-energy photons, electrons, protons) is usually different from calibration radiation, Q_0, (^{60}Co γ rays).



Expression of D_w in measurements by a cavity ion chamber calibrated in terms of K_{air}

$$D_{w,Q} = M_Q \, N_{K,Qo} \, C_{Q,Qo}$$

Q = radiation under measurement

Q_0 = radiation used for calibration

M_Q = instrument indication in the beam Q

N_K = calibration coefficient in terms of K_{air}, referred to the beam Q_0

$$C_{Q,Qo} = [(1-g)\, k_{att} k_m k_{cel}]_{Qo} \, [s_{w,air} p_{cav} p_{dis} p_{wall} p_{cel}]_Q$$

factors related to physical parameters and perturbation effects in the calibration (Q_0) and measurement (Q) phases

Remarkable aspects on the "K_{air}-standard-based approach"

$$D_{w,Q} = M_Q \, N_{K,Qo} \, C_{Q,Qo}$$

a) Instrument calibration based on primary standards traditionally available in almost all of the NMIs.

b) Accuracy on D_w adequate for most practical needs in medicine.

c) Conceptually tortuous method: to measure a quantity, such as D_w, an instrument calibrated in terms of another quantity, K_{air}, is used.

Measurement of D_w by a cavity chamber calibrated by a calorimetric primary standard

$$(D_w)_Q = M_Q \, N_{Dw,Qo} \, k_{Q,Qo}$$

$k_{Q,Qo}$ = correction factor accounting for the energy dependence of N_{Dw}

$$N_{D_w,Q_0} = \left| \frac{D_{w,Q_0}}{M_{Q_0}} \right|_{cal}$$

⟹ determined by using the radiation Q_0

Just one calibration radiation (Q_0) is sufficient to measure D_w at any user's radiation (Q).

Comparison between the $N_{K,Qo}$ and $N_{Dw,Qo}$ approaches

(currently the most widely diffused methods)

$$[D_w]_Q = M\, N_{K,Qo}\, C_{Q,Qo} = f\,(N_K) \qquad (1)$$

$$[D_w]_Q = M\, N_{D,w,Qo}\, k_{Q,Qo} = f\,(N_{Dw}) \qquad (2)$$

$$C_{Q,Qo} = [(1\text{-}g)\, k_{att} k_m k_{cel}]_{Qo}\, [s_{w,air} p_{cav} p_{dis} p_{wall} p_{cel}]_Q$$

(*)

$$k_{Q,Qo} = (W_{air} s_{w,air} p_{cav} p_{dis} p_{wall} p_{cel})_Q\, [(W_{air} s_{w,air} p_{cav} p_{dis} p_{wall} p_{cel})_{Qo}]^{-1}$$

***(*)** factor affected by a relatively large uncertainty*

Uncertainty on D_w measurement by calibrated cavity chambers
- RT linac photon beams -
- $N_{K,Qo}$ approach -

Measurement step	Relative standard uncertainty, u(%)
Realization of the K_{air} unit by PS at NMIs	0.2 - 0.5 *(approximate range limits; variability depending on NMI and primary standard)*
intermediate steps not reported	- - - - -
D_w determination in the user's beam reference conditions	2 – 2.5 (*) U% (k=2): 4 - 5

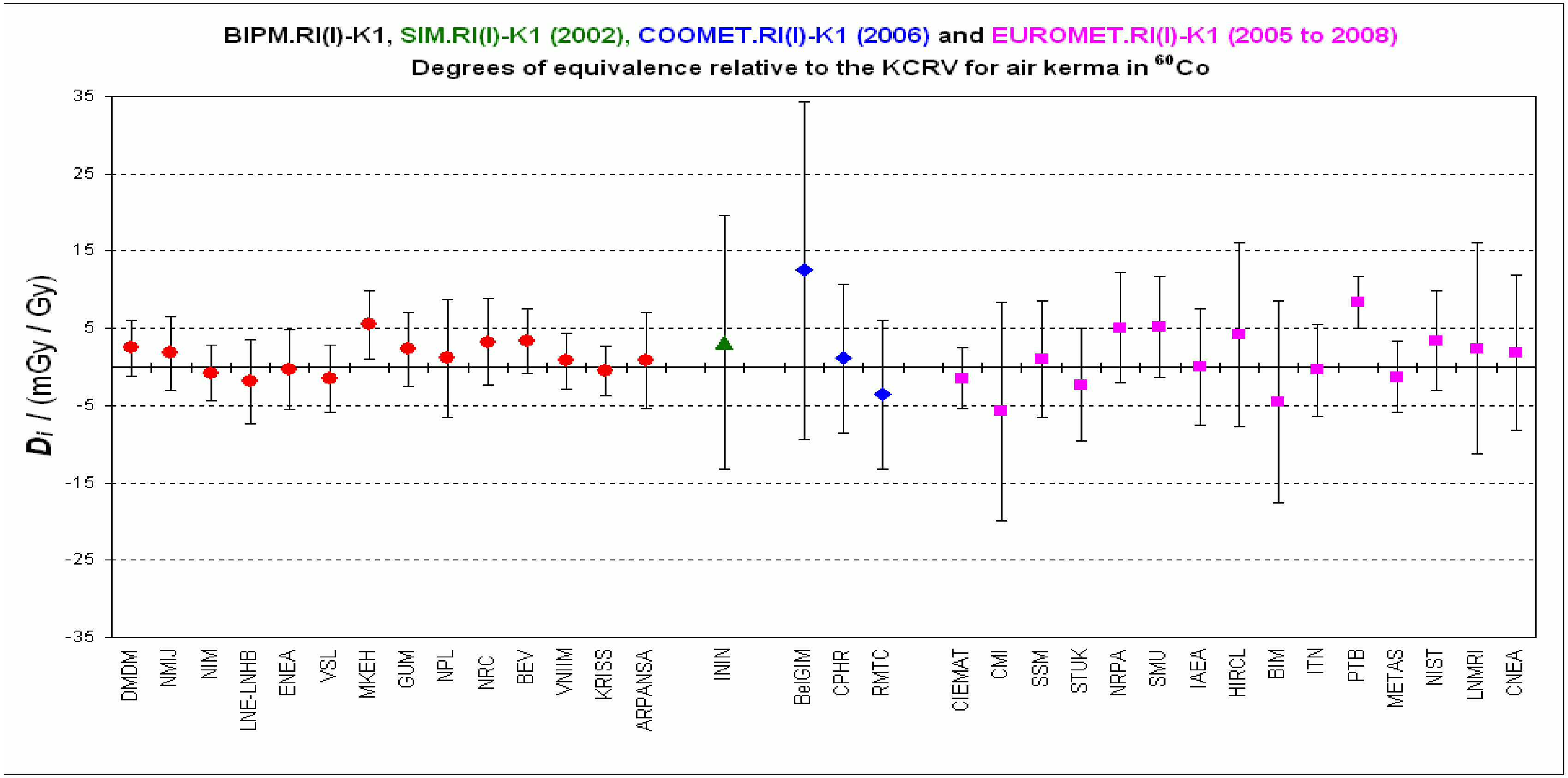
(*) Major uncertainty sources and variability due to cavity chamber parameters and correction factors

Uncertainty on D_w measurement by calibrated cavity chambers
- RT linac photon beams -
- $N_{Dw,Qo}$ approach –

Measurement step	Relative standard uncertainty, u(%)
Realization of the D_w unit at NMIs	0.2 – 0.5 *(approximate range limits; variability depending on NMI and primary standard)*
intermediate steps not reported	- - - - -
D_w determination in the user's beam reference conditions	1 – 1.5 U% (k=2): 2 - 3

(*) Major uncertainty sources and variability due to cavity chamber parameters and correction factors

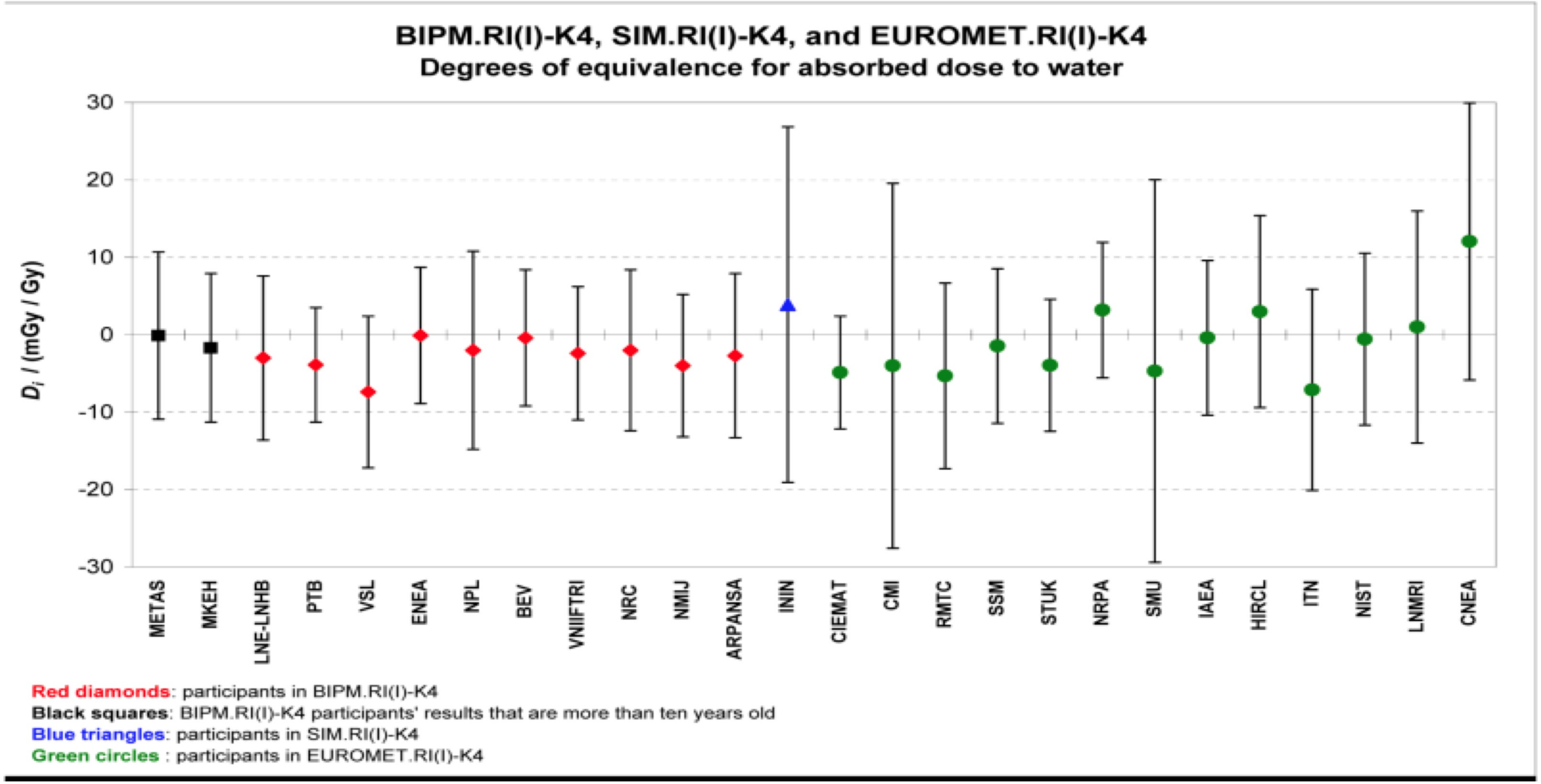
Degrees of equivalence (ref. BIPM) for the air-kerma, K_{air} (Gy), measured at NMIs



Red circles: participants in BIPM.RI(I)-K1
Green triangle: participant in SIM.RI(I)-K1
Blue diamonds: participants in COOMET.RI(I)-K1
Pink squares: participants in EUROMET.RI(I)-K1

$$DoE_{\text{NMI}} = (K_{\text{NMI}} - K_{\text{BIPM}})/K_{\text{BIPM}} = K_{\text{NMI}}/K_{\text{BIPM}} - 1 = R_K - 1\ ;\quad U(R_k)\text{: mGy/Gy, } k = 2$$

Degrees of equivalence (ref. BIPM) for the absorbed-dose-to-water, D_w (Gy), measured at NMIs



$$DoE_{NMI} = (K_{NMI} - K_{BIPM})/K_{BIPM} = K_{NMI}/K_{BIPM} - 1 = R_K - 1\ ;\ \ U(R_k)\text{: mGy/Gy, } k = 2$$

The importance of different reference standards for the quantity absorbed dose, *D* (Gy)

- A slight improvement on uncertainties on D_w is obtained when this quantity is determined by referring to calorimetric standards instead of the traditional ionimetric standards.

- The main reason for developing different primary standards based on independent methods, is to increase the confidence on the absolute measurement even if the accuracy gain is not high.

Examples of accuracy levels required for measurements in various fields of activity

- **Measurement of time intervals: $\Delta t / t \approx 10^{-14}$.**
  (required in accurate satellite-based positioning)

- **Measurement of lenght: $\Delta l / l \approx 10^{-11}$.**
  (because of incresead needs in nanotechnologies)

- **Measurement of absorbed dose in radiotherapy: $\Delta D/D \approx 10^{-2}$.**
  Accuracy levels within 2.5% (*1 SD*) can be obtained for absorbed dose measurement in reference conditions. In irradiation conditions other than those of reference the uncertainty on dose may increase even by a factor 2 or 3.

Measurement traceability problems currently open in some experimental conditions in radiotherapy

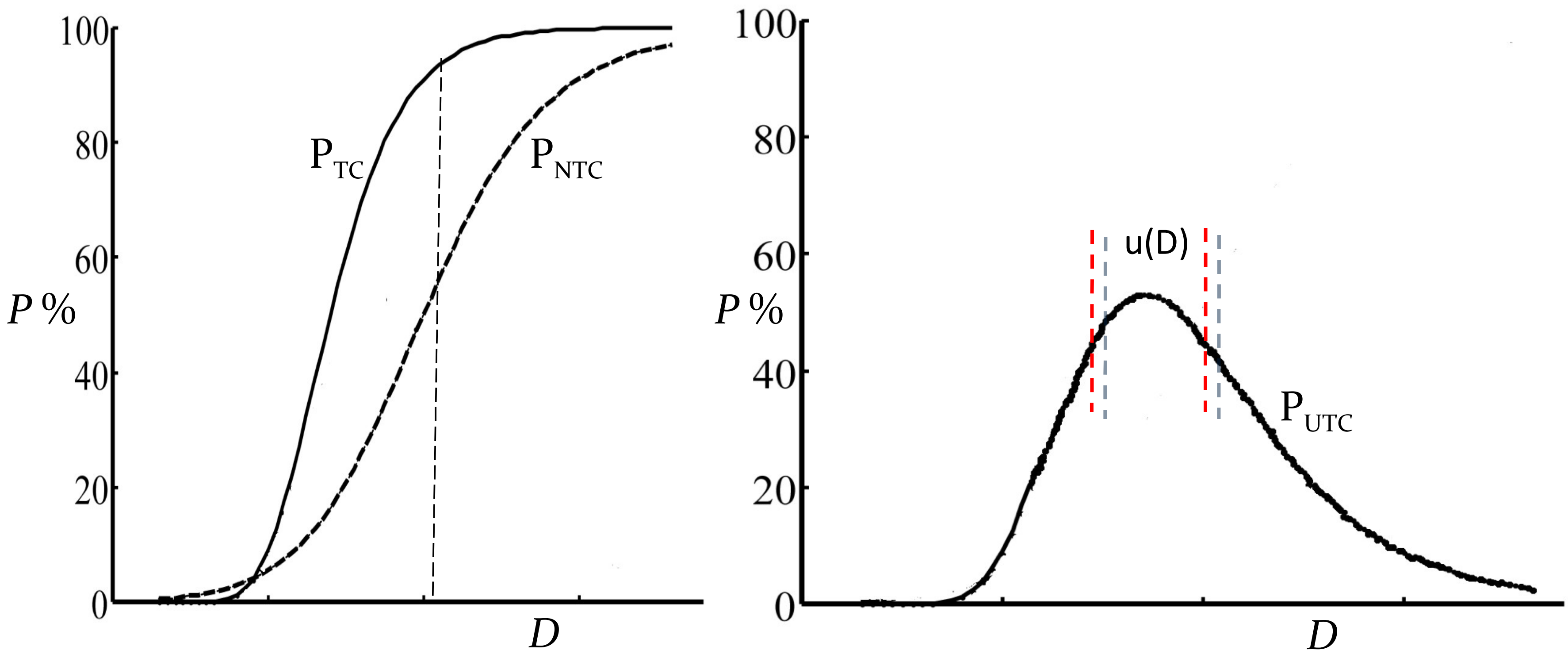
- **Radiation therapy with very small radiation beams (conformation radiotherapy by IMRT accelerators)**

- **Radiation therapy with radioactive sources placed within the human body, close to the treatment volume (brachytherapy)**

- **Radiation therapy with liquid radioactive sources (radiometabolic therapy – diffused radioactivity in the body)**

In all of the above experimental contions the absobed dose accuracy may be far from that achievable in reference conditions. Need for more thorough studies.

Uncertainty, u(D), on absorbed dose, D, as a function of probability of tumor control, P_{TC}, and probability of normal tissue complications, P_{NTC}



$P_{UTC} = P_{TC} \bullet (1 - P_{NTC})$, probability of uncomplicated tumor control

γ= *steepness* of the dose response (γ: from 1 to 6, average ≈ 3)

$\gamma = D\ (\Delta P_{NTC}/\Delta D) = \Delta P_{NTC}(\%)\ /\Delta D(\%)$ $(\Delta D(\%) = 1\%$ ➡ $\Delta P_{NTC} = \gamma\%)$