CAPÍTULO 4

HISTORICAL EVOLUTION OF DOSIMETRY PROTOCOLS

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1. INTRODUCTION

Recommendations for the reference dosimetry of external beam radiotherapy have been issued since the 1960s by national and international organizations, usually under the name of dosimetry protocols and codes of practice (CoP). They include a description of the procedures to be followed for the specification of the quality of a clinical radiation beam and for the reference measurement with ionization chambers, including the necessary geometry arrangements for both type of measurements. Included also are the *measurement equations* to convert measured charge into absorbed dose in a given medium, referred to as the *formalism* of the protocol, as well as the required data for its implementation. Modern protocols are usually explicit in the details on the formalism and data, but it was not that way in the early days, as in some CoPs "little attempt is made to justify or explain the detailed background" (IAEA 1970); thus, many of the early recommendations were simply "cooking recipes" and their full understanding required consulting text books and dosimetry publications.

Chronologically, dosimetry protocols can be grouped according to the quantity used to calibrate the user reference ionization chamber at the standards laboratory, namely, exposure, air kerma and absorbed dose to water. This text will review the most relevant publications following the grouping mentioned and, for sake of harmonization, the nomenclature, symbols and units will often be unified and converted into those used more recently by international organizations such as the International Commission on Radiation Units and Measurements (ICRU) and the International Atomic Energy Agency (IAEA). The focus will be on the formalisms and measurement equations for high-energy photon and electron beams, as together with the data provided, they are what most often differentiate one protocol within a given group from another.

2. EXPOSURE BASED PROTOCOLS

2.1 ICRU Report 10b (photons, 1962)

Although it was not designed as a dosimetry protocol, one of the pioneer dosimetry recommendations to which many protocols have referred to was the seminal ICRU (1962) Report 10b, *"Physical Aspects* *of Irradiation"*, also known as Handbook 85 of the USA National Bureau of Standards (NBS). It provided the most comprehensive discussion of the various techniques for the measurement of exposure and absorbed dose in kilovoltage (kV) and gamma rays and neutrons, including the specification and measurement of beam quality and measurement equations. Data were provided for mass energy-absorption and stopping power ratios, as well as a reviewed of the latter and of the average energy required to produce an ion pair, or an electron, in a gas (W).

In the case of an ionization chamber calibrated in terms of exposure, where both the calibration and user measurements were made in air, the determination of the absorbed dose in a medium is preceded by that of the dose at a point in air. The latter requires the energy absorption in air per roentgen, which recalling the early definition of roentgen as *"the quantity of radiation required to produce one esu of charge in one cm ³ of dry air at standard conditions"* (0 ∘C and 101.325 kPa), is obtained as

$$\begin{aligned} 1\,R &= \frac{1\ \mathrm{esu/cm^3}}{\rho_{\mathrm{air}}} = \frac{3.3356\times10^{-10}\mathrm{C/cm^3}}{1.29305\ \mathrm{kg/m^3}} = 2.5797\times10^{-4}\ \mathrm{C/kg} \\ (E_{\mathrm{abs}})_{\mathrm{air}} &= R\,(W_{\mathrm{air}}/e) = 0.869\times10^{-2}\ \mathrm{J/kg} \end{aligned} \tag{1}$$

with the value $W_{air}/e = 33.7$ J/C ($W_{air} = 33.7$ eV), so that the corresponding conversion from exposure-to-absorbed dose becomes $0{,}869 \times 10^{-2}$ Gy/R. The dose to air following an exposure of X roentgens under conditions of charged particle equilibrium (CPE) is therefore given by[1]

$$D_{\mathrm{air}} \stackrel{\mathrm{CPE}}{=} 0.869\times10^{-2}\ X\ \mathrm{Gy} \tag{2}$$

For low and medium-energy photons, where the response of an ionization chamber is usually entirely due to electrons generated within the detector itself, i.e., the material surrounding the sensitive volume is sufficiently thick to establish CPE, sometimes achieved with a buildup cap, the chamber acts as a *photon detector.* Recall that the CPE condition limits the measurement of exposure to photon energies below about 2 MeV owing to the range of the electrons involved.

The absorbed dose to a medium becomes

$$D_{\mathrm{med}} \stackrel{\mathrm{CPE}}{=} 0.869\times10^{-2}\ X\ [\mu_{\mathrm{en}}/\rho]_{\mathrm{med,air}} = f\,X \tag{3}$$

where $[\mu_{en}/\rho]_{med,air}$ is the ratio of mass energy-absorption coefficients of the medium and of

1 Recall that Eq.(2) strictly corresponds to the collision or electronic air kerma, see for example Andreo et al.(2017), $(K_{el})_{air} = x\ (W_{air}/e)$,while kerma is given by $K_{air} = X\ (W_{air}/e)/(1\text{-}g_{air})$,where g_{air} is the radiation yield in dry air averaged over the spectrum of energies of the charged particles liberated by mono energetic photons.

air evaluated for the photon spectrum at the point of measurement. Values of the roentgen-to-Gy conversion factor f were tabulated in ICRU-10b for water/air, compact-bone/air and muscle/air for monoenergetic photons and, as the goal at the time was to obtain directly the dose to human tissue, the latter two ratios were also tabulated for gamma rays and multiple clinical kV photon beam qualities. Note that because f has units, it is in reality a coefficient and not a factor; this is the term that will be used henceforth for this and for several other denominated "factors" in the older protocols. Equation ((3)) using the symbol $f\lambda$ for the exposure-to-dose conversion coefficient was used in the IAEA (1970) TRS-110 "Manual of Dosimetry in Radiotherapy" for ^{60}Co and 137Cs γ-rays and medium-energy kV x-rays, where the coefficient was given in tabular form but never defined.

An interesting case included in this old ICRU-10b is that of a thick-walled graphite chamber, of the type used in standards laboratories, with the chamber placed within a phantom. Assuming that the cavity is small in comparison with the ranges of most of the electrons present, and that its walls are thick enough to exclude any externally produced electrons, the dose in a thin layer of the wall can be obtained using the Bragg-Gray relation, where the absorbed dose to a medium **Dmed** is related to the number of electrons formed per gram of gas, **Jgas**, by

$$D_{\text{med}} = J_{\text{gas}} \left(W_{\text{gas}} / e \right) s_{\text{med,gas}} \quad (4)$$

where $s_{\text{med,gas}}$ is the mass stopping-power ratio of the medium to that of the cavity gas for the electron spectrum and $J_{\text{gas}} = q/\rho_{\text{gas}}V$, with q being the charged produced in the detector volume V filled with gas of density ρ_{gas}. Accordingly, for an air-filled chamber,

$$D_{\text{wall}} = 0.869 \times 10^{-2}\, q\, s_{\text{wall,air}} \quad (5)$$

where q is the measured charge and $s_{\text{wall,air}}$ is the mass stopping power ratio of the wall material to air evaluated for the electron spectrum at the point of interest. ***(Note that if the chamber would have been a small air-filled cavity inserted in the medium, the dose obtained would have been in the medium itself, not just in the wall).***

For the thick-walled chamber, the dose to the medium is obtained from

$$D_{\text{med}} = p_{\text{dis}} \left[\mu_{\text{en}}/\rho \right]_{\text{med,wall}} D_{\text{wall}} = 0.869 \times 10^{-2}\, q\, s_{\text{wall,air}}\, p_{\text{dis}} \left[\mu_{\text{en}}/\rho \right]_{\text{med,wall}} \quad (6)$$

where p_{dis}, written as B in the ICRU report, is a correction factor close to unity that accounts for the different attenuation and scatter in the chamber wall and in the displaced medium. This is probably the oldest reference to this type of chamber perturbation factor in clinical radiation dosimetry, even if no values were given. It should be noted that Eq. (4) provides the basis for measurements made with conventional ionization chambers within a phantom at energies above the limit of the measurement of exposure, which will be discussed in subsequent dosimetry recommendations.

2.2 HPA photon CoPs (1960, 1964, 1969)

The first properly called code of practice for dosimetry that the author is aware of was issued by the UK Hospital Physicists' Association, HPA (1960), devoted to medium-energy kV x-rays with HVLs in the range 0,5 to 5 mm Cu, where "exposure-dose" could be measured by the user in air with or without back-scatter, or in a water or similar phantom at 5 cm depth. No equations and data were provided, only external references.

The first CoP was soon expanded to HPA (1964) for the dosimetry of 2 to 8 MV x-ray and ^{137}Cs and ^{60}Co γ-ray beams, where the absorbed dose to water was given by

$$D_{\mathrm{w}} = M\, N_X\, C_\lambda \tag{7}$$

where D_w is the absorbed dose to water at the position of the chamber centre, M is the chamber reading in water, corrected to dry air at 22 ∘C and 101.325 kPa (the buildup cap used for the in-air calibration remains in place for in-water measurements), N_X is the calibration coefficient in terms of exposure (roentgen), given by the NPL standards laboratory for 2 MV x-rays, and C_λ is an overall exposure-to-dose conversion coefficient, which is a function of the radiation quality and the chamber type including its buildup cap.

Equation (7) became the classic expression used by several other "C- lambda" exposure-based protocols. Values of $C\lambda$ were given for Farmer- and Victoreen-type ionization chambers for x-ray beams between 2 and 8 MV, and 137Cs and ^{60}Co γ-ray beams. They were based on a value of Wair = 33.7eV but no formulation of $C\lambda$ and information on the data used were provided.

The HPA (1964) code of practice was extended up to 35 MV in HPA (1969) where, in addition to anexpanded data table for $C\lambda$ based on measurements and calculations, the only differences with the previous version were that (a) the exposure calibration coefficient N_X could also be for ^{60}Co γ-rays, (b) N_X was given for dry air at 20 ∘C, 101.325 kPa, and (c) the data table of $C\lambda$ was restricted to a Farmer-type ionization chamber. $C\lambda$ continued to be a kind of black box to the user during several years.

2.3 AAPM-SCRAD (electrons 1966)

Between the publication dates of the two later HPA CoPs a protocol for electron beam dosimetry was released by the Sub-Committee on Radiation Dosimetry (SCRAD) of the American Association of Physicists in Medicine, AAPM-SCRAD (1966). Its first recommendation was the use of Fricke dosimeters and, in addition, measure outputs with a thimble ionization chamber (Farmer and Victoreen) calibrated in terms of exposure in ^{60}Co γ-rays. Electron energy calibration received especial consideration and various methods were described. Cavity ionization, to be measured in a specific SCRAD polystyrene phantom at dose maximum, was converted into absorbed dose to water by means of the Bragg-Gray relation of Eq. (4), but the protocol did not provide details or numerical data to be used except for the use of $W_{\text{air}} = 33.7\text{eV}$; only external references were provided for that purpose.

2.4 ICRU Report 14 (photons, 1969)

ICRU (1969) Report 14 for the dosimetry of photons with energies between 0,6 and 50 MeV was published at this time. As is well-known, for photon energies above about 600 keV the response of an ionization chamber is due primarily to electrons which enter the cavity from the surrounding medium, but not to electrons generated within its own sensitive volume and walls. The chamber may be considered as an *electron detector*, in contrast to the case described previously of a photon detector, and therefore the Bragg-Gray relation of Eq. (4) can be applied.

ICRU-14 was a comprehensive publication used by many, and during more than three decades it was the only ICRU report devoted to photon dosimetry, until the publication of ICRU (2001) Report 64. Although ICRU-14 was still based on a user chamber calibration in terms of exposure, it included the concept of air kerma as an intermediate quantity to be calculated from exposure. Unlike the protocols issued by professional organizations discussed earlier, ICRU-14 provided full transparency in the formalism and measurement equations, contributing to the better understanding of the physics involved. With all the user measurements to be made at an energy-dependent depth in water using an ionization chamber including the buildup cap used for the chamber calibration, the report considered both the determination of absorbed dose at the beam qualities used for chamber calibration (2 MV or ^{60}Co) and at higher photon energies.

The exposure at a point in water, Xw, for 2 MV or ^{60}Co γ-rays was determined according to

$$X_{\text{w}} = M\, N_X\, p_{\text{dis}}\, p_{\text{spt}} \tag{8}$$

where $\boldsymbol{M}$ and $\boldsymbol{N_X}$ have the same meaning as in Eq. (7), and $\boldsymbol{p_{\text{dis}}}$ and $\boldsymbol{p_{\text{spt}}}$ are perturbation factors that correct, respectively, for the effect of the displacement of water by an air volume with the shape of the ionization chamber, and for the difference in chamber response in the photon fluence spectrum at the calibration in air and at the user measurement in the water phantom. They were denoted in ICRU- 14 by d and $\boldsymbol{k2}$, respectively. The only value of $\boldsymbol{p_{\text{dis}}}$ provided was for a Farmer-type chamber, being equal to 0,985, while $\boldsymbol{p_{\text{spt}}}$ was considered to be very close to unity.

Water kerma was then derived using

$$K_{\mathrm{w}} = X_{\mathrm{w}}(W_{\mathrm{air}}/e)\frac{(\mu_{\mathrm{tr}}/\rho)_{\mathrm{w}}}{(\mu_{\mathrm{en}}/\rho)_{\mathrm{air}}} \tag{9}$$

where $(\mu_{tr}/\rho)_w$ and $(\mu_{en}/\rho)_{air}$ are, respectively, the energy-fluence weighted mean values of the mass energy-transfer and mass energy-absorption coefficients for the photon spectra at the point of measurement. Note the use of the μ_{tr}/ρ *coefficient in water, instead of* μ_{en}/ρ, *owing to the exclusion of energy absorption from bremsstrahlung in the exposure but not in kerma. Recall that* $\mu_{en}/\rho = (1 - g)\, \mu_{tr}/\rho$, *where* g *is the radiative fraction, i.e., the mean fraction of electron kinetic energy lost in radiative processes (see also footnote 2.1).*

The absorbed dose to water at the calibration quality was then determined from the water kerma through

$$D_{\mathrm{w}} = \beta\, K_{\mathrm{w}} = \beta\, X_{\mathrm{w}}\,(W_{\mathrm{air}}/e)\frac{(\mu_{\mathrm{tr}}/\rho)_{\mathrm{w}}}{(\mu_{\mathrm{en}}/\rho)_{\mathrm{air}}} \tag{10}$$

where β is the ratio between absorbed dose and kerma, sometimes referred to as a correction for the mean centre of electron production (CEP, see e.g. Andreo et al. (2017)) which is very close to unity $(\beta \geq 1)$, and the absorbed dose can be written as

$$D_{\mathrm{w}} = M\, N_X\, p_{\mathrm{spt}}\, C_{\lambda_0} \tag{11}$$

with

$$C_{\lambda_0} = 0.869 \times 10^{-2} \beta\, p_{\mathrm{dis}} \frac{(\mu_{\mathrm{tr}}/\rho)_{\mathrm{w}}}{(\mu_{\mathrm{en}}/\rho)_{\mathrm{air}}}\ \mathrm{Gy/R} \tag{12}$$

which became the exposure-to-dose conversion coefficient at the calibration (reference) quality, most often ^{60}Co γ-rays.

For photon beam qualities higher than the calibration, the measurement equation for the absorbed dose to water was identical to Eq. (11) with $C\lambda_0$ replaced by $C\lambda$, resulting in

$$\begin{aligned} D_{\mathrm{w}} &= M\, N_X\, p_{\mathrm{spt}}\, C_{\lambda} \\ C_{\lambda} &= C_{\lambda_0}\frac{(s_{\mathrm{w,air}})_{\lambda}}{(s_{\mathrm{w,air}})_{\lambda_0}}\frac{p_{\lambda}}{p_{\lambda_0}} = 0.869 \times 10^{-2} \beta\, p_{\mathrm{dis}} \frac{(\mu_{\mathrm{tr}}/\rho)_{\mathrm{w}}}{(\mu_{\mathrm{en}}/\rho)_{\mathrm{air}}}\frac{(s_{\mathrm{w,air}})_{\lambda}}{(s_{\mathrm{w,air}})_{\lambda_0}}\frac{p_{\lambda}}{p_{\lambda_0}}\ \mathrm{Gy/R} \end{aligned} \tag{13}$$

where $(s_{w,air})\lambda$ and $(s_{w,air})\lambda_0$ are the mass stopping-power ratios of water relative to air at the photon beam qualities λ and λ_0 (calibration), respectively, and $p\lambda$ and $p\lambda_0$ are perturbation correction factors.

These perturbations were not defined or provided numerically, and ICRU-14 stated that the ratio $p\lambda/p\lambda_0$ would normally be close to unity (note that the factor p_{dis} should not be included in $p\lambda_0$ and $p\lambda$, as otherwise it would be accounted for twice). Values of the exposure-to-dose conversion coefficients $C\lambda_0$ and $C\lambda$ for the calibration and higher beam qualities were tabulated in ICRU-14.

2.5 AAPM-SCRAD (photons 1971)

Following the publications of HPA (1969) and ICRU (1969), the SCRAD of the AAPM released a dosimetry protocol for photons up to 50 MeV, AAPM-SCRAD (1971), intended to supplement the HPA and ICRU publications adopting their frame of reference and dosimetric data. The SCRAD protocol described in detail the measurement equations following closely those of ICRU-14 while introducing some minor changes and simplifications, also in the symbols. Allowed phantom materials were water, polystyrene and PMMA (acrylic).

For measurements in water, D_w was determined as in Eqs. (13), excluding p_{spt}, Q and $p\lambda/p\lambda$; the coefficient $C\lambda$, for ^{60}Co, was denoted by fc and given the value of 0,965. The values of the exposure-to-dose conversion coefficients $C\lambda$ for water were those in HPA (1969) while those for polystyrene and PMMA, and for the three materials for beam qualities between 35 and 50 MeV were specifically derived for the protocol. When measurements were made in plastic phantoms, the dose to water was derived from

$$D_\mathrm{w} = D_\mathrm{pl} \frac{(\mu_\mathrm{en}/\rho)_\mathrm{w}}{(\mu_\mathrm{en}/\rho)_\mathrm{pl}} \tag{14}$$

Another difference between the SCRAD protocol and the HPA and ICRU publications was the possibility of performing measurements in air for the calibration beam quality, subsequently deriving the absorbed dose to water at the depth of dose maximum or at the isocenter. This was done using

$$D_\mathrm{w} = M_\mathrm{air}\, N_X\, f_c\, T\, A_\mathrm{eq} \tag{15}$$

where T is the tissue-air ratio (TAR), which at the depth of the maximum dose is the backscatter factor, and A_{eq} is a correction for attenuation in the buildup cap, which for 2 MeV and ^{60}Co has a value of 0,985.

2.6 ICRU Report 21 (electrons, 1972)

ICRU (1972) Report 21 for electron dosimetry was the counterpart of ICRU- 14 for photon dosimetry, sharing the thorough treatment of the formalism and data while adding an in-depth study of electron beam energy-related parameters. Stopping powers and their ratios for cavity theory were dealt with in detail, as was the pioneer formulation of mass angular scattering power.

The formulation given for the Bragg-Gray relation, see Eq. (4), had the explicit form

$$\begin{aligned} D_{\text{med}} &= D_{\text{gas}}\, s_{\text{med,gas}}\, p_{\text{med,gas}} = J_{\text{gas}} \left(W_{\text{gas}}/e \right) s_{\text{med,gas}}\, p_{\text{med,gas}} \\ &= \frac{q}{\rho_{\text{gas}} V} \left(W_{\text{gas}}/e \right) s_{\text{med,gas}}\, p_{\text{med,gas}} \end{aligned} \tag{16}$$

where all quantities have already been defined except $p_{\text{med,gas}}$, which is an electron fluence perturbation factor.

For the practical case of measurements made in a water phantom at an electron energy-dependent depth with a chamber having a ^{60}Co or 2 MV x-rays exposure calibration coefficient, the absorbed dose to water was given by

$$\begin{aligned} D_{\text{w}} &= M\, N_X\, C_{\text{E}} \\ C_{\text{E}} &= \left(W_{\text{air}}/e \right) A_{\text{eq}}\, s_{\text{w,air}}\, p_{\text{w,air}} \end{aligned} \tag{17}$$

C_E being the overall conversion coefficient from exposure-to-dose in water, which was tabulated using, as in AAPM-SCRAD (1971), $W_{air} = 33.73\ eV$, $A_{eq} = 0.985$, and $p_{w,air}=1$, together with stopping-power ratios as a function of the electron mean energy and depth in the phantom. The case $p_{w,air} = 1$ corresponded to plane-parallel chambers; fluence perturbation factors for cylindrical ionization chambers were tabulated as a function of the mean energy at depth and the chamber inner radius.

2.7 HPA electron Guide (1971)

Although chronologically it was published one year earlier than ICRU-21, the HPA published “A practical guide to electron dosimetry (5-35 MeV)” (HPA (1971)) that followed almost literally the C_E-formulation and data of the ICRU-21 electron report. Hence, it will not be discussed further.

2.8 NACP (1972) recommendations

The Nordic Association of Clinical Physicists published a protocol innovating the joint treatment of photon and electron dosimetry in a single protocol, NACP (1972); it was based on the ICRU-14 and ICRU-21 reports. Considering the two most commonly used radiation types in the same publication was a trend followed by many other dosimetry protocols.

The measurement equations for both beam modalities were then

$$\begin{aligned} D_\mathrm{w} &= M\,N_X\,C_\lambda \\ D_\mathrm{w} &= M\,N_X\,C_\mathrm{E} \end{aligned} \tag{18}$$

In the case of photons, the C_λ concept was extended to measurement depths other than the classical 5 cm reference depth using experimental data. Perhaps the most important aspect was the pioneer use of an effective point of measurement for the chamber used, so that the values of C_λ became slightly different from those in ICRU-14. An interesting other aspect was the introduction of the ratio of ionization at the depths of 5 and 15 cm, J_5/J_{15} (SSD 100 cm, 10 cm × 10 cm) obtained as an average from multiple clinical accelerators, which plotted as a function of the nominal MV was used to obtain the maximum photon energy. It was not used, however, for dosimetric data as all the available data were in terms of MV, and included a warning for the possibility of electron contamination at 5 cm depth.

For electron beams the energy was evaluated by means of a range analysis, measuring depth-ionization curves that take into account the effective point of measurement of the chamber used. An experimentally derived energy-range relationship was used to obtain the practical range $R\mathrm{p}$, subsequently used to determine the mean energy at depth. This was used to select C_E values at the energy-dependent specific depths using the more general ICRU-21 data table.

2.9 DIN 6800-2 (1980)

German protocols are published in the German language as DIN Norms by the Deutsches Institut für Normung. They were characterized by simplicity and practicality (perhaps not much nowadays), both in the formulation of the measurement equations and in the description of procedures to be followed. It should be noted that the DIN numbering is fixed, so that different versions or updates of norms devoted to ionization chamber dosimetry have all the number 6800-2 (part 1 deals with general aspects); they differ only in their date of publication and slightly in the title. The present protocol, in terms of exposure chamber calibrations, is therefore here referred to as DIN (1980) and in English was entitled *"Procedures in dosimetry: ionisation dosimetry".*

The protocol included the dosimetry of kilovoltage photons, ^{137}Cs and ^{60}Co based on in-air measurements, and in-phantom measurements for photons above 3 MeV and electrons above 1 MeV. Two general equations were given to determine the absorbed dose to a medium from the two measurement procedures; for in-air and in-phantom, respectively, they were

$$D_{\mathrm{m}} = \left[(W_{\mathrm{air}}/e)\,(\mu_{\mathrm{en}}/\rho)_{\mathrm{m,air}}\right] k_{\mathrm{a}}\, N_X\, M$$
$$D_{\mathrm{m}} = \left[(W_{\mathrm{air}}/e)\, s_{\mathrm{m,air}}\right] k_{\mathrm{c}}\, N_X\, M \qquad (19)$$

where the square brackets define coefficients denoted in the protocol by f and g, respectively, tabulated for all the energies involved, k_a and k_c are correction factors for each procedure, and $W_{air} = 33.73$ eV. In particular, k_c had the values 0,98 and 0,95 for graphite-walled and PMMA-walled chambers, respectively. For the present context, in both cases N_X was the exposure calibration coefficient at ^{60}Co, although the protocol used N (applicable also to kV x-rays) and N_{Co}, respectively.

2.10 NCRP Report 69 (photons, 1981)

The recommendations for photon dosimetry by the USA National Council on Radiation Protection and Measurements, NCRP (1981), went one step beyond the AAPM protocols so far, providing a robust theoretical background to the various measurement procedures and equations. Extensive use was made of the correction for the centre of electron production (CEP, see also Eq. (10) given for ICRU-14), the ratio of dose to collision kerma, which was also defined as the ratio of the energy fluence, exposure or collision kerma at two slightly different depths.

Several different situations were considered, now using $W_{air} = 33.85\ J/C$ (ICRU Report 31, 1979), which for the calibration quality of ^{60}Co γ-rays gives the exposure-to-dose coefficient the value 0,873 × 10–2 Gy/R. The situations of clinical interest were:

a. The dose to air and to a medium derived from exposure at the calibration qualities

$$D_{\mathrm{air}} = 0.873 \times 10^{-2}\, \beta_{\mathrm{air}}\, X_{\mathrm{air}}$$
$$D_{\mathrm{med}} = 0.873 \times 10^{-2}\, \beta_{\mathrm{med}}\, A_{\mathrm{eq}}\, X_{\mathrm{air}}\, (\mu_{\mathrm{en}}/\rho)_{\mathrm{med,air}} \qquad (20)$$

where X_{air} is the exposure in air at the point of interest, equal to $M_{air} N_X$, and A_{eq} has been defined earlier as a correction for attenuation in the chamber buildup cap.

b. The dose to water derived from exposure at energies above 600 keV with measurements in water

$$D_{\mathrm{w}} = M_{\mathrm{w}}\, N_X\, C_\lambda$$
$$C_\lambda = 0.873 \times 10^{-2}\, (\beta_{\mathrm{wall}} A_{\mathrm{wall}})_{\lambda_0}\, (s_{\mathrm{w,air}})_\lambda \left[s_{\mathrm{air,wall}}\, (\mu_{\mathrm{en}}/\rho)_{\mathrm{wall,air}}\right]_{\lambda_0} \frac{p_\lambda}{p_{\lambda_0}} \qquad (21)$$

where A_{wall} corrects for attenuation and scatter by the chamber wall and buildup cap at the calibration quality λ_0, and the various p_i are perturbation correction factors of the photon and electron energy fluences by the chamber, chamber stem, central electrode, etc. at the calibration quality and at the higher quality λ.

NCRP-69 discussed most of the recent research and developments leading to different sets of values for the C_λ coefficient. Refinements were described to include in an approximate way the chamber wall material (water-like as PMMA, or air-like as graphite), use or not of the chamber buildup cap during measurements in water, use of new data on spectra-derived mean values of quantities rather than using mean energies, new stopping power ratios and different perturbation factors, and even the classical attenuation factor A_{eq} for ^{60}Co (denoted by $A_{wall,c}$) to become 0,97 (instead of 0,985 as previously); it also considered the effective point of measurement of ionization chambers. These discussions were in some aspects "inspired" by the air-kerma based NACP (1980) protocol, acknowledging that "The most comprehensive recent consideration of the problem appears in a new protocol for electron and photon beams by the Nordic Association of Clinical Physicists. In this document seven factors are recommended to replace C_λ." Despite the availability of new data, NCRP-69 still recommended that values of C_λ previously given in several protocols be continued in use and, estimating that differences were only up to about 2% at some energies, provided the same tabulated data as in HPA (1969). Interesting enough, the report did provide updated values of the exposure- to-dose conversion coefficients for kV x-rays, using $W_{air} = 33.85\ eV$ (ICRU (1979)) and updated values of energy-absorption coefficients.

2.11 AAPM TG-21 protocol (1983)

AAPM (1983) TG-21 was the first AAPM protocol including both high-energy photon and electron beams. It pertained to the new generation of dosimetry protocols initiated by the air-kerma based NACP (1980), to be discussed below, where the C_λ and C_E concepts were abandoned, although still was based on chamber calibrations in terms of exposure at 22 $^\circ$C and 101.33 kPa, and included both a new type of formalism and extensive new dosimetric data. The protocol was applicable to most types of ionization chambers used in the USA.

As in NACP (1980), the formalism was based on an intermediate chamber coefficient calculated by the user from the exposure calibration coefficient N_X, termed cavity-gas calibration factor N_{gas} which, following the work by Almond and Svensson (1977), considered the fraction α of ionization due to electrons from the chamber wall and $(1 - \alpha)$ from the buildup cap. Note the use of "gas" even if practically all chambers for clinical use have an air-filled cavity. It was defined as

$$N_{\text{gas}} = N_X \frac{2.5798 \times 10^{-4} \text{C kg}^{-1} \text{R}^{-1} \, (W_{\text{air}}/e) A_{\text{ion}} A_{\text{wall}} \beta_{\text{wall}}}{\alpha \, s_{\text{wall,gas}} (\mu_{\text{en}}/\rho)_{\text{air,wall}} + (1-\alpha) \, s_{\text{cap,gas}} (\mu_{\text{en}}/\rho)_{\text{air,cap}}} \tag{22}$$

where the meaning of all quantities (values for ^{60}Co) has already been given above except A_{ion}, which is the ion-collection efficiency of the user chamber during the ^{60}Co exposure calibration at the standards laboratory. The updated stopping-power ratios were of the Spencer-Attix type and TG-21 used the symbol $(\bar{L}/\rho)_a$ instead of $s_{a,b}$. Providing N_X in units of R/C, N_{gas} resulted in units of Gy/C (given as rad/C).

Allowed phantom materials were water, polystyrene and PMMA. The absorbed dose to these media was given by a general expression, valid for both clinical photon and electron beams, and related to the dose in the gas (air) of the chamber

$$D_{\text{med}} = M N_{\text{gas}} \, s_{\text{med,gas}} \, P_{\text{ion}} \, P_{\text{repl}} \, P_{\text{wall}} \tag{23}$$

where P_{ion} is the correction for ionization recombination losses in the user's beam (reciprocal of A_{ion}), P_{repl} is the replacement correction for the phantom material replaced by the chamber (called displacement correction factor p_{dis} in other protocols), and P_{wall} accounts for the difference between the chamber wall and the phantom materials; for photons it was given by

$$P_{\text{wall}} = \frac{\alpha \, s_{\text{wall,gas}} (\mu_{\text{en}}/\rho)_{\text{med,wall}} + (1-\alpha) \, s_{\text{med,gas}}}{s_{\text{med,gas}}} \tag{24}$$

which is unity when the chamber wall and the phantom are of the same material, and for electron beams. Expressions and scaling data to derive the absorbed dose to water from the dose to a plastic phantom were provided. For the especial case of ^{60}Co therapy units, TG-21 allowed for in-air calibrations using the procedure described for Eq. (15).

TG-21 also included the use for the first time of an absorbed dose calibration coefficient $N_{D,w}$ (denoted by N_D in the protocol), measured in ^{60}Co with a graphite calorimeter at the USA standards laboratory (NIST, formerly NBS), where the absorbed dose to water in the user's ^{60}Co beam was given by the simple equation

$$D_{\text{w}} = M N_{D,\text{w}} \tag{25}$$

The $N_{D,w}$ procedure would take years to be developed and extended to other beam qualities at standards laboratories worldwide, being later on generalized into absorbed dose to water dosimetry protocols.

It is worth noting that TG-21 is the only dosimetry protocol so far that does not include the corrections for ionic recombination during chamber calibration (A_{ion}) and user's beam measurements (P_{ion}) in what are known as corrections to the reading of an ionization chamber, unlike e.g. a polarity or leakage correction. This is a choice maintained in other AAPM protocols.

2.12 AAPM TG-39 (1994)

AAPM (1994) TG-39 on the calibration and use of plane-parallel ionization chambers for the dosimetry of electron beams was an extension of the TG-21 protocol. The absorbed dose to water at the depth of the maximum ionization z_{max} in both plastic and water phantoms was derived using Eq. (23), which for electrons excludes the P_{wall} perturbation factor.

The most important novelty of the TG-39 protocol was the derivation of an N_{gas} calibration coefficient for plane-parallel chambers, N_{pp} . This was always derived by cross-calibration against a cylindrical chamber of known N_{PP}, given by Eq. (22), with measurements performed (a) in a phantom with an electron beam at the depth of z_{max} using the highest energy available, (b) in a phantom with a ^{60}Co beam at the depth of 5 cm, and (c) in air with a ^{60}Co beam. Methods (a) and (b) were originally the recommendations of NACP (1981). Factors to be applied for five plane-parallel chamber types were provided, as well as scaling factors and formulation for transferring the dose from plastic phantoms to water.

TG-39 referred to N_K chamber calibration coefficients provided by NIST, to be converted to exposure coefficients (see footnote 2.1) using $N_X = 113.7\ N_K$, where the values of g_{air} $= 0{,}0032$ and $(W_{air}/e) = 33.97$ J/C were used.

3. AIR-KERMA BASED PROTOCOLS

During its meeting in 1977, the CCEMRI[2] had as a main question the replacement of standards in terms of exposure by those in terms of air kerma; the recommendation of the meeting was to maintain exposure standards *"and, in case of need, in terms of air kerma using the appropriate conversion factors"*. In 1981 the Committee stated that calibrations of instruments performed in terms of exposure *"may also be expressed in terms of air kerma or water kerma"*. Discussions during the CCEMRI meeting in 1983 pointed out that "exposure is becoming less and less used, being replaced by air kerma and water kerma." It was mentioned that "air kerma can now be realized with better accuracy than exposure for cavity chambers" and some standards laboratories already provided calibrations in terms of both air kerma and exposure. The result of this hesitancy and discussions was that some of the

2 Comité Consultatif pour les Etalons de Mesure des Rayonnements Ionisants (Consultative Committee for Standards of Ionizing Radiation). Since 1997 the CCEMRI was renamed the CCRI, Comité Consultatif des Rayonnements Ionisants (Consultative Committee for Ionizing Radiation). See the reports of the different meetings in https://www.bipm.org/en/committees/cc/ccri/publications.

air kerma-based protocols also included measurement equations in terms of an exposure calibration coefficient.

3.1 NACP (1980, 1981)

The formerly used $C\lambda$ and CE concepts were solely valid for air-equivalent and water-equivalent ionization chamber walls, respectively, and a new procedure for the determination of absorbed dose was put forward in NACP (1980) which became the standard in practically all air kerma-based protocols (and in some NX-based such as AAPM (1983) TG-21). It was based on a user-derived absorbed-dose chamber coefficient $N_{D,air}$ (termed N_D in the protocol) derived from an air kerma calibration N_K in a ^{60}Co γ-ray beam. The absorbed dose to water in high-energy photon and electron beams was subsequently obtained as the product of meter readings, $N_{d,air}$, stopping-power ratios and experimentally derived perturbation factors.

For photon beams, NACP changed its former ratio of ionization at the depths of 5 and 15 cm to the ratio at the depths of 10 and 20 cm, J_{100}/J_{200}, to avoid the potential influence of electron contamination at 5 cm depth. Above 10 MV the reference depth for beam calibration was changed to 10 cm. Mean values of the ratio J_{100}/J_{200} obtained in multiple accelerators were plotted as a function of the nominal MV and used to approximate the maximum photon energy, but dosimetry data were still related to MV values (even if J_{100}/J_{200} was recommended as input data for stopping-power ratios). For electron beams, the most probable energy at the phantom surface $E_{p,0}$ was used to specify a dose distribution while the mean energy at the surface $\bar{E}_0$ was used as reference to dosimetric data. They were obtained with new energy-range relationships using the practical range R_p and the half-value depth R_{50} of depth-dose distributions,

$$\begin{aligned} E_{p,0} &= 0.22 + 1.98 R_p + 0.0025 R_p^2 \\ \bar{E}_0 &= 2.33 R_{50} \\ \bar{E}_z &= \bar{E}_0 (1 - z/R_p) \end{aligned} \tag{26}$$

that were also used by ICRU (1984) Report 35 and other dosimetry protocols. The absorbed-dose chamber coefficient $N_{d,air}$ was defined as the ratio between the mean absorbed dose to air in the chamber cavity $\bar{D}_{air,c}$ and the chamber reading M_c, both at the ^{60}Co calibration quality. Getting $\bar{D}_{air,c}$ is straightforward from the air kerma calibration coefficient so that the expression for $N_{d,air}$[3] became

3 $N_{D,air}$ can also be derived from an exposure calibration coefficient using the exposure kerma relationship, i.e. $N_{D,air} = N_X (W_{air}/e)\, k_{att}\, k_m$, together with the corresponding exposure-to- dose conversion.

$$N_{D,\text{air}} = \frac{\bar{D}_{\text{air,c}}}{M_{\text{c}}} = N_K \left(1 - g_{\text{air}}\right) k_{\text{att}} \, k_{\text{m}} \tag{27}$$

where k_{att} is a correction factor that accounts for attenuation and scatter in the chamber wall and buildup cap and k_m corrects for the lack of air equivalence of the chamber material. It is emphasized that $N_{D,air}$ and the factors k_{att} and k_m are defined solely at the calibration ^{60}Co beam.

In a second step, the Bragg-Gray equation was used for the determination of the absorbed dose at the reference point in water in the absence of the ionization chamber at the user's radiation quality,

$$D_{\text{w,u}} = \bar{D}_{\text{air,u}} \left(s_{\text{w,air}}\right)_{\text{u}} \, p_{\text{u}} \tag{28}$$

where $\bar{D}_{air,u}$ is the mean absorbed dose to air in the cavity of the ionization chamber measured in water at the user's radiation quality, $(s_{w,air})_u$ is the mass stopping-power ratio and p_u is an overall perturbation factor that includes corrections for (a) the lack of water equivalence of the chamber material at the user's radiation quality, (b) the change in fluence due to the insertion of the air cavity, and only for photon beams, for the location of the effective point of measurement of a cylindrical chamber.

Based on the constancy of W_{air} = 33.85 eV at the energies involved, both for photons and electrons, it can be assumed that the chamber coefficient $N_{D,air}$ is also constant, leading to the essential general equation

$$D_{\text{w,u}} = N_{D,\text{air}} \, M_{\text{u}} \left(s_{\text{w,air}}\right)_{\text{u}} \, p_{\text{u}} \tag{29}$$

where M_u is the chamber reading at the user's radiation quality, corrected for temperature, pressure, recombination, humidity, etc.

The NACP (1980) protocol was applicable only to electrons with energy above 10 MeV and a Supplement for the dosimetry of electron beams with mean energies at the phantom surface below 15 MeV was subsequently published, NACP (1981). The Supplement contained also more recent values of water/air stopping- power ratios for electron beams. The most interesting aspect of the Supplement was the introduction of the NACP plane-parallel chamber, detailing procedures for its cross-calibration against a cylindrical chamber of known $N_{D,air}$ in a high-energy electron beam, although a direct calibration in ^{60}Co at the standards laboratory was also recommended. The absorbed dose was derived in this case with Eq. (29) assuming a perturbation factor of unity.

3.2 Revised HPA CoPs (1983, 1985)

The HPA revised its codes of practice for photons (HPA 1983) and for electrons (HPA 1985) in a period of considerable progress in the understanding of concepts related to ionizing dosimetry, even if HPA's CoPs continued to be based on the $C\lambda$ and $C\mathrm{E}$ concepts. It should be noted that, since air kerma and absorbed dose are both expressed in grays, any conversion between the two quantities is dimensionless, that is, $C\lambda$ and $C\mathrm{E}$ have no units and should therefore be called factors. As in earlier CoPs, the revised versions were cooking recipes without theoretical foundations and transparency in the numerical data (to a lesser extent in the CoP for electron dosimetry). As the recommendations for ionization chambers were specific for instruments used in hospitals practically only in the UK, it is questionable that these CoPs were used somewhere else.

For photon beams, while most protocols at that time implemented the formulation developed by Almond and Svensson (1977), the HPA opted for using the slightly different equation by Shiragai (1978). More importantly, as in the UK every radiotherapy department is assumed to have a secondary standard graphite- walled ionization chamber NE-2561, the new $C\lambda$ values were given solely for this specific chamber type; hence, the CoP was not very useful in other parts of the world. The NK-based equation for the absorbed dose to water was

$$D_{\mathrm{w}} = 1.139 M N_K C_\lambda \tag{30}$$

where the meaning of the different quantities has been defined earlier and the factor 1.139 to convert air kerma into absorbed dose to water includes a 0,5% correction for the effect of bremsstrahlung production from secondary electrons for 2 MV x-radiation. The CoP also included the expression for dose determination in medium-energy x-rays, identical to Eq. (30) except for using a factor F (corresponding to a photon detector) instead of $C\lambda$, and a constant 1.145 instead of 1.139.

For electron beams, where the NE-2561 chamber is not recommended, two additional chambers were recommended, both widely available in the UK. These were the Farmer type NE-2571 for electron beams above 10 MeV and the plane- parallel Vinten-631 (denoted as "flat chamber") for low- and high-energy electrons. Both chambers were to be cross-calibrated by the user in ^{60}Co against a NE-2561 secondary standard. Electron dosimetry with the NE-2571 chamber should be made in a water phantom, and in a Perspex or polystyrene phantom with the Vinten-631 chamber. The effective point of measurement $P\mathrm{eff}$ of the Vinten-631 chamber was taken to be at the centre of the inside surface of the front face. For the cylindrical chamber $P\mathrm{eff}$ was situated about two-thirds of the internal radius of the cavity in front of (i.e. nearer the source than) the axis of the chamber.

The absorbed dose to water in an electron beam was obtained using

$$D_{\mathrm{w}} = M N_K^{\mathrm{cross}} C_{\mathrm{E}} \tag{31}$$

where N_{cross} is the cross-calibration coefficient of the chamber used. Values of the factor C_{E} for the two chambers were evaluated following the ICRU-21 equations using $W\mathrm{air}$ = 33.85 eV and radiation interaction data from AAPM TG-21. As C_{E} is dimensionless, the symbol of this factor was changed to C_{E} to indicate a difference with the values in previous CoPs.

An addendum to the electron beam CoP, in the form of "interim additional recommendations" was published years later as IPSM (1992), where the NACP and Markus plane-parallel chambers replaced the previous Vinten model, which went out of commercial production, and $C\mathrm{E}$ values were updated.

3.3 ICRU Report 35 (electrons, 1984)

The ICRU (1984a) Report 35 on electron dosimetry superseded ICRU-21 and was the latest ICRU publication on the field. It was strongly influenced by the NACP (1980, 1981) protocols with regard to energy-range relationships, formalism and certain data, and included a substantial theoretical background, e.g., for the different types of stopping-power ratios (Bragg-Gray, Spencer-Attix, Harder) as well as for measurement techniques. ICRU-35 was developed at a time of major changes in the basic quantities entering into the calculation of stopping powers, and the report provided updated values of water/air stopping-power ratios using the Spencer-Attix formulation and new values for the mean excitation energy, the I-value of water and air, 75.0 eV and 85.7 eV, respectively.

Using the effective point of measurement of ionization chambers, taken as 0,5 r (where r is the radius of the air cavity) in front of the chamber centre for cylindrical chambers and at the front surface of the air cavity for plane-parallel chambers, the absorbed dose to water was determined with the Bragg-Gray relationship

$$D_{\mathrm{w}}(P_{\mathrm{eff}}) = N_{D,\mathrm{air}} M s_{\mathrm{w,air}} p_{\mathrm{w,air}} \tag{32}$$

where, following NACP (1980), $ND\mathrm{,air}$ is the absorbed-dose chamber coefficient giving the dose to air in the chamber cavity expressed in terms of both air kerma and exposure calibration coefficients, see Eq. (27) and footnote 3, and $p\mathrm{w,air}$ are experimentally determined chamber perturbation factors for cylindrical chambers.

3.4 SEFM (1984)

The Spanish dosimetry protocol for high-energy photon and electron beams, SEFM (1984a), was also based on NACP (1980, 1981) and its data, adopting as well data from

AAPM TG-21 and ICRU-35, and extended to the ionization chambers used in Spanish centres. Written in Spanish, it provided excellent pedagogical and detailed descriptions of all the correction and perturbation factors used in the two steps of the formalism.

Defining the absorbed-dose chamber coefficient $N_{d,\mathrm{air}}$ as in Eq. (27) and footnote 3.1, the factors k_m and k_att at the calibration ^{60}Co beam were given by

$$\begin{aligned} k_\mathrm{m} &= \alpha\, s_\mathrm{air,wall} (\mu_\mathrm{en}/\rho)_\mathrm{wall,air} + (1-\alpha) s_\mathrm{air,cap} (\mu_\mathrm{en}/\rho)_\mathrm{cap,air} \\ k_\mathrm{att} &= 1 - \kappa x_\mathrm{t} \end{aligned} \tag{33}$$

where a is the fraction of ionization due to electrons from the chamber wall (see Eq. (22) for TG-21 N_gas), κ is a correction for attenuation and scattering in the chamber wall and buildup cap which depends on the chamber radius and length, and x_t is the mass thickness of the wall plus cap.

The general equation for the absorbed dose to water was expressed as

$$D_\mathrm{w} = M N_{D,\mathrm{air}}\, s_\mathrm{w,air}\, p_\mathrm{fl}\, p_\mathrm{dis}\, p_\mathrm{wall} \tag{34}$$

where p_fl is the fluence perturbation factor, equal to one for photons and for electrons is a function of the chamber radius and $\bar{E}_z$; p_dis is the displacement factor, which for both beam types depends on the chamber radius (alternatively, the factor could be taken as unity and the dose referred to the effective point of measurement); and p_wall is the chamber wall perturbation, equal to one for electrons and for photons is given by

$$p_\mathrm{wall} = \alpha\, (\mu_\mathrm{en}/\rho)_\mathrm{w,wall} s_\mathrm{wall,w} + 1 - \alpha \tag{35}$$

where a is as above but for high-energy photons.

A complementary publication, SEFM (1984b), was made for ^{60}Co measurements in air based on an exposure chamber calibration.

3.5 CFMRI (1985)

The Comité Français Mesure des Rayonnements Ionisants developed a dosimetry protocol for photon and electron beams written in French, CFMRI (1987) which, as the Spanish protocol, was based on the NACP (1980, 1981) and the AAPM TG-21 protocols.

For photon beams the French protocol was pioneer in their proposal for specifying the beam quality index as *"the ratio I_{20}/I_{10} of the relative ionizations measured respectively at depths 20 and 10 cm of water in non-diverging conditions ($SSD = \infty$) with a 10×10 cm ^{2} field* *size at the detector distance"*. This proposal coincides with what later on was termed tissue-phantom ratio at depths of 20 and 10 cm, TPR $_{20,10,}$ adopted by most dosimetry protocols for the beam quality specification of photon beams. Other than this interesting novelty, the CFMRI protocol followed very closely the formalism, data and recommendations of NACP (1980, 1981).

3.6 IAEA TRS-277 (1987)

Following the new generation of N_k-based national dosimetry protocols emerged in the early 1980s, the international Code of Practice TRS-277 was published by IAEA (1987). It established a quantum leap on the IAEA's role to harmonize international radiotherapy dosimetry based on scientific development as, since the release of the old IAEA (1970) TRS-110 manual, no other dosimetry recommendations had been published by the Agency. TRS-277 was based on the dosimetry protocols presented above within the N_K-group, adopting the best of each protocol, avoiding mistakes and inconsistencies, and providing a general balance among the published protocols.

The beam quality for photon beams was specified by TPR $_{20,10,}$ the tissue- phantom ratio at the depths of 20 and 10 cm in water, for a source-to-chamber distance (SCD) of 100 cm and a field size of 10 cm×10 cm at the SCD. For electron beams it was specified by the most probable energy E_p and the mean energy at the surface E_0, related to the practical range R_p and the half-value depth R_{50}, respectively.

TRS-277 emphasized the importance of maintaining overall consistency of data along the dosimetric chain, and all the numerical values for constants followed the recommendations of CCEMRI(I) (1985b), namely stopping powers for electrons from ICRU Report 37 (1984b), W_{air} = 33.97 eV from CCEMRI(I) (1985a) and Boutillon and Perroche-Roux (1987), g_{air} values from Boutillon (1985), and mass energy-absorption coefficients from Hubbell (1982). Additionally, it included new and consistent dosimetric data specifically developed for the CoP, such as water/air stopping-power ratios for photon beams (Andreo and Brahme, 1986) and chamber- wall perturbation factors (Andreo et al., 1986), both correlated with the photon beam quality index TPR 20,10. Of special interest was the evaluation of uncertainties according to Giacomo (1981) and Kaarls (1981), which later on became the worldwide used GUM, the *"Guide to the expression of Uncertainty in Measurement",* see ISO (1993) and JCGM (2008).

TRS-277 was based on the NACP (1980) formalism, assigning the dose to water to the position of the effective point of measurement of the chamber, and included detailed equations for all the correction and perturbation factors used in the two steps of the formalism, which for convenience are duplicated here

$$N_{D,\mathrm{air}} = N_K(1-g_{\mathrm{air}})\,k_{\mathrm{att}}\,k_{\mathrm{m}}$$
$$D_{\mathrm{w}}(P_{\mathrm{eff}}) = N_{D,\mathrm{air}}\,M_{\mathrm{u}}\,(s_{\mathrm{w,air}})_{\mathrm{u}}\,p_{\mathrm{u}} \tag{36}$$

where “u” stands for the user beam and the perturbation factor p_{u} corrects for (a) the different properties in electron production and scattering in the chamber wall and corresponding volume of water; and (b) the difference in electron scattering in the air cavity and in the water which is ’replaced’ by the air cavity.

The new data in TRS-277 were subsequently included in practically all the N_K dosimetry protocols developed since 1986. The CoP became the “standard protocol” against which others were compared. It was widely disseminated and adopted by the medical physics community in all regions and translated into different languages. All the worksheets were made available as Excel files, facilitating the worldwide implementation of the CoP.

A second edition of TRS-277 updating some of its data, mostly related to the dosimetry of kV x-rays, was published in 1997.

3.7 IAEA TRS-381 (1997)

Most national and international dosimetry protocols recognized the advantages of plane-parallel ionization chambers, explicitly for electron beams and especially for low-energy electrons (below 10 MeV). Although this was acknowledged in TRS-277, the calibration and use of these chambers were not fully developed. The IAEA (1997) TRS-381 complements and extends TRS-277. The CoP (a) describes options to calibrate plane-parallel chambers, against air kerma or absorbed dose to water standards at ^{60}Co, in order to obtain N_{pp} , the absorbed- dose-to-air chamber coefficient, or N_{pp} , the chamber absorbed-dose-to-water calibration coefficient, respectively; (b) describes the use of these chambers to calibrate electron beams, as well as relative dose measurements for photon and electron beams; and (c) updates some of the data and concepts in TRS-277. As TRS-381 includes both modalities for chamber calibration, it constitutes a bridge between air kerma and absorbed dose to water dosimetry protocols. It became a textbook on plane-parallel ionization chambers which, unlike previous CoPs, included a proper Code of Practice in a separate chapter containing all the necessary equations and data.

The main recommendation to determine N_{pp} was an experimental determination by cross-calibration in a high-energy electron beam against a reference ionization chamber having a calibration coefficient N_K and a known chamber coefficient $N_{D,\mathrm{air}}$. Note that to avoid confusion between the two chamber calibration modalities, TRS-381 introduced the symbol $N_{D,\mathrm{air}}$ for what so far had been termed N_D. It also introduced the central-electrode correction factor at the chamber calibration k_{cel}, so that the absorbed-dose-to-air coefficient became defined as

$$N_{D,\text{air}} = N_K(1 - g_{\text{air}})\, k_{\text{att}}\, k_{\text{m}} k_{\text{cel}} \tag{37}$$

Other options to obtain N_{pp} were based on using ^{60}Co radiation in a phantom or in air.

The air kerma and absorbed dose to water formalisms were introduced as follows:

(a) For the $N_K - N_{D,\text{air}}$ modality, the absorbed dose to water in the user's beam of quality **Q,** when the effective point of measurement of the ionization chamber is positioned at the reference depth was given by

$$\begin{aligned} D_{\text{w},Q}\,(P_{\text{eff}}) &= M_Q\, N_{D,\text{air}}\, (s_{\text{w,air}})_Q\, p_Q \\ p_Q &= (p_{\text{wall}}\, p_{\text{cav}}\, p_{\text{cel}})_Q \end{aligned} \tag{38}$$

where the factors p_{wall} and p_{cav} correct for the lack of phantom equivalence of the chamber wall and for the perturbation of the electron fluence due to differences in the scattering properties between the air cavity and phantom, respectively. The factor p_{cel} corrects for the effect of the central electrode of the chamber during in-phantom measurements in the user's beam.

(b) For the $N_{D,\text{w}}$ modality, the absorbed dose to water at the reference point of the chamber was given by

$$D_{\text{w},Q} = M_Q N_{D,\text{w},Q_0} k_Q \tag{39}$$

where Q_0 is the calibration quality, in this case ^{60}Co, and k_Q is the beam quality correction factor, which corrects the calibration coefficient N_{D,w,Q_0} for the difference between the reference beam quality Q_0 and the actual quality being used, Q.

The factor k_Q should ideally be determined experimentally at the same quality as the user's beam, although this is seldom achievable. When no experimental data are available a general expression for k_Q was developed by Andreo (1992) having the form

$$k_Q = \frac{(s_{\text{w,air}})_Q}{(s_{\text{w,air}})_{Q_0}} \frac{(W_{\text{air}})_Q}{(W_{\text{air}})_{Q_0}} \frac{p_Q}{p_{Q_0}} \tag{40}$$

which for photons and electrons, where $(W_{\text{air}})_Q = (W_{\text{air}})_{Q_0}$, is simplified to the equation given by Hohlfeld (1988) and other $N_{D,\text{w}}$ protocols that will be discussed below. Equations ((39)) and ((40)) are used in practically all absorbed-dose-to-water protocols.

3.8 Other air-kerma protocols

Following the publication of IAEA TRS-277 and TRS-381, some national protocols were issued that included the updated $N_{D,air}$ formalism and data of the IAEA CoPs; some were even published months ahead of the IAEA publications because drafts had been widely distributed. These protocols were in some cases claimed to be “adapted to the idiosyncrasy of the country” but the reality is that they added little science or development to the field. In some cases, there were simplifications combining several correction and conversion factors for a given chamber, although at the cost of making the protocol less flexible. Some of these protocols were the Netherlands CoPs for photons, NCS-2 (1986), and for electrons, NCS-5 (1989); the Swiss recommendations for the dosimetry of photon and electron beams, SSRMP-6 (1986); a supplement to the Spanish protocol, SEFM (1987); the Italian protocol, AIFB (1988); and the British IPEMB (1996) code of practice for electron dosimetry.

4. ABSORBED-DOSE-TO-WATER PROTOCOLS

The calibration of ionization chambers in terms of absorbed dose to water, $N_{D,w}$, was proposed by Reich (1979), from the PTB, and it took almost 10 years to be finally recommended by the CCEMRI(I) (1988) to the Primary Standards Dosimetry Laboratories (PSDLs). A kind of race followed for the laboratories to develop metrology standards in terms of absorbed dose to water and implement $N_{D,w}$ calibrations at different beam qualities, initiated by the German PTB, see Hohlfeld (1988), using ^{60}Co as reference quality, and the British NPL, see Burns et al. (1988), using high-energy photons between 4 MV and 19 MV. Thereafter other PSDLs followed, starting the "modern age" of absorbed-dose-to-water dosimetry protocols and $N_{D,w}$ chamber calibrations became widely used.

4.1 IPSM (photons, 1990)

NPL was the first standards laboratory to set up a calibration service for megavoltage photon beams in terms of absorbed dose to water based on graphite calorimetry. It was applicable only to the secondary standard graphite-walled ionization chamber NE-2561 for ^{60}Co and 4-19 MV photon beams.

The formalism in the IPSM (1990) protocol, issued by the UK Institute of Physical Science in Medicine, was extremely simple: the absorbed dose to water at the position of the centre of the chamber when the chamber and water-proof sheath are replaced by water was given by

$$D_w = M N_{D,w,Q} \tag{41}$$

where the chamber reading M is corrected to 20 ∘C, 101.325 kPa, relative humidity of 50% and for ion recombination, and $N_{D,w,Q}$ is the NPL chamber calibration coefficient for an specific beam quality Q that converts the corrected reading to absorbed dose to water (denoted by N_D in the protocol). $N_{D,w,Q}$ was given in terms of the beam quality index TPR 20,10 but, strange enough, the NPL relation between MV and the beam quality index for clinical beams was taken from a Figure in AAPM TG-21 (1983), instead of being measured for the NPL beams.

A cross-calibration in water or in a PMMA phantom was recommended for routine measurements with a field chamber, noting that Farmer-type chambers with wall materials of A-150 plastic, graphite, Tufnol, aluminium or PMMA showed no significant differences for the ratio of responses in PMMA and water phantoms for ^{60}Co and photon beams up to 25 MV.

4.2 DIN 6800-2 (1997, 2008)

Already described by Hohlfeld (1988) but published much later, DIN (1997) was, together with IAEA TRS-381, the pioneer absorbed-dose-to-water protocol using ^{60}Co as the reference beam quality. It was developed for the dosimetry of photons with energies above 100 keV and electrons up to 50 MeV, and was published in German.

The absorbed dose to water at the position of the chamber effective point of measurement was given by

$$D_w(P_{eff}) = k N_{D,w,Co} M \tag{42}$$

where k was the product of detailed corrections for influence quantities, which for photon and electron beams were, respectively, given by

$$\begin{aligned} k &= k_Q\, k_\rho\, k_r\, k_S\, k_P\, k_T\, k_F\, k_z \\ k &= k_E\, k_\rho\, k_r\, k_S\, k_P\, k_T \end{aligned} \tag{43}$$

kQ and kE were the beam quality correction factors that correct the ^{60}Co calibration coefficient ND,w,Co (written as N) for the difference between ^{60}Co and the actual quality being used, and the remaining ki were corrections to the chamber reading for pressure and temperature, ion recombination, polarity, field size, depth in the phantom etc, which were considered in great detail. In addition to consider kQ and kE as one more type of influence quantity correction, an interesting aspect was their splitting into two separate components, one for the quotient of stopping-power ratios, which depends only on energy and particle type, and another for the perturbation factors, which additionally depends on the chamber type used. For example,

$$k_Q = k'_Q\, k''_Q = \frac{(s_{w,air})_Q}{(s_{w,air})_{Co}}\ \frac{p_Q}{p_{Co}} \tag{44}$$

(compare with Eq. (40)). Beam qualities were expressed in term of TPR 20,10 and R50 for photon and electron beams, respectively. In general, DIN (1997) shared a considerable amount of data with IAEA TRS-277 and TRS-381, and also included some own data fits especially for perturbation effects in electron beams.

The updated version DIN (2008) did not change practically the formalism and implemented some details and data from the IAEA TRS-398 (2000) Code of Practice. For example, it maintained the splitting of the beam quality factors into two separate components, now providing a second component with detailed perturbation factors, which for the case of electrons and a cylindrical chamber had the form

$$k''_E = \frac{(p_{\text{wall}}\, p_{\text{cav}}\, p_{\text{cel}}\, p_\Delta)_{R_{50}}}{(p_{\text{wall}}\, p_{\text{cav}}\, p_{\text{cel}}\, p_\Delta)_{\text{Co}}} \tag{45}$$

p_Δ being the displacement factor, called p_{dis} throughout this review, and the remaining factors have the same meaning as in Eq. (38).

A revision of DIN 6800-2 is currently under development where the photon beam quality factors will be given as a semi-empirical function fitting k_Q data from different sources, mostly Monte Carlo but also experimental and theoretical (from IAEA TRS-398). For electrons, beam quality factors based on Monte Carlo calculations will be given as semi-empirical functions for cylindrical and plane- parallel chambers, providing coefficients for some chambers.

4.3 AAPM TG-51 (1999)

The AAPM (1999) TG-51 absorbed-dose-to-water protocol replaced the old exposure-based AAPM (1983) TG-21. With some exceptions, it basically followed the DIN 6800-2 formalism presented by Hohlfeld (1988) and the IAEA TRS-381 (1997) CoP, updating the dosimetric data when available, and was applicable to photon beams between ^{60}Co and 50 MV and electron beams between 4 and 50 MeV.

A novelty was that the beam quality for photon beams was specified by %dd(10)x, the photon component of the depth-dose at 10 cm depth in a 10×10 cm 2 field on the surface of a water phantom at an SSD of 100 cm. Note that TG-51 is the only protocol worldwide specifying megavoltage photon beam quality by %dd(10)x. For electron beams the beam quality was specified by R_{50}, the half-value depth. Reference dosimetry was performed in a water phantom using reference depths of 10 cm for photons and 0,6 R_{50} – 0,1 cm for electron beams.

For a beam of quality Q, the absorbed dose to water at the point of measurement of the ion chamber at the reference depth was obtained using

$$D_{\text{w}}^{Q} = M\, N_{D,\text{w}}^{^{60}\text{Co}}\, k_Q \tag{46}$$

where, as in other protocols, M is the chamber reading corrected for pressure (101.33 kPa), temperature (22 ∘C in AAPM protocols), polarity and ion recombination, $N_{D,w}^{^{60}Co}$ is the absorbed dose to water chamber calibration coefficient in ^{60}Co and k_Q is the beam quality factor which converts the ^{60}Co calibration coefficient to the coefficient for a beam of quality Q.

For photon beams k_Q was calculated for a large number of ionization chambers according to the well-established equation,

$$k_Q = \frac{(s_{\text{w,air}})_Q}{(s_{\text{w,air}})_{\text{Co}}} \frac{P_Q}{P_{\text{Co}}} \tag{47}$$

where the perturbation factors were expressed as the product $P_{\text{wall}} P_{\text{fl}} P^Q_{\text{gr}} P_{\text{cel}}$ (note the use of capital P's), with P_{fl} being the fluence perturbation correction factor, which coincides with the p_{cav} of Eq. (38), and P^Q_{gr} , the gradient correction, which coincides with the displacement correction factor p_{dis} used throughout this review.

For electron beams k_Q was written in terms of separate components

$$k_Q = P^Q_{\text{gr}} k_{R_{50}} = P^Q_{\text{gr}} k_{\text{ecal}} k'_{R_{50}} \tag{48}$$

where P^Q_{gr} is the gradient correction (equal to one for plane-parallel chambers), k_{ecal} converts N^{60}Co into an electron coefficient $N_{Q\text{ecal}}$ for a selected beam quality Q_{ecal}, taken as R_{50}= 7.5 cm for the protocol values of k_{ecal}, and k'_{R50} converts $N_{Q\text{ecal}}$ into N_Q for any electron beam quality. The factor k_{ecal} is fixed for a given chamber type and $k'_{R_{50}}$ is calculated using an expression similar to Eq. (47) but with electron beam qualities in the numerator and denominator and excluding P^Q_{gr} . The latter was given in the protocol as analytical expressions in terms of R_{50} for cylindrical (Farmer type) and plane-parallel chambers.

An addendum to TG-51 has been published for the dosimetry of high-energy photon beams, AAPM (2014), mostly based on Monte Carlo calculated k_Q factors.

4.4 IAEA TRS-398 (2000)

The IAEA (2000) TRS-398 Code of Practice was developed in parallel with the AAPM TG-51 (sharing one of the working group members), but owing to administrative reasons it took longer to get published. This was the first (and only) CoP ever including all radiation modalities from low-energy kV x-rays to protons and heavy ions, and had an enormous scientific development to produce data for all beam types (except kV x-rays).

TRS-398 formalism followed very closely that of TRS-381 (1997) described by Eq. (39) with a minor modification in the symbol for the beam quality factor, which became generalized to $k_{Q,Q0}$, where Q_0 is the reference beam quality used for chamber calibration, which could be any of the radiation modalities covered by TRS- 398. The absorbed dose to water at the reference depth, where the reference point of an ionization chamber is placed in a water phantom irradiated by a beam of quality Q, was given by

$$D_{\text{w},Q} = M_Q N_{D,\text{w},Q_0} k_{Q,Q_0} \tag{49}$$

and $k_{Q,Q}$ is simplified to k_Q when Q_0 is a ^{60}Co beam. There was, additionally, another major difference with the DIN and TG-51 protocols, as the first option for k_{Q,Q_0} was to be determined experimentally as a ratio of calibration coefficients measured at the Primary Standards Laboratory

$$k_{Q,Q_0} = \frac{N_{D,\mathrm{w},Q}}{N_{D,\mathrm{w},Q_0}} = \frac{D_{\mathrm{w},Q}/M_Q}{D_{\mathrm{w},Q_0}/M_{Q_0}} \tag{50}$$

and only if measured k_Q values were not available, values calculated according to Eq. (40)

$$k_{Q,Q_0} = \frac{(s_{\mathrm{w,air}})_Q}{(s_{\mathrm{w,air}})_{Q_0}} \frac{(W_{\mathrm{air}})_Q}{(W_{\mathrm{air}})_{Q_0}} \frac{p_Q}{p_{Q_0}} \tag{51}$$

would be used, which for photon and electron beams, where $(W_{air})_Q = (W_{air})_{Q_0}$, was simplified to

$$k_{Q,Q_0} = \frac{(s_{\mathrm{w,air}})_Q}{(s_{\mathrm{w,air}})_{Q_0}} \frac{p_Q}{p_{Q_0}} \tag{52}$$

where all the symbols have been described before.

The beam quality for photon beams was specified, as in most dosimetry protocols, by TPR $_{20,10}$. For electron beams it was specified by R_{50}, the half-value depth. Reference dosimetry was performed in a water phantom using reference depths of 10 cm for photons and 0,6 R_{50} – 0,1 cm for electron beams. Emphasis was given to the cross-calibration of chambers in a high-energy electron beam, resulting in a beam quality correction factor $k_{Q_{\mathrm{cross}},Q_0}$; its use was simplified introducing a fictitious intermediate beam quality Q_{int} with R_{50} = 7.5 cm and tables provided calculated values of $k_{Q,Q_{\mathrm{int}}}$ for various chamber types calibrated in electron beams (in addition to k_Q values for chambers calibrated in ^{60}Co). Note the agreement of several specifications for electron beams with those of TG-51, though using different symbols.

TRS-398 was written as a collection of independent CoPs including detailed procedures and worksheets for the different radiation modalities so that a reader could determine the reference absorbed dose to water for a given modality using solely the appropriate chapter. It also included four appendices on different topics, and the one dealing with the calculations of k_{Q,Q_0} and its uncertainty received special attention. The expression of uncertainties followed very closely that in TRS-277 based on the GUM, ISO (1993) and JCGM (2008).

A second edition of TRS-398 is currently under development, based on the update of key data given by ICRU (2016) Report 90 and on experimental and Monte Carlo calculated dosimetric data published since the first edition. An interesting aspect is that when the availability of data allows, mean values derived from the statistical analysis of multi-author produced consensus data will be recommended, see e.g. Andreo et al. (2020).

4.5 ICRU Report 64 (2001)

After many years since ICRU-14 (1969), the ICRU released a report on photon dosimetry, ICRU (2001) Report 64. Its introduction recalled that "*ICRU-14 recommended that standards laboratories should develop absorbed-dose-to-water standards, preferably calorimetric standards, in order to provide calibration coefficients in terms of absorbed dose to water for radiotherapy purposes".* Hence, ICRU-64 dealt with the dosimetry of high-energy photon beams based on standards of absorbed dose to water. It described in detail the different methods for fundamental dose measurements, namely calorimetry, ionometry and chemical dosimetry, with a description of the primary absorbed dose standards in most Primary Standards Laboratories.

The formalism in ICRU-64 is identical to that of IAEA TRS-398, and so are the symbols used. The report includes a detailed and illustrative section on the "Relation to dosimetry procedures based on air-kerma calibrations", as well as a comprehensive Appendix on "Perturbation effects for ionisation chambers in photon beams".

4.6 IPEM (electrons, 2003)

This code of practice, issued by the UK Institute of Physics and Engineering in Medicine, IPEM (2003), was based on the absorbed dose to water calibration service for electron beams provided by the NPL and applies to electron beams with initial energy between 4 and 25 MeV. The $N_{D,w}$ chamber calibration coefficients are traceable to a graphite calorimetric primary standard, at specified reference depths over a range of electron energies up to approximately 20 MeV.

As in AAPM TG-51 and IAEA TRS-398, electron beam quality was specified in terms of R_{50}. The reference depth for chamber calibration at the NPL and also for calibration measurements of clinical beams was 0,6 R_{50} – 0,1 cm in water. Designated chambers were graphite-walled Farmer-type cylindrical chambers and the NACP- and Roos-type plane-parallel chambers.

For a given electron beam quality, the absorbed dose to water at the position of the effective point of measurement of the chamber at the reference depth, when the chamber is replaced with water, was simply given by

$$D_w(P_{eff}) = M N_{D,w} \quad (53)$$

which parallels Eq. (41) for the photon protocol IPSM (1990). Specified as $N_{D,w}(R_{50})$, the calibration coefficient was to be interpolated from the data given in the chamber calibration certificate to obtain the appropriate coefficient for the R_{50} value of the clinical beam under consideration.

4.7 Other absorbed-dose-to-water protocols

The Swiss Society of Radiobiology and Medical Physics issued recommendations for the dosimetry of photon beams, SSRMP-08 (2000) revised in 2018, and electron beams, SSRMP-10 (2002) revised in 2019. Both followed IAEA TRS-398 with regard to using experimental absorbed dose to water calibration coefficients for the different beam qualities, $N_{D,w,Q}$, measured at the Swiss standards laboratory. The photon protocol provided the experimental k_Q factors in the form of a semi-empirical function. For electrons, no k_Q factors were used and direct $N_{D,w,Q}$ calibration coefficients for the clinical R_{50} were obtained by interpolation from the measured data given in the chamber calibration certificate. In a way, these protocols were similar to the IPSM and IPEM discussed above.

The Code of Practice of the Netherlands Commission on Radiation Dosimetry for the dosimetry of high-energy photon and electron beams, NCS-18 (2008), was based on absorbed dose to water standards for ^{60}Co. It followed closely IAEA TRS- 398 and AAM TG-51, particularly TRS-398. For photon beams the beam quality was specified as TPR 20,10, and k_Q values were given as a semi-empirical function fitting own experimental data with coefficients for four graphite-walled chambers. For electron beams the beam quality was specified as R_{50}; k_Q theoretical values were given by another analytical function with coefficients for Farmer-type and two plane- parallel chambers. A revision, mostly a corrigendum, was published in 2012.

REFERENCES

AAPM-SCRAD 1966 American Association of Physicists in Medicine (Sub-Committee on Radiation Dosimetry) Protocol for the dosimetry of high energy electrons Phys. Med. Biol. 11 505-520

AAPM-SCRAD 1971 American Association of Physicists in Medicine (Sub-Committee on Radiation Dosimetry) Protocol for the dosimetry of X and gamma ray beams with maximum energies between 0,6 and 50 MeV Phys. Med. Biol. 16 379-396

AAPM 1983 American Association of Physicists in Medicine. A protocol for the determination of absorbed dose from high-energy photon and electron beams (AAPM TG-21) Med. Phys. 10 741- 771

AAPM 1994 American Association of Physicists in Medicine, The calibration and use of plane- parallel ionization chambers for dosimetry of electron beams: An extension of the 1983 AAPM protocol (AAPM TG-39) Med. Phys. 21 1251-1260

AAPM 1999 American Association of Physicists in Medicine AAPM's TG-51 protocol for clinical reference dosimetry of high-energy photon and electron beams Med. Phys. 26 1847-1870

AAPM 2014 Addendum to the AAPM's TG-51 protocol for clinical reference dosimetry of high- energy photon beams Med. Phys. 41 041501 1-20

AIFB 1988 Associazione Italiana di Fisica Biomedica. Protocollo per la dosimetria di base nella radiote-rapia con fasci di fotoni ed elettroni con E max fra 1 e 40 MeV Fisica Biomedica Vol VI(2) Almond P R and Svensson H 1977 Ionization Chamber Dosimetry for Photon and Electron Beams Acta Radiol. Ther. Phys. Biol.. 16 177-186

Andreo P 1992 Absorbed dose beam quality factors for the dosimetry of high-energy photon beams Phys. Med. Biol. 37 2189-2211

Andreo P and Brahme A 1986 Stopping power data for high-energy photon beams Phys. Med. Biol. 31 839-858

Andreo P, Burns D T, Kapsch R P, McEwen M, Vatnitsky S et al 2020 Determination of consensus k Qvalues for megavoltage photon beams for the update of IAEA TRS-398 Phys. Med. Biol. 65 095011

Andreo P, Burns D T, Nahum A E, Seuntjens J and Attix F H 2017 Fundamentals of Ionizing Radiation Dosimetry (Weinheim: Wiley-VCH)

Andreo P, Nahum A and Brahme A 1986 Chamber-dependent wall correction factors in dosimetry Phys. Med. Biol. 31 1189-1199

Boutillon M 1985 Comité Consultatif des les Etalons de Mesure des Rayonnements Ionisants (Section I): Values of g in air for BIPM radiation qualities Report CCEMRI(I) 85-18 (Sèvres, FRA: Bureau International des Poids et Mesures)

Boutillon M and Perroche-Roux A M 1987 Re-evaluation of the W value for electrons in dry air Phys. Med. Biol. 32 213-219

Burns J E, Dale J W G, Dusautoy A R, Owen B and Pritchard O 1988 New calibration service for high-energy X-irradiation at NPL Dosimetry in Radiotherapy vol 2 (Proc. Conf. Vienna, 1987) (IAEA, Vienna) pp 125-132 CCEMRI(I) 1985a Comité Consultatif des les Etalons de Mesure des Rayonnements Ionisants (Section I): Effect of a change of stopping-power values on the W value recommended by ICRU for electrons in dry air Report CCEMRI(I) 85-8 (Sèvres, FRA: Bureau International des Poids et Mesures)

CCEMRI(I) 1985b Comité Consultatif des les Etalons de Mesure des Rayonnements Ionisants (Section I): Report to the Comite International des Poids et Mesures (S C Ellis, Rapporteur) 8th Meeting CCEMRI(I) (Sèvres, FRA: Bureau International des Poids et Mesures)

CCEMRI(I) 1988 Comité Consultatif des les Etalons de Mesure des Rayonnements Ionisants (Section I), . Report to the Comite International des Poids et Mesures (N J Hargrave, Rapporteur) 9th Meeting CCEMRI(I) (Sèvres, FRA: Bureau International des Poids et Mesures)

CFMRI 1987 Recommandations pour la mesure de la dose absorbée en radiothérapie dans les faisceaux de photons et d'électrons d'énergie comprise entre 1 MeV et 51 MeV Report no 2 (Paris: Comité Français Mesure des Rayonnements Ionisants,)

DIN 1980 Dosismessverfahren in der radiologischen Technik - Teil 2: Ionisationsdosimetrie Norm

DIN 6800-2 (Berlin: Deutsches Institut für Normung)

DIN 1997 Dosismessverfahren nach der Sondenmethode für Photonen- und Elektronenstrahlung - Teil 2: Ionisationsdosimetrie Norm DIN 6800-2 (Berlin: Deutsches Institut für Normung)

DIN 2008 Dosismessverfahren nach der Sondenmethode fur Photonen- und Elektronenstrahlung - Teil 2: Dosimetrie hochenergetischer Photonen- und Elektronenstrahlung mit Ionisationskammern Norm DIN 6800-2 (Berlin: Deutsches Institut für Normung)

Giacomo P 1981 News from the BIPM Metrologia 17 73-74

Hohlfeld K 1988 The standard DIN 6800: Procedures for absorbed dose determination in radiology by the ionization method Dosimetry in Radiotherapy vol 1 (Proc. Conf. Vienna, 1987) (IAEA, Vienna) pp 13-22

HPA 1960 Hospital Physicists' Association. A code of practice for x-ray measurements Brit. J. Radiol. 33 55-59

HPA 1964 Hospital Physicists' Association. A code of practice for the dosimetry of 2 to 8 MV X-Ray and Caesium-137 and Cobalt-60 γ-ray beams Phys. Med. Biol. 9 457-463

HPA 1969 Hospital Physicists' Association. A code of practice for the dosimetry of 2 to 35 MV X- Ray and Cs-137 and Co-60 gamma ray beams Phys. Med. Biol. 14 1-8

HPA 1971 A practical guide to electron dosimetry (5-35 MeV). Report Series No. 4 (London: Hospital Physicists' Association)

HPA 1983 Hospital Physicists' Association. Revised Code of Practice for the dosimetry of 2 to 25 MV x-ray, and of caesium-137 and cobalt-60 gamma-ray beams Phys. Med. Biol. 28 1097-1104

HPA 1985 Hospital Physicists' Association. Code of practice for electron beam dosimetry in radiotherapy Phys. Med. Biol. 30 1169-1194

Hubbell J H 1982 Photon Mass Attenuation and Energy-Absorption Coefficients from 1 keV to 21 MeV Int. J. Appl. Radiat. Isot. 33 1269-1290

IAEA 1970 Manual of Dosimetry in Radiotherapy Technical Report Series no. 110 (Vienna: International Atomic Energy Agency)

IAEA 1987 Absorbed dose determination in photon and electron beams: An International Code of Practice IAEA Technical Reports Series no. 277, 2nd ed in 1997 (Vienna: International Atomic Energy Agency)
IAEA 1997 The use of plane-parallel ionization chambers in high-energy electron and photon beams. An International Code of Practice for dosimetry IAEA Technical Reports Series no.381 (Vienna: International Atomic Energy Agency)

IAEA 2000 Absorbed dose determination in external beam radiotherapy: An International Code of Practice for dosimetry based on standards of absorbed dose to water IAEA Technical Reports Series no. 398 (Vienna: International Atomic Energy Agency)

ICRU 1962 Physical aspects of irradiation ICRU Report 10b (Bethesda, MD: International Commission on Radiation Units and Measurements)

ICRU 1969 Radiation Dosimetry: X rays and gamma rays with maximum photon energies between 0,6 and 50 MeV ICRU Report 14 (Bethesda, MD: International Commission on Radiation Units and Measurements)

ICRU 1972 Radiation dosimetry: Electrons with initial energies between 1 and 50 MeV ICRU Report 21 (Bethesda, MD: International Commission on Radiation Units and Measurements)

ICRU 1979 Average Energy Required to Produce an Ion Pair ICRU Report 31 (Bethesda, MD: International Commission on Radiation Units and Measurements)

ICRU 1984a Radiation Dosimetry: Electron beams with energies between 1 and 50 MeV ICRU Report 35 (Bethesda, MD: International Commission on Radiation Units and Measurements)
ICRU 1984b Stopping Powers for Electrons and Positrons ICRU Report 37 (Bethesda, MD: International Commission on Radiation Units and Measurements)

ICRU 2001 Dosimetry of high-energy photon beams based on standards of absorbed dose to water ICRU Report 64 (Bethesda, MD: International Commission on Radiation Units and Measurements) ICRU 2016 Key data for Ionizing Radiation Dosimetry: Measurement Standards and Applications ICRU Report 90 (Bethesda, MD: International Commission on Radiation Units and Measurements)

IPEM 2003 Institute of Physics and Engineering in Medicine: The IPEM code of practice for electron dosimetry for radiotherapy beams of initial energy from 4 to 25 MeV based on an absorbed dose to water calibration Phys. Med. Biol. 48 2929-2970

IPEMB 1996 Institution of Physics and Engineering in Medicine and Biology: The IPEMB code of practice for electron beam dosimetry for radiotherapy beams of initial energy from 2 to 50 MeV based on an air kerma calibration Phys. Med. Biol. 41 2557-2603

IPSM 1990 Institute of Physical Science in Medicine: Code of Practice for high-energy photon therapy dosimetry based on the NPL absorbed dose calibration service Phys. Med. Biol. 35 1355- 1360

IPSM 1992 Institute of Physical Science in Medicine: Addendum to the code of practice for electron beam dosimetry in radiotherapy (1985): interim additional recommendations Phys. Med. Biol. 37 1477-1483

ISO 1993 Guide to the expression of uncertainty in measurement (Geneva: International Organization for Standardization) [Published by ISO in the name of BIPM, IEC, IFCC, IUPAC, IUPAP and OIML]

JCGM 2008 Joint Committee for Guides in Metrology: Evaluation of measurement data - Guide to the expression of uncertainty in measurement Report JCGM 100:2008 (Sèvres, FRA: Bureau International des Poids et Mesures)

Kaarls R 1981 Rapport du groupe de travail sur l'expression des incertitudes au CIPM BIPM Proc.- Verb. Com. Int. Poids et Mesures 49 A1-A12

NACP 1972 Nordic Association of Clinical Physics, Procedures in radiation therapy dosimetry with 5 to 50 MeV electrons and roentgen and gamma rays with maximum energies between 1 and 50 MeV Acta Radiol. Ther. Phys. Biol.. 11 603-624

NACP 1980 Nordic Association of Clinical Physics, Procedures in external radiation therapy dosimetry with electron and photon beams with maximum energies between 1 and 51 MeV Acta Radiol. Oncol. 19 55-79

NACP 1981 Nordic Association of Clinical Physics, Electron beams with mean energies at the phantom surface below 15 MeV. Supplement to NACP (1980) Acta Radiol. Oncol. 20 401-415

NCRP 1981 Dosimetry of x-ray and gamma-ray beams for radiation therapy in the energy range 10 keV to 50 MeV NCRP Report 69 (Bethesda, MD: National Council on Radiation Protection and Measurements)

NCS 1986 Code of practice for the dosimetry of high-energy photon beams Report NCS-2 (Amsterdam: Nederlands Commission for Radiation Dosimetry)

NCS 1989 Code of Practice for the dosimetry of high-energy electron beams Report NCS-5 (Amsterdam: Nederlands Commission for Radiation Dosimetry)

NCS 2008 Code of Practice for the absorbed dose determination in high-energy photon and electron beams Report NCS-18 (Amsterdam,NLD: Nederlands Commission for Radiation Dosimetry)

Reich H 1979 Choice of the measuring quantity for therapy-level dosemeters Phys. Med. Biol. 24 895-900

SEFM 1984a Procedimientos recomendados para la dosimetra de fotones y electrones de energas comprendidas entre 1 MeV y 51 MeV en radioterapia de haces externos Report SEFM 84-1 (Madrid: Sociedad Española de Fsica Médica)

SEFM 1984b Normas para la determinación de dosis absorbida en agua, para radiación gamma de cobalto-60, partiendo de medições realizadas en aire y en unidades de exposición Report SEFM 84-1a (Madrid: Sociedad Española de Fsica Médica)

SEFM 1987 Suplemento al Documento 84-1: Procedimientos recomendados para la dosimetra de fotones y electrones de energas comprendidas entre 1 MeV y 50 MeV en radioterapia de haces externos Report SEFM 87-1 (Madrid: Sociedad Española de Fsica Médica)

Shiragai A 1978 A proposal concerning the absorbed dose conversion factor Phys. Med. Biol. 23 245-252

SSRMP 1986 Dosimetry of high energy photon and electron beams: Recommendations Recomm SGSMP Nr. 6 (Ber, CHE: Swiss Society of Radiation Biology and Radiation Physics)

SSRMP 2000 Reference Dosimetry of High-Energy Therapy Photon Beams with Ionisation Chambers Recomm SSRMP Nr. 8 (Bern, CHE: Swiss Society of Radiobiology and Medical Physics) revised 2018

SSRMP 2002 Reference Dosimetry of High-Energy Therapy Electron Beams with Ionisation Chambers Recomm SSRMP Nr. 10 (Bern, CHE: Swiss Society of Radiobiology and Medical Physics) revised 2019.