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A New Trend of Dosimetry with Photons and Electrons with High Energy

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Introduction

During the past few years, national or international organizations have introduced a number of codes of practice, protocols and documents[1-8] that provide a systematic approach to the calibration and determination of absorbed dose from radiation beams used for the treament of cancer. In general, however, they are somewhat too specific for them to serve the requirements of the facilities in the countries where the documents originated. In this review, useful information available within the current several protocols are summarized.

Equipment

It should be possible to use the same ionization chamber for ^{60}Co γ radiation, high energy X-rays and electron beam with $E_o \geq 10$ MeV. It is desirable that the chamber wall is made of air-equivalent material and the thickness of the wall is less than 0.1 g · cm^{-2}. In the calibration of such a chamber, free in air using ^{60}Co γ radiation, a buildup cap has to be added. The thickness for wall plus buildup cap should be between 0.4 g · cm^{-2} and 0.6 g · cm^{-2}.

It is convenient to use a cylindrical chamber (thimble type) for measurements at these radiation qualities. The chamber volume should be between about 0.1 cm^3 and 1 cm^3, that is a compromise between the need for sufficient sensitivity and the ability to measure dose at a point. These requirements are met in cylindrical chambers with an internal diameter of not greater than 7 mm and an internal length of not greater than 25 mm. The chamber must be aligned in such a way that the radiation fluence is uniform over the cross-section of the chamber.

The construction of the chamber should be as homogeneous as possible, but for technical purposes the central electrode will most likely be of a material different from that of the wall and indeed the choice of all these materials may play an important role in ensuring that energy response is flat. It is not necessary that the chamber wall and the buildup cap be made of same material but it is essential that the composition of both be known.

The air cavity should not be sealed so that it would equilibrate rapidly with exterior pressure condition.

For measurement in electron beams of $\bar{E}_o < 10$ MeV, plane parallel chambers are recommended and must be used below 5 MeV. Cylindrical chambers with a radius less than 2 ㎜ may be used for 5 MeV $\leq \bar{E}_o \leq$ 10 MeV but the uncertainty may increase by 1−2%. Plane parallel chambers can, however, also be used above 10 MeV. The front window should be thin and the material surrounding the cavity should be as water-equivalent as possible. The distance between the plates of the chamber should be less than 2 ㎜ and the diameter of the collecting electrode surrounded by a guard electrode should be less than 20 ㎜. The chamber should not exhibit a polarity effect. It is desirable that the chamber be immersible into water.

The charge (or current) induced in an ionization chamber is extremely small and must be measured by a very sensitive charge-measuring device with a high input impedance ($> 10^{14}$ Ω) known as an electrometer. The electrometer should be provided with a digital display and should be of four digit resolution or 0.1%. The change in response due to lack of long term stability should not exceed ± 5% in a year. The electrometer and the ionization chamber can be calibrated separately or as a unit. It should be possible (at least in the chamber is used in pulsed beams) to vary the voltage applied to the chamber so as to determine ion collection efficiency and to reverse the polarity so that the polarity effect of the ionization chamber may be determined.

Water is recommended as the reference medium for absorbed dose measurements for both photon and electron beams. Plastic phantoms in slab form may be used but dose determination must always be referenced to water. However, great care is needed with non-conductive plastic phantoms because charge buildup can take place, mainly in electron beams. Measurements for absorbed-dose determination should, at least for electron beams, always be performed in water or conductive plastics. The dimensions of the phantom should be such that a margin of 5 ㎝ is provided on all 4 sides at the depth of measurement with the largest field size and beyond the maximum depth to be measured.

Radiation Quality

The several parameters, i. e. photon absorption coefficients, electron stopping powers, and various perturbation parameters, required for absorbed dose determination depend on the photon or elĕctron energy. A complete characterization of a radiation beam would involve specification of the type of particles and their energy and angular distribution.

The electrom beam already has a certain energy spread before meeting the accelerator exit window. This spread depends on a larege number of facotrs such as accelerating mechanism, method of injection and extraction, and beam handling system. As the electron beam passes through the different materials between the accelerator window and the phantom surface, energy losses displace the spectrum to lower energies and at the same time fluctuations in such energy losses widen the spectrum. This also happens when the electrons pass into the phantom.

The most probable energy $E_{p,o}$ at phantom surface is a conveinent parameter for characterizing isodose curves or depth odse distributions because it can be related to the practical range R_p Different electron beams with the same $E_{p,o}$ and the same field size and SSD, however, may produce different absorbed dose distributions. This is because the energy and angular spread of the electron incident on the phantom surface may be different.

As the electron spectrum at the depth of interest is not known, the mean energy $\bar{E}_o$ at the phantom surface together with the depth of measurement z are used as input parameters for stopping power ratios. This method gives only approximate values for these prarameters as the data available from reference are strictly valid for monoenergetic and monodirectional broad electron beams perpendicularly incident on the phantom surface. The mean energy $\bar{E}_z$ of the electrons at the depth of interest is an essential parameter for determining some dosimetric factors.

The determination of $E_{p,o}$ and $\bar{E}_o$ is based on empirical relationships between electron energy and range parameters. Range parameters, in paticular, practical range R_p and half-value depth R_{50}, are determined from depth absorbed dose distributions. The empirical energy-range relations are strictly valid for broad and parallel electron beams only, perpendicularly incident on semi-infinite water phantom. It is difficult to set a limit beyond which depth dose distributions on central axis are independent of field size. The use of field sizes of 12 cm×12cm or larger are recommended for energies up to $\bar{E}o = 15$MeV, and sizes of 20 cm×20 cm or larger are recommended above that energy. For electron beams with $\bar{E}o < 10$ MeV for which slabs of plastic are used to determine range parameters, it is necessary to scale R_p and R_{50} to water equivalent ranges by using the relationship[8-10]

$$\frac{R_{plastic}}{R_{water}} = \frac{(r_o\rho)_{plastic}}{(r_o\rho)_{water}}$$

where $r_o\rho$ is the linear continuous-slowing-down range. The energy-range relations are strictly valid only for depth absorbed dose distributions. In practical dosimetry, however, depth ionization distributions are generally used instead for convenience.

In the measurement of depth ionization distribtuions it is necessary to use the effective point of measurement of a vylindrical chamber and to correct the readings for the ion recombination and polarity effects. For energies $\bar{E}_o < 10$ MeV, or whenever the inherent uncertainty associated with the determination of the effective point of measurement and (or) the perturbation correction effects has to be reduced, the use of plane parallel chambers is recommended.

At the phanom surface, the most probable energy $E_{p,o}$ and mean energy $\bar{E}_o$ are related to the practical range R_p and half-value depth R_{50}.[4,7,8]

$$E_{p,o} = C_1 + C_2R_p + C_3 \cdot R_p^2$$
$$\bar{E}_o = C_4R_{50}$$

where $C_1 = 0.22$ MeV, $C_2 = 1.98$ MeV $\cdot$ cm,$^{-1}$ $C_3 = 0.025$ MeV $\cdot$ cm^{-2} and $C_4 = 2.33$ MeV $\cdot$ cm.$^{-1}$

These equations are valid for large field sizes in the range between 5 and 35 MeV. R_p can be determined from depth ionization or absorbed dose distribtuions measured at SSD $\geq$ 1m. R_{50} is determined from absorbed dose distribtuions at a fixed source-chamber distance.

For monenergetic electron beams with energy Eo at phantom surface, mean energy $\bar{E}_z$ at depth z could be approximated by a simple relation

$$\bar{E}_z \approx Eo(1-z/R_p).$$

Usually, E_o is replaced by $\bar{E}_o$ in this equation. This approximation is recommended only for $\bar{E}_o$ less than 10 MeV or for small depths at higher energies. Monte Carlo calculations or table based on Monte Carlo calculations are recommended for the evaluation of $\bar{E}_z$.

The radiation from ^{137}Cs is monoenergetic at 0.662 MeV and that from ^{60}Co is nearly monoenergetic at 1.25 MeV. However, the beams from SSDL(Secondary Sdandard Dosimetry Laboratory) or therapy sources include a certain amount of scattered photons, thus somewhat reducing the effective energies.

The spectrum of photon beams from accelerators depends on the electron energy, target and flattening filter. The most commonly used parameter for quality specification of photon beams is a 'nominal maximum energy' (or 'nominal accelerating potential')[1] which approximates the energy of the electrons striking the target. This is not good enough to specify either beam parameters such as depth dose data and isodose charts or dosimetric parameters such as stopping power ratios and perturbation corrections. For proper specification of these parameters, TPR_{10}^{20} or D_{20}/D_{10} is recommended.[1,4]

Measurement Network

For the transfer of a calibration expressed in terms of calibration factors, the irradiation conditions such as the photon energy and spectrum and the field size must be similar as possible at the PSDL(Primary Standard Dosimetry Laboratory), the SSDL and also at the user's beam.[1] However, in the most usual situation at a hospital neither the same quantity is wanted as is available for calibration nor are the same beam qualities used. The more general aim is to determine the absorbed dose to water at several photon and electron beam qualities using an ionization chamber calibrated in air kirma or exposure. It is necessary to use a consistent set of interaction coefficients at all the steps.

Primary standards for absorbed dose to graphite(D_{ar}), exposure free in air (X), and air kerma (K_{air}) have been developed by several PSDLs. Intercomparisons of standards of the same type generally give agreement within 0.2−0.3% at ^{60}Co γ ray quality.

The absolute uncertainty in the exposure standard for ^{60}Co is much larger than the proven constancy between standards, because exposure is measured in terms of electric charge and mass. Interaction coefficients ($s_{gr,air}$ and $(\bar{\mu}_{en}/\rho)_{air,gr}$ for graphite chamber) must be used to convert these measurements to absorbed energy.

The determination of air kerma, $K_{air,c}$ at the calibration radiation quality from measurements of the mean specific ionization J_{air} inside the air cavity of an ionztion chamber also includes

the values of $(1-g)$ and $(W/e)_c$. The value of g is close to 0.3% for ^{60}CO γ and lower than this value for medium and low energy X-rays. The uncertainty in the value of g is insignificant compared to other sources for K_{air}.

The mean energy expended in air per ion pair per electron charge W/e is considered constant for electron and photon. The value of W/e is determined by comparison measurements using a graphite calorimeter and a graphite ionization chamber inside a graphite phantom. The Bragg-Gray equation $D_{gr}=s_{ar,air} \cdot W/e \cdot J_{air}$ is applied to determine the product $S_{gr,air} \cdot W/e$. The stopping power values[11] directly influence the value of W/e. The air kerma includes the product of $s_{ar,air}$ (stopping power ratio) and W/e, but the exposure does not W/e. Therefore the Kair has a much smaller uncertainty than X and so is preferable. [81]

The main task of SSDL is to transfer the calibration from PSDLs to users. The calibration is carried out in terms of air kerma ($\bar{N}_k$) or exposure ($\bar{N}_x$). Another task for the SSDL is to advise the users to calculate chamber factors to be used in the Bragg-Gray equation in order to determine absorbed dose at the user's beam. The derived factor for this purpose is the absorbed-to-air chamber factor, N_D.

The user must have an ionization chamber and a measuring assembly. It is essential that the chamber be checked requlary against a stability check source, (^{90}Sr + ^{90}Y) source of ^{60}Co therapy source. Constancy checks must always be performed before and after the calibration at the SSDL.

Formalism

The calibration quality (subscript c) is assumed to be ^{60}Co γ ray and the user's quality (subscript u) to be ^{137}Cs γ ray, ^{60} Co γ ray photons or electrons from an accelerator.

The secondary standard of the SSDL is used in the calibration of the user's instrument to yield an air kerma calibration factor N_k ($=K_{air}$, c/Mc) or exposure calibration factor Nx ($=Xc/Mc$) of an ionization chamber. For a therapy source, a source-to-chamber distance (SCD) of 1 m and a field size of 10 cm$\times$ 10cm are preferable as the reference condition. For a given field size at the position of the chamber, the scattered photon contribution from the source and collimator will decrease with an increase of SCD. An SCD $>$ 1 m is, however, often impractical as the exposure rate may be too low.

The air kerma $K_{air,c}$ (giving a meter reading M_c) corresponds to a certain mean absorbed dose to air inside the cavity of the chamber, $\bar{D}_{a}^{ir,c}$ which is calculatd. The relation between Kair, c and $\bar{D}_{air,c}$ depends of the construction of an ionization chmber and buildup cap. The absorbed dose to air chamber factor

$$\underline{N}_{D,c} \equiv D_{air,c}M_c$$

can be determined. It is assumed that $M_{D,c}$ also is valid at the user's beam quality,[8] i. e.

$$N_{D,c} \equiv N_{D,u} \equiv D_{air,u}M_u$$

Air kerma $K_{air,c}$ can be related to the mean absorbed dose $D_{air,c}$ inside the air cavity of user's chamber by

$$D_{air,c} \equiv K_{air,c}(1-g)\ k_{att} \cdot k_m$$

i. e. $$N_{D,c} \equiv N_k \cdot (1-g) \cdot k_{att} \cdot k_m.$$

The factor k_m takes into account the lack of air equivalence of the ionization chamber material at the ^{60}Co γ ray beam. In cases where the wall and the buildup cap are made of the same material m,

$$K_m = s_{air,\,m}(\mu_{en}\rho)_{m,\,air}$$

If instead the chamber wall and the buildup cap are made of different materials, then

$$k_m = \alpha \cdot s_{air,\,wall} \cdot (\mu_{en}\rho)_{wall,air} + (1-\alpha) \cdot s_{air,cap} \cdot (\mu_{en}\rho)_{cap,\,air}$$

where α is the fraction of ionization inside the air cavity due to electrons from the chamber wall. The factor katt takes into account the attenuation and scatter of the photons in the material of the wall and buildup cap of an ionization chamber. For cylindrical, thimble type, chambers with the recommended dimensions having a total thickness of wall plus buildup cap between 0.45 and 0.6 $g \cdot cm^{-2}$, $k_{att}=0.990 \pm 0.005$. The tabulated product $k_m \cdot k_{att}$ can be used to determine N_D for a chamber calibrated in air kerma.

Dose Determination

The absorbed dose to water at the point of interest (the effective point of measurement of the chamber, P_{eff})

$$D_w(P_{eff}) = \bar{D}_{air,u} \cdot (s_{w,air})_u \cdot P_u$$

can be determined by Bragg-Gray equation. $(s_{w,air})u$ is the stopping power ratio of water to air at user's quality at the point of interest, and p_u the perturbation correction factor. For electron the P_u takes into account the difference in scattering in the phantom (and also chamber wall) material and in the air cavity. For photon beams it must be considered that electrons are produced and stopped differently in the chamber wall material and in water. It is always assumed that the measurement in the water phantom is carried out without a buildup cap. Then the P_u can be approximately calculated by the following.

$$P_u = \frac{\wedge \cdot s_{wall,air} \cdot (\mu_{en}\rho)_{w,air} + (1-\alpha) \cdot s_{w,air}}{S_{w,air}}$$

$$D_w(P_{eff}) = M_u \cdot N_D \cdot (s_{w,air})_u \cdot p_u$$

The effective point of measurement will be situated at the front surface of the air cavity. Recommended values of $z_p - z_{peff}$ for a cylindrical chamber with an internal radius r are:
(a) for electron beams 0.5r

(b) for high energy photon beams 0.75r

(c) for ^{60}Co γ radiation o.5r

(d) for ^{137}Cs γ radiation 0.35r.

But $Z_{peff}=z_p$ for a plane parallel chamber.

In calibrating a dosimeter as many influence quantities as possible are kept at reference condition. However, some influence quantities, e. g. temperature, pressure, humidity, dose rate and polarity effect, must generally be corrected for to yield the influence corresponding to the reference conditions. The reference conditions for both calibration of ionization chambers and measurement of absorbed dose are followings:

(a) for ^{60}Co γ rays; free in air, 10 cm×10 cm at 1 m SCD

in phantom

(b) for ^{60}Co γ rays; reference depth=5 cm, 10 cm × 10 cm at treatment SSD

(c) for $TPR_{10}^{20} \leq 0.70$: same as for ^{60}Co γ rays

(d) for $TPR_{10}^{20} > 0.70$: depth=10 cm, 10 cm × 10 cm at treatment SSD $10 < 0.70 \simeq$ depth$\wedge$ 10 cm, 10 cm×

for electron

(e) Eo/MeV <5; R_{100}, 10 cm at treatment SSD

(f) $5 \leq$ Eo/MeV <10; R_{100} or 1 cm, 10 cm × 10 cm at treatment SSD

(g) $10 \leq$ Eo/MeV <20; R_{100} or 2 cm, 10 cm × 10 cm at treatment SSD

(h) $20 \leq$ Eo/MeV <50; R_{100} or 3 cm, 5 cm × 5 cm at treatment SSD

Before measurements are made with an ionization chamber system, enough time should be allowed for the chamber to reach thermal equilibrium and for the measuring system to warm up.

The leakage current must be measured and must be insignificant compared to that curent obtained for the real measurements.

The polarity effect of the chamber must be checked, particularly for plane parallel chambers, and found to be within the limits; 1% for electrons of $\bar{E}o$ <5 MeV, 0.2% for cotherwise.

With ionization chambers open to ambient air, the correction factor p_{TP} for temperature and pressure must be applied to the measured current or charge.

$$p_{TP}=\frac{P_o(273.2+T)}{P(273.2+T_o)}$$

If the calibration factor is related to a relative humidity of 50% then in a range of 20% to 70% relative humidity no correction is needed for temperature between 15℃ and 25℃.

The two-voltage method is recommended to determie the recombination factor of an ionization chamber.[12] The recombination correction factor p_a at the normal operating V_1 can be obtained from a quadratic relation for pulsed and pulsed-scanned radiation

$$p_a=a_o+a_1\cdot(Q_1/Q_2)+a_2\cdot(Q_1/Q_2)^2$$

where Q_1 and Q_2 are charges collected at applied voltage V_1 and V_2, respectively, and

V_2 should be less than a half of V_1.

In the case of electron beams, relative absorbed dose distributions are different from relative ionization dirstributions because of the continuous decrease in energy and increased scatitering with depth of the electrons. Both stopping power ratio and the perturbation factor vary significantly with energy. Consequently, it will be necessary to determine the absorbed dose at each point of interest.

In the case of high energy photons the factors to be applied to the readings of the measurement system can be assumed to be independent of depth for a given quality. This means that relative ionization distributions can be used as relative absorbed dose distributions.

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