

Absorbed dose conversion factors for Megavoltage photon beams

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1 Introduction

For high-energy photon radiation the IPEM recommends its 1990 Code of Practice [1], in which radiotherapy dosimetry is traceable to the UK standard of absorbed dose to water. This standard consists of a graphite calorimeter used to calibrate reference standard ionisation chambers in terms of dose to graphite, and a method [2] to convert this calibration to one in terms of absorbed dose to water. The aim of the present work [3] is to re-evaluate these conversion factors. We compare results previously obtained using cavity ionisation theory and the photon fluence scaling theorem (PFST), for lightly filtered X-ray beams generated by the NPL linac, to recent measurements and EGS4 Monte-Carlo simulations in both lightly and heavily filtered X-ray beams.

2 General Overview of the Method of Dose Ratios

The absorbed dose calibration factor, N_m , converts the electric charge Q_m from ionisation in the chamber cavity, to the absorbed dose D_m at the position of the chamber in the undisturbed medium, m:

$$N_m = D_m / Q_m \quad (1)$$

Under the assumptions of the photon fluence scaling theorem, when all dimensions are scaled in the inverse ratio of the electron densities, the ratio of calibration factors in water (w) to graphite (c) is given by:

$$\frac{N_w}{N_c} = \frac{Q_c}{Q_w} \cdot \frac{f_c^2}{f_w^2} \cdot \frac{\int_0^{E_0} dE \cdot w[E] \cdot (\mu_{en}[E] / \rho)_w \cdot \beta_w[E]}{\int_0^{E_0} dE \cdot w[E] \cdot (\mu_{en}[E] / \rho)_c \cdot \beta_c[E]} \quad (2)$$

Where E is the energy of the photon fluence with maximum energy E_0 , f is the source-chamber distance, μ_{en}/ρ is the mass-energy absorption coefficient of the medium, β is the ratio of absorbed dose to collision kerma at a point and w is a weighting factor common to both numerator and denominator.

Equation (3) is obtained using the relation between photon fluence and absorbed dose from the more general form:

$$\frac{N_w}{N_c} = \frac{D_w}{D_c} \cdot \frac{Q_c}{Q_w} \quad (3)$$

In the present work, Monte-Carlo simulation was also used to estimate the absorbed doses D_w , D_c .

3 Overview of methods A and B

Ionisation measurements were made in graphite and in water under two sets of conditions. In method (A) both the chamber-source distance and the chamber depth in phantom were scaled by the inverse electron density of the media, while in method (B) the chamber-source distance was kept fixed, and only the depth was scaled. The effective position of the source was determined from the inverse square law, after correcting for scatter and air-attenuation.

The ratio of absorbed doses at the chamber position was obtained using (A) the PFST and (B) Monte-Carlo simulation. The required conversion factor is the product of this dose ratio with the ratio of measured ionisations, and the results of the two methods were compared. The second method avoids the need to estimate various corrections to the PFST, but places more reliance on Monte-Carlo calculations.

3.1 Virtual Source Correction

It has been assumed that as the primary component of the photon fluence obeys the inverse square law the chamber response to this fluence would vary similarly. Chamber response measurements made at depth in a water phantom at varying source to chamber distances were corrected to give the chamber response to the primary contribution. The EGS4 usercode DOSRZPAR (see section 4.2) was used to calculate the ratio of primary to total dose which was used to correct measurements of total collected charge to give the chamber response to the primary component. The calculations determined dose rather than charge ratios and so it was necessary to assume that chamber response (charge/dose) is the same for primary and scattered radiation. After correcting also for air attenuation the chamber response in water to the primary fluence should obey the inverse square law. Any deviation from this was assumed to be due to a displacement of the virtual source of X-radiation from the centre of the target.

3.2 Air Attenuation Correction

As measurements were made at different target-chamber distances it is necessary to apply a correction for the differing amount of attenuation of the intervening air. Narrow beam attenuation coefficients for air were applied to the binned photon energy fluence at the scoring plane to give the fluence at the front face of the phantom. The effective value of the attenuation of the air between the scoring plane and phantom is given by the ratio of the photon energy fluences at the front face and at the scoring plane integrated over all energies. The air attenuation correction is determined by taking the ratio of this value for the water and graphite setups.

3.3 Correction for Pair Production

The PFST assumes that photons interact only by Compton scattering whose cross-section is proportional to the electron density of the medium. This en-

sures that the primary and the proportion of scattered to primary photon fluence at corresponding scaled depths in the two media is the same. In contrast bremsstrahlung and pair production do not obey the PFST as their differential effect in two phantoms scaled by electron density does not cancel.

The correction to account for the different proportion of the primary photon fluence scattered out of the beam due to pair production in the two phantoms can be determined by considering the narrow-beam attenuation of the photons that includes attenuation due to pair production. Firstly the correction for narrow beam attenuation of the beam in air was applied to the binned photon energy fluence from the scoring plane to the front face of the corresponding phantom. For each set-up the correction for narrow beam attenuation of the beam from the front face of the phantom to the point of measurement in the medium was applied to this corrected photon energy fluence. The effective attenuation factor of the medium that includes attenuation due to pair production is given by the integrated ratio of the photon energy fluence at the depth in the medium to the front face of the phantom. The pair production correction can then be determined by taking the ratio of the attenuation factors in water and graphite.

3.4 Correction for Bremsstrahlung and Annihilation Radiation

The intensity and spectrum of radiation due to bremsstrahlung and annihilation will differ in the two media. Positrons produced from pair production events give rise to annihilation photons which can add to the scattered radiation reaching the point of measurement. Compton scattered electrons may subsequently create bremsstrahlung radiation that will also add to the scattered radiation reaching the point of measurement.

DOSRZPAR can score the dose due to Compton and Rayleigh scattered photons separately to that due to bremsstrahlung and annihilation photons. Estimated values of the average energy of the primary and scattered components of the fluence were used to give an estimate of the average mass-energy absorption coefficients and the correction for the centre of electron production for the two components. Values for the ratio of the scatter factors in water and graphite at a point in the undisturbed medium could then be determined for the situation when bremsstrahlung and annihilation radiation was included in the total dose and when it was excluded. The maximum correction was of the order +0.05% with uncertainties of the same order of magnitude and so it was decided not to apply any correction to account for bremsstrahlung and annihilation.

3.5 Ratio of Mass-Energy Absorption Coefficients

Values of the photon mass-energy absorption coefficients for water and graphite at the point of measurement in the respective phantoms were determined by taking a weighted average over the photon energy fluence at the measurement depth. Values were interpolated from the tabulated data of Hubbell [4].

3.6 Correction for Centre of Electron Production

In a slab of material with a broad parallel beam of high-energy photons (free of electron contamination) perpendicularly incident on it, at depths greater than the maximum electron range, transient charged particle equilibrium exists. Kase [5] defines a mean distance $\bar{x}$ that the secondary electrons carry kinetic energy "downstream" before depositing it as absorbed dose. The value of $\bar{x}$ is given by the horizontal separation of the curves for absorbed dose and collision kerma anywhere past the build-up.

The correction for centre of electron production was determined by interpolating values of $\bar{x}$ obtained from Attix [6] and taking a weighted average over the photon energy fluence at depth in the water and graphite phantoms.

4 EGS4 Monte-Carlo Simulations

The Monte-Carlo calculations described here were carried out using the EGS4 code system [7] with the PRESTA [8] electron transport algorithm. Appropriate values for the electron transport cut-offs were chosen for the NPLINAC and DOSRZPAR calculations and the PEGS4 datasets. The IAPRIM and EPSTFL options were used with density effect corrections obtained using EPSTAR. Where possible correlated sampling techniques were employed in the calculations of absorbed dose in the graphite and water phantoms by using the same phase space data generated in the linac simulation.

4.1 Simulations of the NPL LINAC

A detailed model of the NPL linac (the EGS4 usercode NPLINAC) was used to generate phase space data representing the X-ray beam as it emerges from the collimator, filter and transmission monitor. These data were validated by comparing simulated central axis depth dose curves and beam quality parameters with measured data. In the model the electrons incident on the X-ray target were taken to form a pencil beam, with no attempt to include the angular distribution produced by the focussing magnets. Particular care has been taken to minimise the effects of this incorrect angular dependence in all the simulations which used these phase space data.

NPLINAC stores the full phase space information of each particle striking a predefined scoring plane that is perpendicular to the beam axis. The code has been validated extensively by comparing TPR values for calculated spectra with measured values. Depth dose curves for measured and calculated spectra have also been compared and good agreement has been found. In all cases, the phase space spectra was binned into 200 energy bins.

4.2 Simulations of the measurement set-up

Simulations of the measurement set-up were carried out using the usercode DOSRZPAR which has been well tested and validated against the established code

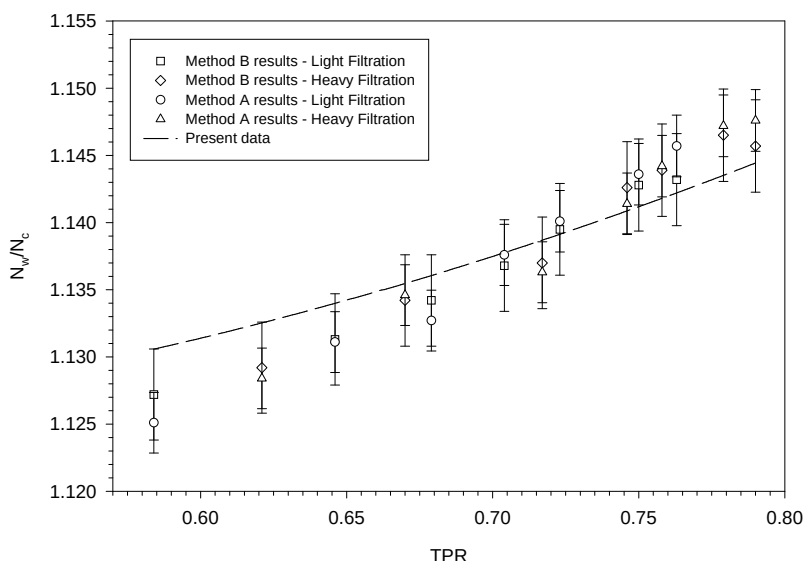


Fig. 1. Plot of N_w/N_c versus TPR ([2], [3]) with uncertainties shown at 1σ level

DOSRZ. DOSRZPAR calculates the dose to the internal regions of a cylindrical-slab geometry and so it was necessary to approximate the measurement set-up by using a cylindrical water or graphite phantom with a radius chosen to give the same area as the front face of the respective phantom. The phase space spectra were used with DOSRZPAR to calculate the total and primary dose to the scoring region at the points of measurement in the respective phantoms. The scoring region was approximated by a cylinder of length 1 cm, and radius 0.5 cm for target-chamber distances of 125 cm or less and radius 1 cm for greater target-chamber distances. In the case of the water phantom, the Perspex walls were replaced by water.

5 Results

The total uncertainty in the determination of N_w/N_c at the 1σ level was calculated to be 0.32% using method A and 0.37% using method B. The non-random uncertainty in the ratios of mass-energy absorption coefficients is present in each total uncertainty for methods A and B and should be ignored when comparing results from these two methods. Also, all random uncertainties can be reduced by a factor of $\sqrt{N}$, where N is the number of estimates made.

The values of N_w/N_c determined using methods A and B agree to within 1σ uncertainty where the uncertainties on method A results are 0.20% and the uncertainties on method B results are 0.30%. Non-random uncertainties common to both methods have not been included in each total uncertainty and all random

uncertainties are reduced by a factor of $\sqrt{N}$. The best fit to both sets of results agrees with values determined in previous work to within 2σ uncertainty, the greatest discrepancy being found at the lowest and highest energies.

One of the main aims of this work was to test the interpolation and extrapolation of results obtained for light filtration to give values for heavy filtration. It can be seen from Fig. 1 that, for this work, no noticeable difference was observed between results for light and heavy filtration measurements. It can therefore be concluded that interpolation and extrapolation was adequate.

The values of N_w/N_c determined in this work agree to within 1σ uncertainty to values in present use at the NPL. The uncertainty quoted on the values in present use is $\pm 0.5\%$. It is worth noting that much of the work used to determine the values of N_w/N_c in both cases makes use of the PFST and so non-random uncertainties common to both results should not strictly be included when comparing values. The greatest discrepancy between the two sets of results is observed to be at the extremes of the energy range with the largest difference (0.4%) at 4 MV with light filtration. Further work is required to determine the value of N_w/N_c for a ^{60}Co beam. New facilities are soon to be commissioned at the NPL that will allow measurements in ^{60}Co to be made at a greater range of distances. However, extrapolation of the data given in Fig. 1 of N_w/N_c versus TPR gave values for ^{60}Co which are in good agreement (within 0.3%) to the average value obtained by the Australian Radiation Laboratory [9] using the PFST.

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