Original Article

An Experimental Slope Method for a More Accurate Measurement of Relative Radiation Doses using Radiographic and Radiochromic Films and Its Application to Megavoltage Small-Field Dosimetry

Raghavendra Holla[1,2], D. Khanna[1], Bhaskaran K. Pillai[2], K. V. Jafar Ali[2], P. S. Renil Mon[2], C. O. Clinto[2], Tharmarnadar Ganesh[3]

[1]Department of Physics, Karunya Institute of Technology and Sciences, Coimbatore, Tamil Nadu, [2]Department of Medical Physics, Amrita Institute of Medical Sciences, Amrita Vishwa Vidyapeetham, Kochi, Kerala, [3]Manipal Hospitals, New Delhi, India

Abstract

Purpose: An experimental method using the linear portion of the relative film dose–response curve for radiographic and radiochromic films is presented, which can be used to determine the relative depth doses in a variety of very small, medium, and large radiation fields and relative output factors (ROFs) for small fields. **Materials and Methods:** The film slope (FS) method was successfully applied to obtain the percentage depth doses (PDDs) for external beams of photon and electrons from a Synergy linear accelerator (Elekta AB, Stockholm, Sweden) under reference conditions of 10 cm × 10 cm for photon beam and nominal 10 cm × 10 cm size applicator for electron beam. For small-field dosimetry, the FS method was applied to EDR2 films (Carestream Health, Rochester, NY) for 6 MV photon beam from a linac (Elekta AB, Stockholm, Sweden) and small, circular radiosurgery cones (Elekta AB, Stockholm, Sweden) with diameters of 5, 7.5, 10, 12.5, and 15 mm. The ROFs for all these cones and central axis PDDs for 5, 10, and 15 mm diameter cones were determined at source-to-surface distance of 100 cm. The ROFs for small fields of CyberKnife system were determined using this technique with Gafchromic EBT3 film (Ashland, NJ, USA). The PDDs and ROFs were compared with ion chamber (IC) and Monte Carlo (MC) simulated values. **Results:** The maximum percentage deviation of PDD_{FS} with PDD_{IC} for 4, 6, and 15 MV photon beams was within 1.9%, 2.5%, and 1.4%, respectively, up to 20-cm depth. The maximum percentage deviation of PDD_{FS} with PDD_{IC} for electron beams was within 3% for energy range studied of 8–15 MeV. The gamma passing rates of PDD_{FS} with PDD_{IC} were above 96.5% with maximum gamma value of >2, occurring at the zero depths for 4, 6, and 15 MV photons. For electron beams, the gamma passing rates between PDD_{FS} with PDD_{IC} were above 97.7% with a maximum gamma value of 0.9, 1.3, and 0.7 occurring at the zero depth for 8, 12, and 15 MeV. For small field of 5-mm cone, the ROF_{FS} was 0.665 ± 0.021 as compared to 0.674 by MC method. The maximum percentage deviation between PDD_{FS} and PDD_{MC} was 3% for 5 mm and 10 mm and 2% for 15 mm cones with 1D gamma passing rates, respectively, of 95.5%, 96%, and 98%. For CyberKnife system, the ROF_{FS} using EBT3 film and MC published values agrees within 0.2% for for 5 mm cone. **Conclusions:** The authors have developed a novel and more accurate method for the relative dosimetry of photon and electron beams. This offers a unique method to determine PDD and ROF with a high spatial resolution in fields of steep dose gradient, especially in small fields.

Keywords: Percentage depth dose, CyberKnife, EBT3 film, EDR2 film, film slope method, relative dosimetry, relative output factor, small-field dosimetry

Received on: 17-02-2019 **Review completed on: 27-05-2019** **Accepted on: 27-05-2019**

Introduction

With the advancement of image guidance and improved radiation treatment delivery techniques, the treatment field sizes are now being reduced down to a few millimeter range. In radiation treatment techniques such as stereotactic

Access this article online

Quick Response Code:

Website: www.jmp.org.in

DOI: 10.4103/jmp.JMP_17_19

Address for correspondence: Dr. D.Khanna, Department of Physics, Karunya Institute of Technology and Sciences, Karunya Nagar, Coimbatore - 641 114, Tamil Nadu, India. E-mail: davidkhanna@karunya.edu

How to cite this article: Holla R, Khanna D, Pillai BK, Jafar Ali KV, Renil Mon PS, Clinto CO, *et al*. An experimental slope method for a more accurate measurement of relative radiation doses using radiographic and radiochromic films and its application to megavoltage small-field dosimetry. J Med Phys 2019;44:145-55.

radiosurgery (SRS) or stereotactic body radiosurgery, very large doses, of the order of 8–25 Gy per fraction, are delivered to one or multiple tumors in the brain or body utilizing field sizes as small as 3–5 mm diameter. The success of radiation treatments using small-field delivery systems such as SRS with high-resolution multileaf collimator or stereotactic cones, Gamma Knife, and CyberKnife relies on accurate dosimetry for these small-field sizes. In conventional radiotherapy using treatment field sizes over 5 cm × 5 cm, the reference dose calibration is performed to determine the dose at a point through an available dosimetry protocol.[1-3] In all these protocols, the dose is determined for a reference field size of 10 cm × 10 cm. For small-field sizes of 3 cm × 3 cm or less, the dosimetry needs special attention, both in dose measurements and dose calculations. These measurements of small fields with nonequilibrium conditions are used to treat small target volumes using optimization techniques in the treatment planning software.

The physics of small radiation fields differs from larger fields since the accuracy of these measurements is more sensitive to the properties of the radiation detectors used.[4] With a variety of radiation detectors covering sizes from mini to micro, types of detectors including ionization chamber, semiconductor, chemical, film, etc., and various available shapes of the detectors such as thimble, spherical, and plane parallel, the choice of a suitable detector for small-field dosimetry could be confusing and challenging.

The dosimetric challenge in the physics of small field includes but is not limited to loss of lateral electronic equilibrium, lack of charged-particle equilibrium, partial source occlusion, fluence perturbations, dose-averaging effects, and the geometrical detector misalignment.[5-11] For relative dosimetry involving small fields, differences of measured percentage depth dose (PDD), output factors, and profiles including penumbra region can be observed among different detectors. Due to the non-water equivalence of the diode detector, the increase of the importance of secondary electrons in small fields leads to an overestimation of output factors.[12] The measurements involving ionization chambers underestimate the output factors due to the increase of lateral electron disequilibrium with an increase in the measuring volume of the ionization chambers, called volume effect.[11,12]

For beam profile measurements, diode detectors provide best results due to their small dimensions; however, the possible energy dependence of silicon renders it unsuitable for PDD or relative output factor (ROF) measurements. The diamond detector is expected to have minimal energy dependence making it suitable for more accurate PDD and output factor measurements, but the uncertainty about its size makes it difficult to correct for the effects of dose averaging in the smallest fields.[6]

Film dosimetry

Alternatively, radiographic film of EDR2 Ready-Pack film (Carestream Health, Rochester, NY, USA) and radiochromic (RC) films including Gafchromic EBT3 film (Ashland, NJ, USA) do have very high spatial resolution that allows them to be used for very small fields that are difficult to measure with ion chambers (ICs). Unlike ionization chambers, the volume effect is not a concern while using films; however, both of these film types exhibit strong energy dependence.[13-16] The application of these films for small-field planar dose maps, however, showed it to be superior to other detectors due to their high resolution.[17-19]

Further, reciprocity law does fail in megavoltage beams, especially for EDR2 Ready-Pack films showing reductions in the optical density (OD) when dose rate was decreased.[14] In the newer linear accelerators using flattening filter-free photon beams, dose rates vary from 0.80 to 10 Gy/min, and furthermore, it varies from central axis to the beam penumbra making EDR2 Ready-Pack films unsuitable for dosimetry. Some of these demerits of EDR2 films are overcome by the use of RC films for dose measurements in small fields. However, the response of earlier RC films (EBT and EBT2) has a poor spatial homogeneity which has been improved in the newer, EBT3 film. The observed spatial inhomogeneity was 5% for EBT2 film and 2% for EBT3 film.[20] Another important factor to be considered while using RC films with flatbed scanner is the lateral inhomogeneities introduced by the scanner which affects the OD.[21,22] These inhomogeneities are mostly canceled by means of averaging the measurements over a number of segments taken from different parts of one sheet of film.[23] There are several other approaches to overcome this problem where the relative dosimetry was performed using the RC films without establishing a calibration curve.[24-26]

In the present work, we have developed a novel but simple method for a more accurate measurement of relative doses using films for both radiographic (EDR2 Ready-Pack) and RC (EBT3) films. The method is versatile and is of general applicability, where it has been successfully applied in the determination of relative depth doses in a variety of very small, medium, and large radiation field sizes and ROFs for small fields. The measured PDDs and ROFs were compared with the Monte Carlo (MC) calculated and published values.

Materials and Methods

In relative dose measurements, we compare the doses at two different depths or locations; for example, in PDD measurements using photon or electron beams, at depths, 'd_{max}'and 'd', where 'd_{max}' is the depth of dose maximum and 'd' is the depth under consideration. While measuring PDD, the radiation fields at the two locations are different due to depth and distance attenuations and spectral changes (energy degradation or beam hardening) of the fields we are measuring. Consequently, often, the measuring device will have uncertain response variations, which could be difficult to evaluate and correct for.

Referring to Figure 1a and b on central axis depth dose measurements, using ionization chambers,

'D_{max}' is the dose or dose rate at point A, at depth, 'd_{max}'

'D_d' is the dose or dose rate at any typical point B, at depth 'd', below or beyond "d_{max}"

The PDD is defined as

$$\text{PDD} = \frac{D_d}{d_{max}} \times 100 \qquad \text{Eq. (1)}$$

The film method

Hurter and Driffield (H&D) introduced the sensitometric curve for films in 1890 and it is referred as film characteristic curve or the H&D curve.[27] The H&D curve is the response curve of a film where the log (exposure) is plotted on the X-axis and the net OD on the Y-axis [Figure 2a]. However, for radiation dosimetry, we plot net OD versus dose and called it the sensitometric curve [Figure 2b]. The net OD can be represented as a function of several parameters,[13] namely

OD = f (D, Dr, E, γ, d, S)

where "D" is the radiation dose, "D_r" is the dose rate, "E" is the radiation energy, "γ" is the type of the primary radiation, "*d"* is the depth of measurement, and "S" is the field size.

Although Gafchromic EBT3 films are less energy dependent, at high absorbed dose value, we cannot ignore the effect of it in dosimetry. Figure 3 shows the energy dependence of the H&D curve for 6 and 15 MV photons scanned using Epson 10000XL flatbed scanner. Both the curves merge at low doses for less than about 200 cGy, and they deviate from each other at high doses.

For both of these energies, H&D curves have a linear response in the dose range of 0–200 cGy, as shown in Figure 3. In the method of dosimetry described in the present work, the use of the linear region of H&D curve is required for both the film types.

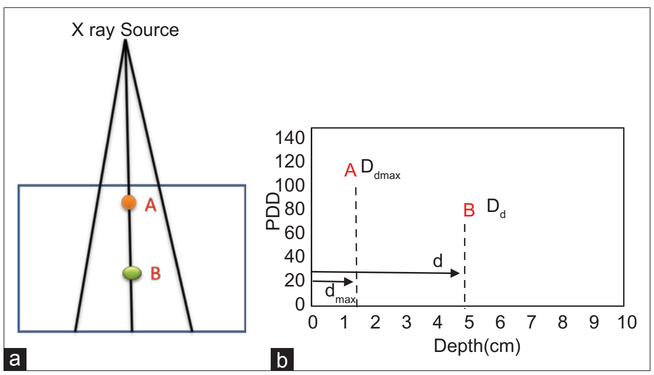

Figure 1: (a) and (b) Phantom measurement of PDD at points A and B at depths 'd_{max}' and 'd' with dose rates 'D_{max}' and 'D_d', respectively

The new film slope method

Percentage depth dose

The H&D curve necessitates the knowledge of absolute dose on the film. In the present method, for the film response curve, a relative dose which (by machine calibration in cGy/monitor unit (MU)) is proportional to the dose at 'd_{max}' was plotted on the abscissa with the net OD on the ordinate. We prefer to call this plot, the relative film dose–response (RFDR) curve, to distinguish it from the conventional H&D curve. For RFDR plots, dose ranges in abscissa for depths are different, and in fact, they are derived from their respective linear ranges.

Referring to the setup in Figure 1a and b, we exposed films sandwiched in a solid water phantom at two depths *A* and *B*, in separate exposure sessions, to different doses and plotted RFDR curves.

In the RFDR plot [Figure 4], the doses required to get the same optical density, 'OD_1' at depths 'd_{max}' and '*d'*, are D1 and D2, respectively. For the films at deeper depths, the reference doses are higher with respect to the reference dose of the film at 'd_{max}', and the actual dose rates seen by the respective films which resulted in the linear OD range are lower. We can see that these curves at various depths shift to the right at farther depths. The MUs delivered by the linac for the depth film were scaled appropriately so that the resulting ODs were in the linear range.

Examining the RFDR plot in its linear portion, for a given dose to the film, the OD is reached at the same time as the corresponding dose since the accumulated OD on the film is proportional to the dose. Hence, if we divide the ordinate and abscissa of the RFDR plots by exposure time, we can see that

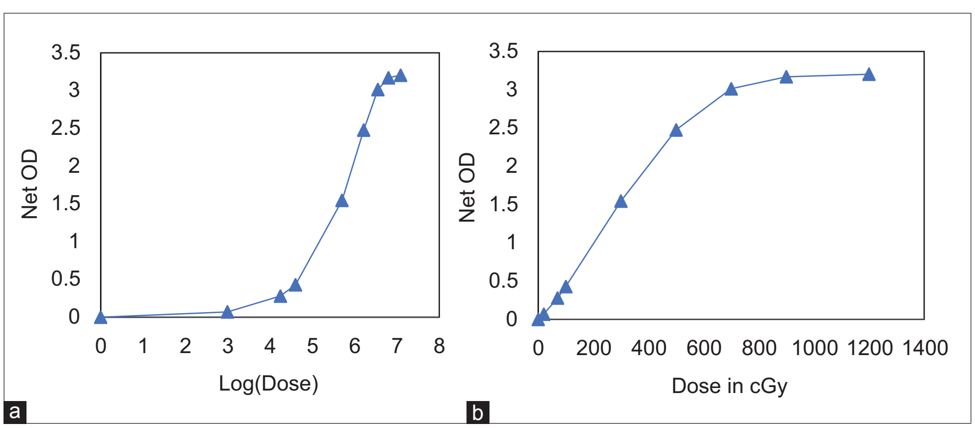

Figure 2: The different representations of characteristic curves used in dosimetry for EDR2 Ready-Pack film using (a) net optical density versus Log_{10} (dose) or (b) net optical density versus dose for 6 MV photon beam

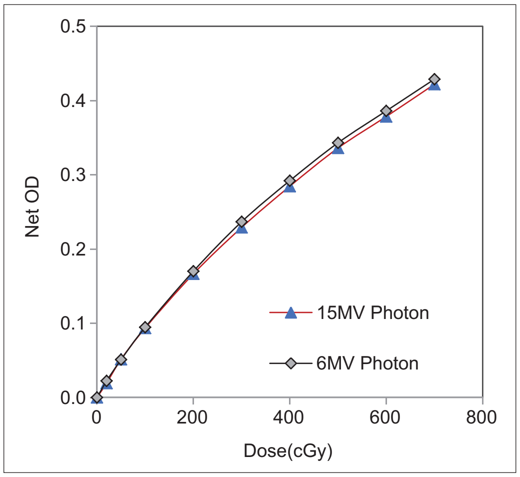

Figure 3: Hurter and Driffield curve using Gafchromic EBT3 film for 6 and 15 MV photon beams showing the energy dependence

the RFDR plot is equivalent to the plot of the OD rate versus the corresponding dose rate at the point of measurement. Therefore, in the linear portion of the RFDR plots, the slope of the curve is proportional to the dose rate at the point of measurement.

Thus, applying this principle to the RFDR plots at the two depths, we have

$OD_d \ \alpha \ MU_d$ ------------------Eq. (2)

$OD_{dmax} \ \alpha \ MU_{dmax}$ ------------Eq. (3)

where OD_d and OD_{dmax} are the net OD at depth 'd' and 'd_{max}'. MU_d and MU_{dmax} are MUs delivered to the films. The MU is the dose rate in cGy for the machine calibration of 1 cGy/MU at the reference point for the machine-specific reference conditions, for our machines.

The proportionality is equal to their respective scaling factors m_A and m_B at their respective depths.

Hence,

$$\Delta\ OD_d = m_B.\Delta MU_d \qquad \text{Eq. (4)}$$

$$m_B = \frac{\Delta OD_d}{\Delta MU_d}$$

$$\Delta OD_{dmax} = m_A.\Delta MU_{dmax} \qquad \text{Eq. (5)}$$

and $m_A = \frac{\Delta OD_{dmax}}{\Delta MU_{dmax}}$

The proportionality constants, m_A and m_B, are the slopes from the linear range of the RFDR plot and $m_A > m_B$. At deeper depths, the slopes are low due to inverse square fall and depth attenuation in addition to the modification due to spectral changes.

Further, $D_{max} \ \alpha \ m_A$ Eq. (6)

and $D_d \ \alpha \ m_B$

$$\frac{D_d}{D_{max}} = \frac{m_B}{m_A} \qquad \text{Eq. (7)}$$

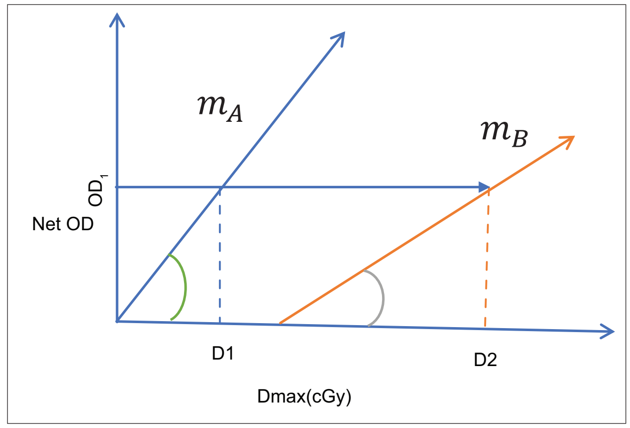

Figure 4: The linear portion of the relative film dose–response plots at two different depths A and B with the slopes, m_A and m_B

Substituting Eq. (7) in Eq. (1),

$$\therefore \text{PDD} = \frac{m_B}{m_A} \times 100 \qquad \text{Eq. (8)}$$

The PDD is simply the ratio of the slopes of the two linear RFDR curves normalized to 100 at depth "$d_{max.}$"

It should be noted that the differences in the film sensitivities for the fields at the two measuring depths, 'd_{max}' and 'd', are reflected in the differences in the slopes of the RFDR curves for the two depths. The quantity chosen for the X-axis of the RFDR plot at either point needs not be the absolute value of the doses at these points; it only needs to be proportional to the absolute doses. This eliminates the need of establishing a reference dosimetry with absolute dose values for creation of calibration curve for the relative film dosimetry. For example, it can be the reading of a monitor chamber placed anywhere in the radiation field, without casting a shadow at the points of measurement.

Relative output factor

The ROF is defined as the ratio of dose in water D_w *(A, d)* for a given beam collimator aperture size '*A*' at a reference depth, '*d*' to the dose at the same point and depth, '*d*' for the reference collimator aperture size, and 'A_{ref}' in the linear portion of the RFDR plot,

D_w *(A, d)* $\alpha \ m_A$,

and, D_w (A_{ref}, d) $\alpha \ m_{Aref}$, at a reference depth '*d*'

Hence, the ROF is,

$$\text{ROF} = \frac{Dw(A,d)}{Dw(Aref,d)} = \frac{m_A}{m_{Aref}} \qquad \text{Eq. (9)}$$

The reference field is 10 cm × 10 cm or any intermediate field size, and the reference depth is 'd_{max}' for linac-based radiosurgery with 6 MV photon beam. For CyberKnife® radiosurgery system, the reference field is 60 mm diameter.

Measurement of percentage depth doses for external beams of photons and electrons

The film slope (FS) method was successfully applied to obtain the PDDs for external beams of photon and electron energies from a Synergy linear accelerator (Elekta AB, Stockholm, Sweden) under reference conditions of 10 cm × 10 cm for photon beams and nominal 10 cm × 10 cm applicator size for electron beams. The RFDR curves were plotted using EDR2 Ready-Pack films processed in Promax automatic X-ray film processor (Chayagraphics India Pvt. Ltd., Bengaluru, India), and OD was measured using X-Rite 331 (X-Rite Incorporated, Grand Rapids, Michigan) Transmission Densitometer of 1 mm aperture size with a spectral response at 560 nm.

The experimental setup consisted of a solid water phantom of size 30 cm × 30 cm × 30 cm. EDR2 Ready-Pack films, cut to convenient small size and repacked light tight were sandwiched tightly between the solid water slabs, placed at depths ranging from 5 mm to 25 cm, and irradiated in separate sessions of exposure, in perpendicular orientation to the beam for the 'd_{max}' doses ranging from 30 cGy to 200 cGy. The exposures were designed to keep the resulting optical densities above fog, in the linear range of the RFDR plots. The slopes for the respective depths were determined from the RFDR plots [Figure 5a]. Normalizing the slopes of the RFDR plots, to that at the 'D_{max}' depth as per Eq. (8), the PDDs were obtained.

For Gafchromic EBT3 film, the film exposure was included in the d_{max} range of 50 cGy to 675 cGy, and all the films were scanned 24 h after irradiation using a flatbed scanner (10000XL, Microtek, CA) in transmission scan mode, maintaining the same film scan orientation. The scans were acquired in the 48-bit red-green-blue (RGB) mode (16 bits per color) and resolution of 300 dpi (0.0847 mm per pixel) without any image correction. The red color channel images were extracted and analyzed using ImageJ software (National Institutes of Health, USA). The RFDR curves of the films were plotted and the slopes were determined [Figure 5b].

The PDD of photon energies, 4, 6, and 15 MV, and electron energies, 8, 12, and 15 MeV linac beams, were plotted using EDR2 Ready-Pack film. For 6 MV photon beam, Gafchromic EBT3 film was also used. In addition, for all these beams, PDDs were measured using PTW 31010 IC (PTW-Freiburg, Germany) for comparison.

Measurement of percentage depth doses and relative output factors for small-diameter radiosurgery circular cones with 6 MV flattened photon beam from linac

For small-field dosimetry, the FS method was applied to EDR2 films for 6 MV photon beam from a linac (Elekta AB, Stockholm, Sweden) and small, circular radiosurgery cones (3D line, Elekta AB, Stockholm, Sweden) with diameters of 5, 7.5, 10, 12.5, and 15 mm. The ROFs for all these cones and central axis PDDs for 5, 10, and 15 mm cones were determined at source-to-surface distance (SSD) of 100 cm.

To obtain the linear response range of the film, the EDR2 Ready-Pack films were exposed in a solid water phantom of dimensions 30 cm × 30 cm × 30 cm. The films were cut to 11 cm × 16 cm and exposed with 6 MV photon at SSD = 100 cm and field size = 10 cm × 10 cm. For the 10mm cone, the D_{max} dose range delivered to the film was between 0 and 100 cGy at depth, 'd_{max}' and reference dose at 'd_{max}' of 1000 cGy delivered for film at 25 cm; [Figure 6a and b]. The linear response range was identified, and the exposure to the films was confined to within linear dose range at the respective depths. For small circular fields of 5, 10, and 15 mm diameter, this was achieved by rescaling the dose at each depth with the help of a monitor chamber placed at depth below the film. The exposed films were processed in a Promax automatic X-ray film processor, and net ODs were measured using X-Rite 331 transmission densitometer. The RFDR curves were plotted at each depth for all the circular fields in the respective linear ranges for PDD measurements. For ROF, the films were exposed at 'd_{max}' and slopes were determined from the RFDR plots [Figure 7]. The PDDs and ROFs were calculated for all these circular fields as per Eq. (8) and Eq. (9).

Comparison of percentage depth doses and relative output factors with direct measurements

For comparison, the PDDs and ROFs were also measured for

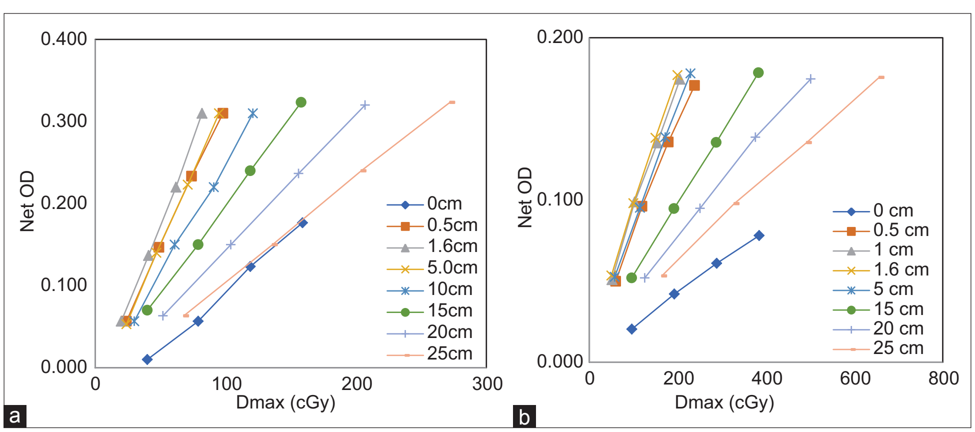

Figure 5: The relative film dose response at their respective depths for determining percentage depth dose; (a) EDR2 Ready-Pack films, (b) Gafchromic EBT3 films, Photon energy: 6 MV photon, field size: 10 cm × 10 cm, source-to-surface distance: 100 cm

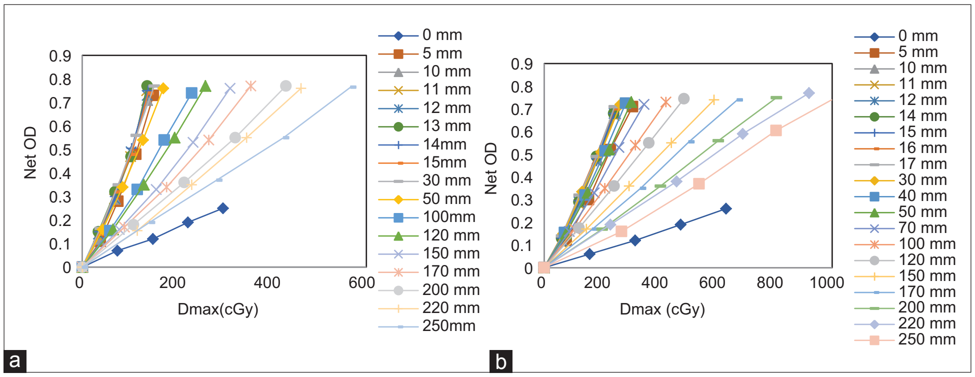

Figure 6: The relative film dose response at their respective linear ranges plotted at various depths using EDR2 Ready-Pack film to determine percentage depth dose of 6 MV photon beam with (a) 5-mm and (b) 10-mm diameter stereotactic radiosurgery cones

different small circular field sizes using shielded p-type silicon photon diode (N60008, PTW-Freiburg, Germany) in a water phantom (60 cm × 50 cm × 40.75 cm) (PTW-Freiburg, Germany).

Monte Carlo simulation

The validation of the experimental measurements was done by MC simulation of the treatment head of linear accelerator which was simulated according to manufacturer's specifications. The linear accelerator head design included fixed secondary collimators of 3D line (Elekta Medical Systems, Crawley, UK). All simulations were performed using BEAMnrc (Rogers *et al*. 2005) acting as a particle source, which is a user code from the EGSnrc MC system (Kawrakow 2000 and Kawrakow and Rogers 2003). The treatment head geometry was simulated using component modules, and the dose calculation was performed using DosXYZnrc (Blake Walters, 2001) to a small water volume of 0.5 mm × 0.5 mm × 0.5 mm for PDD and 0.25 mm × 0.25 mm × 0.25 mm for ROF. The number of histories was adjusted for each cone size so that the achieved uncertainty was below 1%. The PDDs and ROFs were calculated using the simulated head geometry.

Relative output factor measurements for 1000 MU/min M6 CyberKnife® system equipped with fixed cone collimators

The ROFs for a 1000 MU/min CyberKnife® system (Accuray Inc., Sunnyvale, CA) equipped with fixed cone collimators were measured by FS method using EBT3 Gafchromic films. The films were irradiated to a D_{max} ranging from 50 cGy to 675 cGy at 1.5 cm depth for the applicator sizes ranging from 5 mm to 50 mm diameter. The red-colored channel images were extracted from 48-bit RGB image and analyzed using ImageJ software. All EBT3 film dose measurements were repeated three times using a cut film of 3 cm × 3 cm sizes and three scans of the same film, making in total 9 readings for each depth for one dose level. Minimum of five dose levels were used for a depth to obtain RFDR plot. The slopes from the linear portion of all the RFDR plots were normalized to slope of reference field 60 mm diameter as per Eq. (9).

The ROFs were also measured using SNC Edge diode detector (Sun Nuclear Corporation, Melbourne, USA). The measured ROFs were corrected using the MC simulated correction

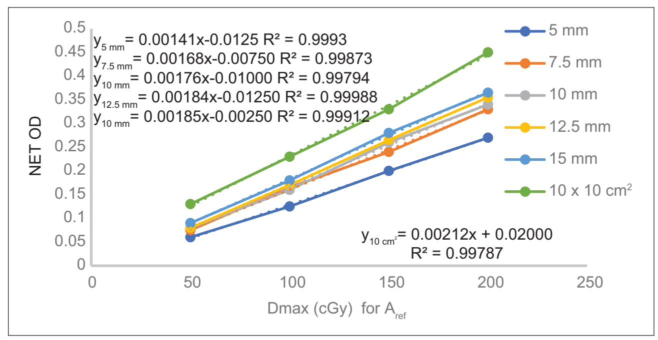

Figure 7: Calculated slopes from the linear curve fit of the relative film dose–response curves for radiosurgery fields of 5, 7.5, 10, 12.5, and 15 mm diameter at 'd_{max}' using EDR2 film. The output factors for these circular fields were calculated by normalizing the slopes from the linear portion of the relative film dose–response curve to the slope of reference field, 10 cm × 10 cm

factors to convert measurement ratios into the corresponding dose ratios that define output factors for small circular photon field, which accounts for the difference in the detector response in clinical field of beam quality (f_{clin}) and machine-specific reference field (f_{msr}).[28] The measured ROF from FS method and SNC diode corrected values were compared with the published MC values.[29]

For both the film types, the ROFs were also measured by direct film method for comparison. In this method, the ratio of the net OD values between the small circular fields and the machine-specific reference field (10 cm × 10 cm linac and 60 mm diameter for CyberKnife photon beam) was taken directly. This was performed by irradiating the film in solid water phantom with the film sandwiched tightly between slabs and irradiated in perpendicular orientation to the beam. All the three results were compared.

Results and Discussion

Percentage depth doses for photon and electron beams

The PDD curves for 4, 6, and 15 MV photons of 10 cm × 10 cm obtained by the FS method are presented in Figure 8. For 4, 6, and 15 MV photon beams, deviations between the

FS method (PDD_{FS}) and IC (PDD_{IC}) measurements were within 1.9%, 2.5%, and 1.4%, respectively, up to 20-cm depth. However, at the zero depth (surface), the observed percentage deviation for 4 MV was 1.8%, and for 6 and 15 MV photons, it was above 10% with PDD_{IC}. This result was confirmed by the pass–fail gamma index analysis between PDD_{FS} and PDD_{IC}. For the evaluation of two different PDDs, we performed a one-dimensional gamma index analysis, which is a well-established method for quantitatively comparing dose distributions.[30] The average gamma values with individual acceptance criteria of 2% dose difference and 1 mm distance to agreement (DTA) for 4, 6, and 15 MV photons using EDR2 film were 0.36, 0.34, and 0.29, respectively with maximum gamma value of more than 2 occurring at the zero depth. The gamma passing rates for all photon PDDs were above 96.5%. As the depth increased beyond 20 cm, the deviation between PDD_{FS} and PDD_{IC} increased to 3.5% and 3% for 6 MV and 15 MV, respectively, showing the consistent increase in the gamma values [Figure 8a-c]. This could be due to the change in slope becoming too small, making the FS method too insensitive and difficult to measure at deeper depths.

The maximum deviation of PDD_{FS} with PDD_{IC} for electron beams was within 3% for energy range studied of 8–15 MeV.

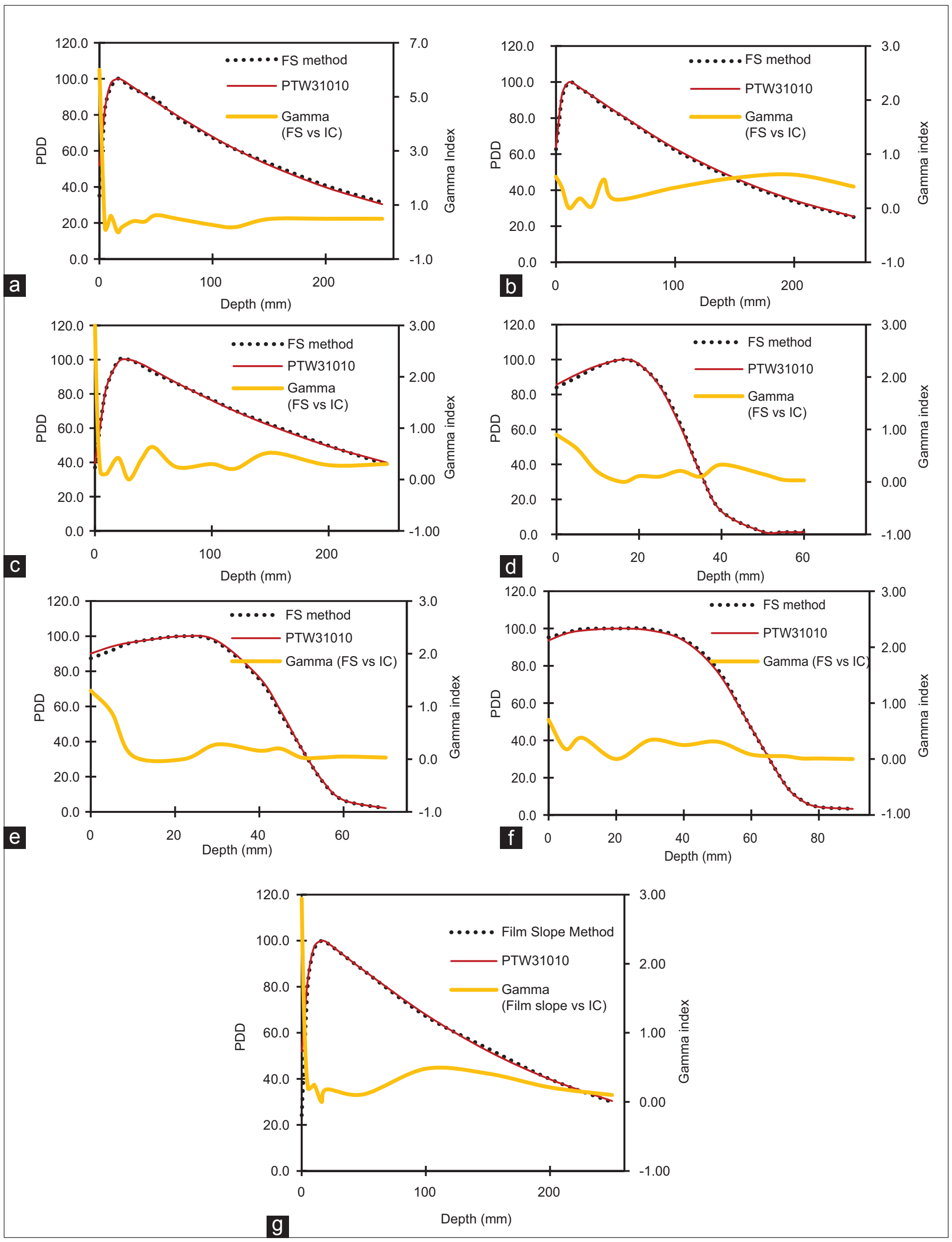

Figure 8: Percentage depth dose comparison for different energy beams; using EDR2 film; (a) 6 MV photon, (b) 4 MV photon, (c) 15 MV photon, (d) 8 MeV electron, (e) 12 MeV electron, and (f) 15 MeV electron; using EBT3 film (g) 6 MV photon; percentage depth dose: Film slope method (dotted black line), PTW 31010 (solid red line); 1D gamma evaluation between film slope method and PTW 31010 (solid orange line)

The gamma passing rates of PDD_{FS} with PDD_{IC} were above 97.7% with a maximum gamma value of 0.9, 1.3, and 0.7 occurring at the zero depth for 8, 12, and 15 MeV electron energies.

Poor agreement in the region below the depth of d_{max} was observed for both photons and electron PDDs, where the IC measurements were considerably high. This is because, in the steep gradient of the buildup region, the large size of the IC (a cylindrical volume of 5.5 mm inner diameter and 6.5 mm length) averages the values over its volume (0.125cc), whereas the film measures "at a point" (the size of the aperture, of the order of 1 mm, of the densitometer), i.e., the film resolution is far superior to that of IC and this is the strength of the FS method, compared to other detectors.

It is to be acknowledged that the FS method of relative dose measurement is tedious and the success of this method is subject to the integrity of the film processor for radiographic films. Hence, we applied the film method to the EBT3 films for 6 MV photons [8g]. The FS method showed good agreement with IC method with average gamma value of 0.26 with the passing rate above 98% for dose difference/DTA, 2%/1 mm. Hence, as demonstrated here, the FS method was successfully applied to the PDD measurements of the field size 10 cm × 10 cm for photon and electron energies, and its accuracy was superior to the IC measurements in high-field gradients, where there was a lack of electronic equilibrium.

Percentage depth doses for linear accelerator radiosurgery small fields of 6 MV flattened photon beams

The measured PDDs for small fields of cone sizes 5, 10, and 15 mm diameter, showed [Figure 9] good agreement with the Monte Carlo (MC) calculated values at depth deeper than 'd_{max}'. The gamma evaluation was performed with the criteria of Dose difference / DTA, 2% / 1mm with no low dose threshold between PDD_{FS} and PDD_{MC} values. The gamma passing rates between PDD_{FS} and PDD_{MC} calculated at depths deeper than zero depths, were above 95.5%, 96% and 98% for 5 mm, 10 mm and 15 mm cones respectively [Figure 9] with the average gamma values of 0.3, 0.41, and 0.2. The maximum % deviations for PDD_{FS} and PDD_{MC} were 3%, 3% and 2% respectively for 5 mm, 10 mm and 15 mm cones. In the buildup region including at zero depth, the FS method, due to its excellent resolution, gave more accurate results than the diode [Figure 9 d-f]. At depths beyond 20 cm,

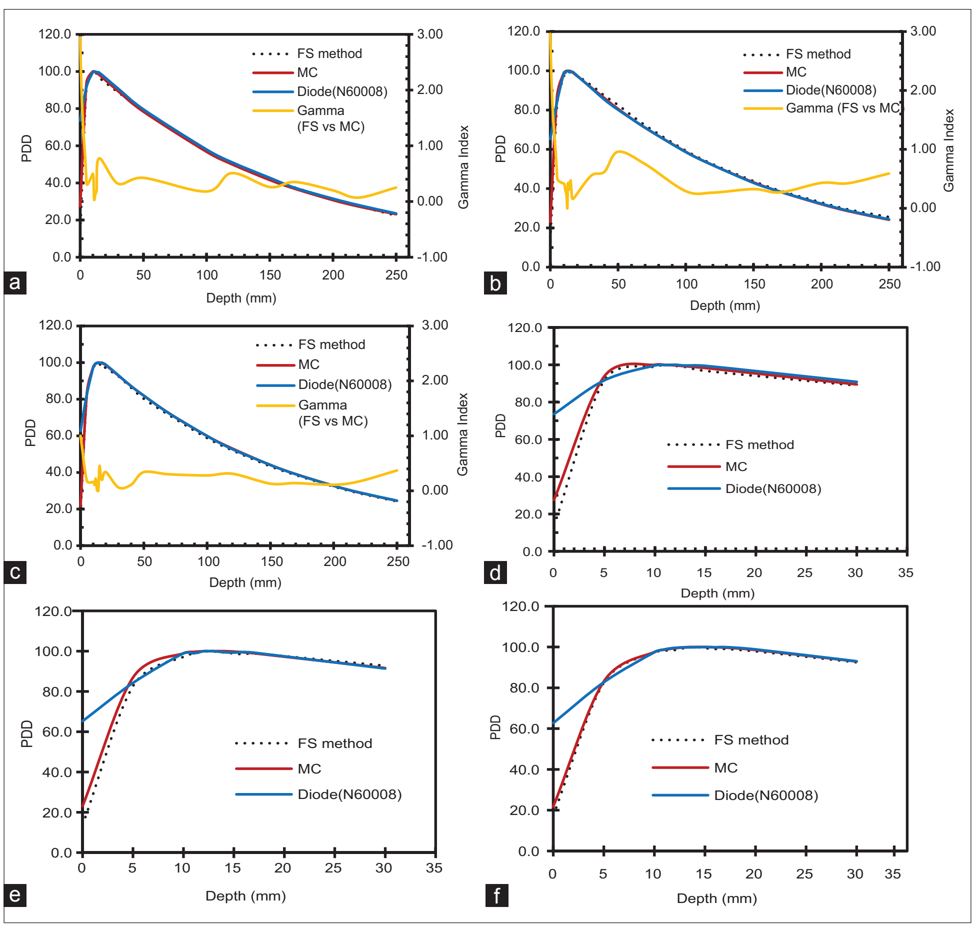

Figure 9: Percentage depth dose comparison for different radiosurgery cones. (a) 5 mm diameter, (b) 10 mm diameter, and (c) 15 mm diameter; percentage depth dose: Film slope method (dotted black line), Monte Carlo (solid red line), diode (N60008) (solid blue line), and 1D gamma evaluation between film slope method and Monte Carlo (solid orange line). Percentage depth dose in the buildup region for (d) 5 mm diameter, (e) 10 mm diameter, and (f) 15 mm diameter

Table 1: Relative output factors measured using EDR2 Ready-Pack film, with film slope method, direct method, Monte Carlo simulated, and diode (N60008) for Elekta radiosurgery cones

Field diameter (mm)	5	7.5	10	12.5	15
FS method	0.665 (±0.02)	0.792 (±0.02)	0.83 (±0.02)	0.868 (±0.01)	0.896 (±0.01)
Direct film method	0.60	0.733	0.755	0.788	0.811
MC	0.674	0.785	0.839	0.882	0.9
Diode N (60008)	0.672	0.797	0.837	0.875	0.897
Percentage difference (FS−MC)	−1.34	0.89	−1.08	−1.6	−0.45

The percentage difference of film slope - MC simulated values are also shown. The values in parenthesis are 1 SD values of the FS method. FS: Film slope, MC: Monte Carlo, SD: Standard deviation

Table 2: Relative output factors obtained with the EBT3 film slope method, direct film method, SNC Edge, Monte Carlo corrected, and Monte Carlo published for 1000 MU/min CyberKnife M6

Field diameter (mm)	FS method	Direct film method	SNC Edge	MC corrected	MC published	Percentage difference FS−MC published	Percentage difference SNC−MC published
5	0.653 (± 0.003)	0.662	0.679	0.647	0.654	−0.2	3.8
7.5	0.805 (±0.002)	0.815	0.84	0.806	0.808	−0.4	3.9
10	0.861 (±0.0003)	0.859	0.887	0.863	0.866	−0.6	2.4
12.5	0.91 (±0.003)	0.902	0.923	0.903	0.907	0.3	1.8
15	0.932 (±0.003)	0.92	0.945	0.932	0.937	−0.5	0.9
20	0.956 (±0.003)	0.95	0.966	0.959	0.962	−0.6	0.4
25	0.971 (±0.001)	0.956	0.976	0.975	NA	NA	NA
30	0.983 (±0.001)	0.967	0.982	0.982	0.983	0.00	−0.1
35	0.986 (±0.001)	0.985	0.986	0.986	NA	NA	NA
40	0.987 (±0.002)	0.978	0.989	0.989	0.991	−0.4	−0.2
50	0.993 (±0.001)	0.984	0.995	0.995	0.998	−0.5	−0.3

The values in the parenthesis are 1 SD values of the FS method. FS: Film slope, MC: Monte Carlo, SD: Standard deviation

the % deviation and the gamma value between the two PDDs increased. The observed 'd_{max}' depths using FS method were 11, 12.6 and 14 mm for 5, 10, and 15 mm cones respectively, as against the MC calculated 'd_{max}' depths of 10, 13, 14 mm.

The relative output factor for linear accelerator radiosurgery small fields of 6 MV flattened photon beams

The measured ROFs by FS method, direct film method using EDR2 ready pack film, diode (N60008), and Monte Carlo calculated values for 5, 7.5, 10, 12.5, and 15 mm diameter radiosurgery fields normalized to 10 ×10 cm^2 open field of 6 MV photon beam presented in Table 1. The ROFs measured by the FS method showed good agreement with the MC calculated values. The observed maximum % difference was within 1.6% as shown in Table1. The measured ROFs by direct film method were systematically lower for all the cone sizes and the maximum % difference was 11.6% for 5 mm cone. The maximum % difference between Diode (N60008) and MC value was 1.5% for the 7.5 mm cone. The calculated slope from the curve fit of the RFDR curves are up to 5 decimals with the R^2 values near unity as shown in the Figure 7.

The relative output factors for fixed cone applicator of 1000 MU/min CyberKnife M6 linac

The ROFs determined by FS method, direct film method, SNC Edge diode, SNC Edge diode corrected using MC factors, and compared with MC published ROFs for 1000 MU/min CyberKnife M6 linac are presented in Table 2. The ROFs measured using EBT3-FS method showed good agreement with the published MC values.

The ROFs by FS method and MC published values agree within ± 0.6%. The maximum % difference between direct Film method - MC published was 1.8% for 15 mm cone and SNC Edge detector – MC published was 3.9% for 5 mm cone. When SNC Edge detector values were corrected using MC simulated correction factors, they agreed within ±0.54% with MC published values.

Discussion

A simple but novel and more accurate method for the determination of relative radiation doses in a variety of radiation fields has been demonstrated. In studying the RFDR plots of radiographic films, it was observed that the slope of the linear portion of the RFDR curve was proportional to the dose rates at the point of measurement.

This principle was applied to the determination of PDDs of megavoltage photon and electron beams and ROFs and PDDs for small fields in radiosurgery with linac and CyberKnife.

The accuracy of the relative dose measurements was first verified for large and medium fields using EDR2 radiographic and EBT3 Gafchromic films. The method was further applied for relative dose measurements in small-field dosimetry, where the accuracy has been verified using MC methods.

The film slope (FS) method reduces the problems associated with the detector size, detector positioning, and volume averaging encountered in direct measurements using conventional ICs and other detectors. The method has the advantage of overcoming problems of poor resolution with measurements in high gradients, uncertainties due to response variation in mixed fields, and errors due to lack of electronic equilibrium in small-field dosimetry.

However, the film dosimetry method suffers from certain practical difficulties of film handling such as cutting of films and repacking them light proof (in case of Kodak EDR2 Ready-Pack film) and film orientation and alignment during scanning (for Gafchromic EBT3 film) to minimize polarization effect. Color density growth with post irradiation elapsed time, especially during the first 24 h, was eliminated by maintaining time interval between irradiation and scanning the same.

The sensitivity of the FS method depends on the dose rate at the point of measurement. Hence, in lower dose fields, such as the tail end of the depth dose curve, the method becomes too insensitive because the change in slope will be too small to measure.

Although this method involves much tedious procedures related to film handling, due to its improved accuracy, it has proven to be a valuable alternative in validating small-field dosimetry using ICs. The accuracy of the derived ROFs and PDDs for linac radiosurgery cones using this new technique was verified with the MC calculation. The agreement of the two methods was within 3% and 1.34%, respectively, for the PDD and ROF values.

The mean of standard uncertainty of Gafchromic EBT3 film observed in our study was 1.4% which is better than the Type A uncertainty (1.8%) reported in the literature.[31] The observed Type I uncertainty for the EDR2 film was 2.4%.

Of all the detectors used so far in experimental dosimetry, the film method described here has the highest resolution (the film being almost a point detector) and is most suitable for relative dose measurements in high gradient fields in the buildup and penumbral regions and in beam profile measurements in unflattened megavoltage beams. The detector size in the film measurements of relative doses is the aperture size of the film scanner which is 89 μm for 16-bit image scanned with VXR-16 Dosimetry PRO™ Film Digitizer (Vidar Systems Corporation, Herndon, Virginia) or 25 μm for Gafchromic EBT3 films.

The high dosimetric accuracy of PDD and ROF measurements presented in this work helps in speedy commissioning of treatment planning system and experimental verification of the planned dose.

Hence, the novel method presented here relating the slope of the relative dose–response curve to dose rate is a simple and versatile dosimetric application.

Conclusions

The authors have developed a novel and more accurate method for the relative dosimetry of photon and electron beams. This offers a unique method to determine PDD and ROF with a high spatial resolution in fields of steep dose gradient and small fields. It eliminates the need for establishing absolute dose values for calibration curve for relative film dosimetry. The method was applied to both types of films, radiographic and RC films. The comparison of PDDs and ROFs measured using this method with the MC calculated values showed good agreement.

Financial support and sponsorship

Nil.

Conflicts of interest

There are no conflicts of interest.

References

1. International Atomic Energy Agency. Absorbed dose Determination in External Beam Radiotherapy: An International Code of Practice for Dosimetry Based on Standards of Absorbed dose to Water. Vienna, Austria: Technical Reports Series; 2000. p. 398.
2. A protocol for the determination of absorbed dose from high-energy photon and electron beams. Med Phys 1983;10:741-71.
3. Almond PR, Biggs PJ, Coursey BM, Hanson WF, Huq MS, Nath R, *et al.* AAPM's TG-51 protocol for clinical reference dosimetry of high-energy photon and electron beams. Med Phys 1999;26:1847-70.
4. Scott AJ, Nahum AE, Fenwick JD. Using a Monte Carlo model to predict dosimetric properties of small radiotherapy photon fields. Med Phys 2008;35:4671-84.
5. Palmans H, Andreo P, Huq MS, Seuntjens J, Christaki K. Dosimetry of Small Static Fields used in External Beam Radiotherapy: An IAEA-AAPM International Code of Practice for Reference and Relative dose Determination. Technical Report Series No 483. Vienna: International Atomic Energy Agency; 2017. Available from: http://www-pub.iaea.org/books/IAEABooks/11075/Dosimetry-of-Small-Static-Fields-Used-in-External-Beam-Radiotherapy-An-International-Code-Of-Practice-For-Reference-And-Relative-Dose-Determination. [Last accessed on :2019 May 17].
6. Nahum AE. Perturbation effects in dosimetry: Part I. Kilovoltage x-rays and electrons. Phys Med Biol 1996;41:1531-80.
7. Sharpe MB, Jaffray DA, Battista JJ, Munro P. Extrafocal radiation: A unified approach to the prediction of beam penumbra and output factors for megavoltage x-ray beams. Med Phys 1995;22:2065-74.
8. Zhu TC, Bjärngard BE. The head-scatter factor for small field sizes. Med Phys 1994;21:65-8.
9. Zhu TC, Bjärngard BE. The fraction of photons undergoing head scatter in x-ray beams. Phys Med Biol 1995;40:1127-34.
10. Zhu TC, Bjärngard BE, Shackford H. X-ray source and the output factor. Med Phys 1995;22:793-8.
11. International Commission on Radiation Units and Measurements. Prescribing, recording and reporting of stereotactic treatments with small field photon beams. ICRU report 91, small field dosimetry. J Int Comm Radiat Units Meas 2014;14;31-53.
12. Laub WU, Wong T. The volume effect of detectors in the dosimetry of small fields used in IMRT. Med Phys 2003;30:341-7.
13. Pai S, Das IJ, Dempsey JF, Lam KL, Losasso TJ, Olch AJ, *et al.* TG-69: Radiographic film for megavoltage beam dosimetry. Med Phys 2007;34:2228-58.
14. Djouguela A, Kollhoff R, Rubach A, Harder D, Poppe B. The Schwarzschild effect of the dosimetry film Kodak EDR 2. Phys Med Biol 2005;50:N317-21.
15. Lindsay P, Rink A, Ruschin M, Jaffray D. Investigation of energy dependence of EBT and EBT-2 gafchromic film. Med Phys 2010;37:571-6.

16. Chiu-Tsao S, Massillon-JG, Domingo-Muñoz I, Chan M. SU-E-T-96: Energy dependence of the new GafChromic – EBT3 film's dose response-curve. Med Phys 2012;39:3724.
17. Paskalev KA, Seuntjens JP, Patrocinio HJ, Podgorsak EB. Physical aspects of dynamic stereotactic radiosurgery with very small photon beams (1.5 and 3 mm in diameter). Med Phys 2003;30:111-8.
18. Zhu XR, Allen JJ, Shi J, Simon WE. Total scatter factors and tissue maximum ratios for small radiosurgery fields: Comparison of diode detectors, a parallel-plate ion chamber, and radiographic film. Med Phys 2000;27:472-7.
19. Ramani R, Lightstone AW, Mason DL, O'Brien PF. The use of radiochromic film in treatment verification of dynamic stereotactic radiosurgery. Med Phys 1994;21:389-92.
20. Sipilä P, Ojala J, Kaijaluoto S, Jokelainen I, Kosunen A. Gafchromic EBT3 film dosimetry in electron beams-energy dependence and improved film read-out. J Appl Clin Med Phys 2016;17:360-73.
21. Lynch BD, Kozelka J, Ranade MK, Li JG, Simon WE, Dempsey JF. Important considerations for radiochromic film dosimetry with flatbed CCD scanners and EBT GAFCHROMIC film. Med Phys 2006;33:4551-6.
22. Casanova Borca V, Pasquino M, Russo G, Grosso P, Cante D, Sciacero P, *et al.* Dosimetric characterization and use of GAFCHROMIC EBT3 film for IMRT dose verification. J Appl Clin Med Phys 2013;14:4111.
23. Gonzalez-Lopez A, Vera-Sanchez JA, Lago-Martin JD. Small fields measurements with radiochromic films. J Med Phys 2015;40:61-7.
24. Morales JE, Butson M, Crowe SB, Hill R, Trapp JV. An experimental extrapolation technique using the gafchromic EBT3 film for relative output factor measurements in small x-ray fields. Med Phys 2016;43:4687.
25. Lewis D, Micke A, Yu X, Chan MF. An efficient protocol for radiochromic film dosimetry combining calibration and measurement in a single scan. Med Phys 2012;39:6339-50.
26. Devic S, Tomic N, Aldelaijan S, Deblois F, Seuntjens J, Chan MF, *et al.* Linearization of dose-response curve of the radiochromic film dosimetry system. Med Phys 2012;39:4850-7.
27. Dainty JC, Shaw R. Image Science: Principle, Analysis and Evaluation of Photographic-Type Imaging Processes. New York: Academic; 1974.
28. Francescon P, Kilby W, Satariano N. Monte carlo simulated correction factors for output factor measurement with the cyberKnife system-results for new detectors and correction factor dependence on measurement distance and detector orientation. Phys Med Biol 2014;59:N11-7.
29. Moignier C, Huet C, Barraux V, Bassinet C, Baumann M, Sebe-Mercier K, *et al*. Determination of small field output factors and correction factors using a Monte Carlo method for a 1000 MU/min CyberKnife system equipped with fixed collimators. Radiat Meas 2014;71:287-92.
30. Low DA, Dempsey JF. Evaluation of the gamma dose distribution comparison method. Med Phys 2003;30:2455-64.
31. Shamurailatpam SD, Kumar CR, Dutt SS, Shaju P, Rasal Sachin K, Sawant Mayur B, *et al*. Experimental determination of stereotactic cone size and detector specific output correction factor. Br J Radiol 2017;90:1077.