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Characterization of Wedge Factors and Dose Distributions in Radiotherapy with Symmetric and Asymmetric Physical Wedged Beams of 6 MV Photon Beam

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ABSTRACT

Introduction: Physical wedge by modify photon beam shape and intensity has been utilized in radiotherapy to obtain uniformly dose distribution in tumor site with reduced hot spots. Calculation of dosimetric parameters for both symmetric and asymmetric wedged fields is proved necessary during linear accelerator (Linac) commissioning. The present study aimed to achieve output factors and dose profiles for symmetric and asymmetric wedged fields of 6 MV beams.

Material and Methods: The Siemens PRIMUS Linac head for 6 MV beam was simulated by BEAMnrc and all dose calculations were performed by DOSXYZnrc code. Percentage depth dose (PDD) and profiles for open and wedged (15° and 45°) fields were compared with corresponding measurements. Wedge factors for 10 x 10 cm^2 field were obtained as a function of lateral distance as well for half beam wedged fields.

Results: Based on the results of the present study, the calculated doses were in agreement with the measured data. The output factors on the central axis of symmetric wedged beams decreased to 0.693 and 0.307 for 15˚, and 45˚ wedges. The total photon fluence of 15˚ and 45˚ physical wedged fields reduced to 71.6% and 27.7% of open field, respectively.

Conclusion: The output factor for asymmetric wedged fields was found to be lower than corresponding symmetric open and wedged fields, particularly at field edges. Lack of scattering photons near the half beam edges resulted in dose fall-off in these regions possible to be overestimated by treatment planning system and consequently caused cold spots at target volume.

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Introduction

Delivery of lethal dose to the target volume with minimal possible dose to the peripheral health tissues has remained a major challenge in radiation treatment of tumors due to the steep sigmoidal dose response curves of tumor control probability and normal tissue damage [1].

To overcome this obstacle in conformal teletherapy by megavoltage photon beams, the radiation beam is modified by some useful tools, such as multileaf collimators (MLCs), wedges, and compensators. Accordingly, shifting of isodose curves is a common technique, especially for some clinical situations, such as patients with malignancies of brain, head and neck, breast, upper and lower abdomen, and urinary bladder, in an attempt to improve dose uniformity in the target volume and simultaneously keep the dose as low as possible in organs at risk [2-4]. Physical wedges (PWs) is a beam modifier utilized apart from elaborate techniques, such as field-in-field [3], enhanced dynamic wedges (EDWs) [5] and intensity modulated radiation therapy (IMRT) [6,7]. They are still widely used as a missing tissue compensator in order to shift isodoses curves for the achievement of a uniform dose inside the tumor volume without cold spots and as low as possible a dose in adjacent healthy tissues without hot spots [2, 4, 8].

Implementation of correct dosimetric parameters of modified beams by wedges on treatment planning system (TPS) seems necessary for the accurate estimation of dose distribution. This is due to the considerable attenuation effect of PWs originated

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from their high atomic number (i.e. stainless steel, lead or tungsten alloys) [5, 9-12]. The radiation intensity strongly varies in the angled direction of the wedge; therefore, the detector dimension should be as small as possible to maintain the essential electron equilibrium and spatial resolution [13]. However, the dosimetric parameters are usually measured for symmetric wedged fields rather than various asymmetric types used in clinical situations. Wedge factor is commonly measured on the central axis of beam and its variation with off-axis distance is not implemented on TPS or applied in manual calculation method to predict dose distributions. In addition, the measurement of all essential parameters, such as output factors and dose profiles for a variety of wedge angles, field sizes, depths, and photon energies, is very time-consuming and tedious. Analytical methods were recommended to calculate wedged dose distribution since some of these essential varieties are frequently neglected due to high workload of radiation departments [14].

Monte Carlo (MC) simulation method is one of the most accurate methods currently used to transport radiation beams for medical applications with no limitations of direct measurements, especially for complex radiation treatment procedures, such as beam modification by compensators [15], MLCs [16,17], and wedges [18,19].

For asymmetric physical wedged beams, a reliable dosimetric data based on direct measurements or/and MC calculations are needed to verify dose calculations of commercial TPS. The change in scattered photons in asymmetric fields is an influential factor in the calculation of the accurate dose distribution which is not implemented in TPS and not considered for daily manual calculations. In this regard, owing to aforementioned complexities, dosimetric properties, such as percentage depth dose (PDD), dose profile curves, and output factors of symmetric and asymmetric open and wedged beams for 6 MV photons of PRIMUS Siemens linear accelerator (Linac) were calculated by EGSnrc-based BEAMnrc and DOSXYZnrc codes.

Materials and Methods

Output, Percentage Depth Dose, and Dose Profile Measurements

The PDDs and dose profiles (at depth of 10 cm) were measured for 6 MV photon beam energies of a Siemens Primus Plus medical Linac with and without (open field) PWs by 0.13 cm^3 ionization chamber with DOSE1 electrometer (Scanditronix-Wellhofer, Germany) at source to surface distance (SSD) of 100 cm and for field sizes of 6 × 6, 10 × 10 and 20 × 20 cm^2. The IBA Blue Phantom (IBA-Dosimetry, Schwarzenbruck, Germany) with the dimensions of 50 x 50 x 50 cm^3 was used for data measurements which were processed by Dosimetry Software RFA plus (Version 5.2, Scanditronix-Wellhofer, Germany). Each measurement was repeated three times with the precision of ± 0.2%. All dose measurements were carried out according to the recommendations of international atomic energy agency (IAEA) protocol, TRS-398 [13]. The wedge factor is defined as the ratio of the doses in water at the reference point of 10 x 10 cm^2 field size with and without the wedge [13].

Benchmarking Of 6 MV-Modeled Siemens Linear Accelerator Head: Open and Symmetric Wedged Photon Beams

The Linac head (Siemens PRIMUS-6 MV photon mode, USA) was modeled by EGSnrc-based BEAMnrc code [20]. All the dimensions and materials required to build the MC model of Linac head were obtained from vendor-supplied datasheets. Using BEAMnrc code, the exit window, target, primary collimator and flattening filter, monitoring chambers, mirror, jaws and PW filters were simulated by proper component modules (CMs), including SLAB, FLATFILT, CHAMBER, MIRROR, JAWS and PIRAMIDS, respectively. In this regard, the wedges made of steel alloy with non-linear profiles were positioned under the X-jaws at a distance of 40.2 cm from the x-ray target. A schematic of modeled Linac head is depicted in Figure 1.

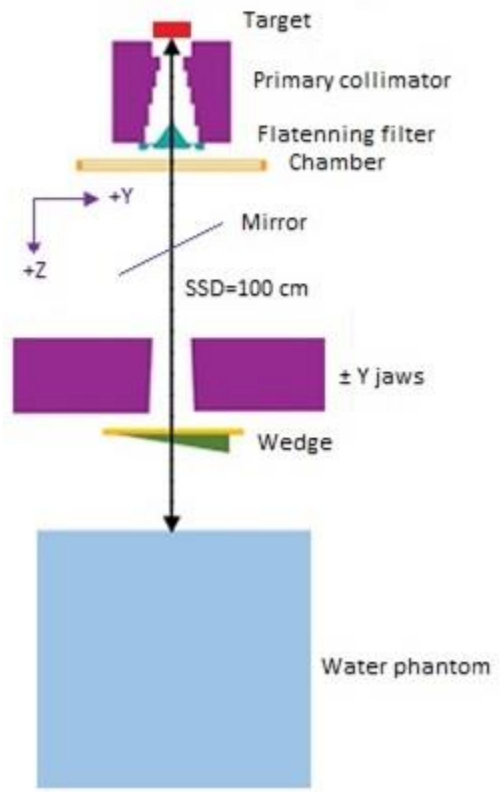

Figure 1. The Z-Y view of a model designed for simulations

Source number 19 was utilized to make an elliptical shape for Gaussian distribution of primary electrons with a Gaussian energy spectrum [20]. Different parameters of incident electron beam (such as energy and radial distribution) were tuned to hit on the transmitting bremsstrahlung target by trial and error method until the attainment of an ideal matching between measured and calculated PDDs , as well as dose profile curves. The phase space files for each mode were generated at the SSD plane (SSD = 100 cm). The history number settings were dependent on the field size, e.g. 100 × 10^6, 50 × 10^6, 20 × 10^6 for 6 × 6, 10 × 10 and 20 × 20 cm^2 field sizes, respectively. The only reported data in this study was related to 10 × 10 cm^2 field size. The global cutoff energy for photon and electron transport were set to 0.01 and 0.700 MeV, respectively. Moreover, directional bremsstrahlung splitting (DBS) technique was utilized with splitting number of 1000, SSD=100 and appropriate field size dependent radius in order to enhance simulation efficiency. Range rejection method with ESAVE=2 MeV for all components except from the target (where ESAVE=0.700 MeV) was also used to reduce running time.

The absorbed dose in defined voxels of water phantom with dimensions of 50 x 50 x 50 cm^3 was calculated using the DOSXYZnrc code. The voxel sizes for the calculated PDDs, in-line and cross-line dose profile curves were 1 × 1 × 0.2 cm^3, 0.2 × 1 × 1 cm^3 and 1 × 0.2 × 1 cm^3, respectively. Dose profile curves were measured and calculated at depth of 10 cm in water phantom. The off-axis variation of output factor (the ratio of absorbed doses at a reference depth of 10 cm with and without wedge) was investigated for Y direction (In-line) at SSD=100 cm.

All calculations were performed until the maximum statistically uncertainty of each detector was < %0.5 inside the field and < %1 outside the field. To reach this statistical uncertainty, the history number of 4 × 10^9 was sampled from the recycled phase space files in DOSXYZnrc code. Simulated PDDs and profiles were obtained by STATDOSE interface and their consistencies with corresponding measurements were investigated by Gamma analysis test (acceptance criteria 3%/3mm). In addition, the photon fluence of generated phase space files was assessed by BEAM Data Processor (BEAMDP). Any other MC parameters were set to default values of EGSnrc. All MC runs were carried out in parallel on a server machine with 21 x 3.00 GHz CPU and 16 GB of RAM.

Monte Carlo Simulation of Asymmetric Open and Physical Wedged Photon Fields

Two asymmetric 10 × 5 cm^2 open fields were modeled by positioning of –Y jaw (for +Y asymmetric open field) or +Y jaw (for –Y asymmetric open field) aligned with the central axis of beam. Two asymmetric wedged fields were simulated by two common mounted 15˚ and 45˚ PWs aligned with the central axis of open beam. Firstly, the X and Y jaws were arranged to model the 10 × 10 cm^2 field at SSD of 100 cm and then for +Y asymmetric wedged field (half beam in direction to thicker part of wedge) only the –Y jaw was positioned aligned with the central axis beam while +y jaw remained fix at its lateral distance. On the same note, for -Y asymmetric wedged field (half beam in direction to thinner part of wedge) only the +Y jaw was positioned aligned with the central axis beam, while -y jaw remained fix. For all of these asymmetric cases, the MC parameters were set as mentioned above.

Results

Validation of Model 6 MV Siemens Linac Head

The simulated incident electron beam to reach the best agreement between the measured and MC calculated was tuned with the mean energy of 6.2 MeV, the Gaussian energy spread with full width at half maximum (FWHM) =1 MeV and the Gaussian spatial spread with FWHM =1.8 mm. The rest of points have good consistencies between measured and calculated doses (gamma index <1) except for build-up regions for PDDs and edge field for profiles. The maximum gamma index for wedged fields was about 1 for dose profile at water depth of 10 cm along the toe region of 45˚ wedge filter. It could originate from uncertainties surrounding geometrical vendor-supplied data regarding wedge's material and geometrical structures.

Open Symmetric Field (Without Physical Wedges)

The estimated gamma index demonstrated that the MC calculated and measured PDDs and dose profiles were revealed to be in good agreement for all investigated fields. Figure 2 only displays the data regarding 10 × 10 cm^2 open field size.

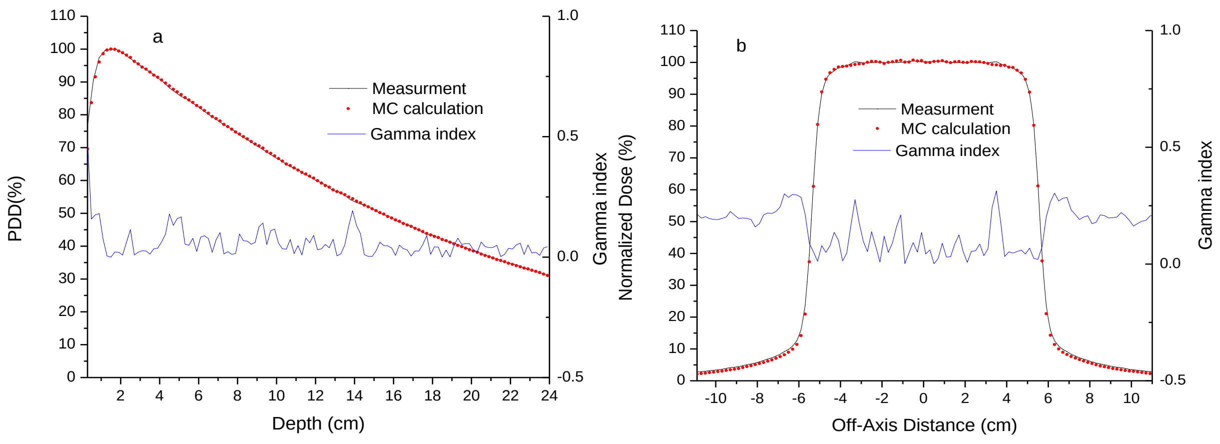

Figure 2. Comparison of the MC calculated and measured a) PDDs and b) dose profile curves for 10 × 10 cm^2 open field size

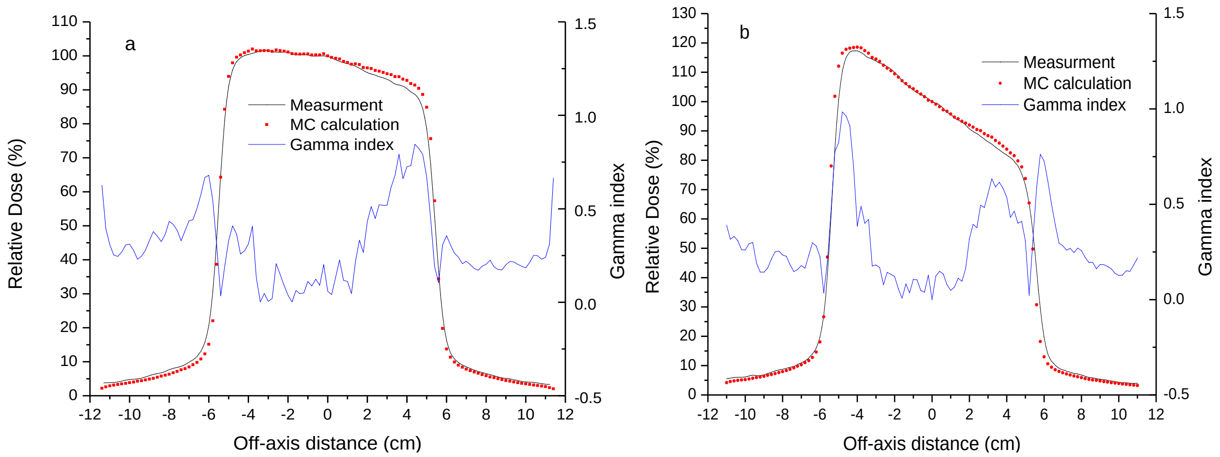

Figure 3. Comparison of the MC calculated and measured dose profile curves for a 10 × 10 cm^2 field size of a) 15˚ PW and b) 45˚ PW

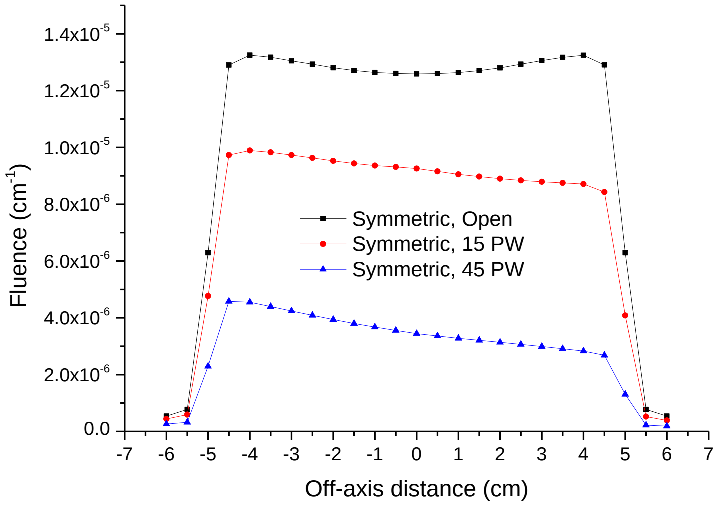

Figure 4. In-line Photon fluences for open field and for 15˚ and 45˚ physical wedged fields of 10 x 10 cm^2 at SSD=100 cm. Each off-axis photon fluence profiles are normalized per incident electron on target

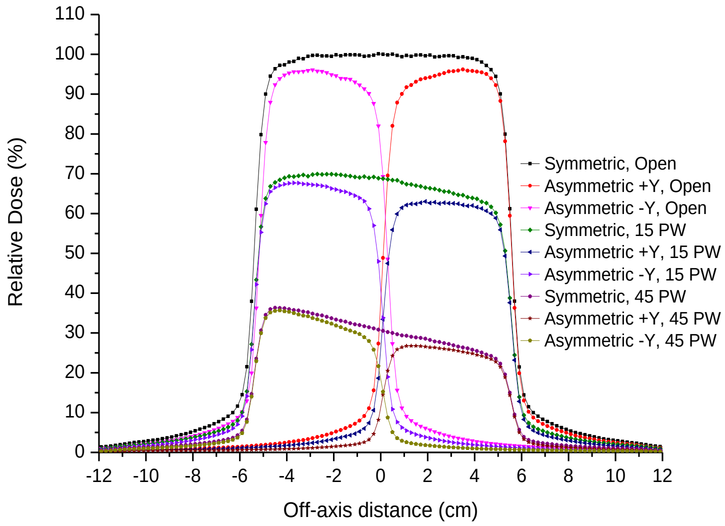

Figure 5. The MC calculated dose profile curves for symmetric and asymmetric of open and 15˚ and 45˚ wedged fields. All dose profile curves were normalized to the central axis dose of symmetric open (standard) 10 × 10 cm^2 field size

Table 1. Calculated dose for symmetric/asymmetric open and wedged fields and related wedge factors

	Position of calculated dose (cm)	Dose (Gy per incident particle)	Wedge Factor
Symmetric, 15 PW	(0,0,10)	5.57E-17	0.687
Asymmetric +Y, 15 PW	(0,+2.5,10)	5.06E-17	0.658
Asymmetric –Y, 15 PW	(0,-2.5,10)	5.40E-17	0.703
Symmetric, 45 PW	(0,0,10)	2.48E-17	0.307
Asymmetric +Y, 45 PW	(0,+2.5,10)	2.12E-17	0.276
Asymmetric –Y, 45 PW	(0,-2.5,10)	2.65E-17	0.345
Symmetric, open	(0,0,10)	8.09E-17	-
Asymmetric +Y, Open	(0,+2.5,10)	7.68E-17	-
Asymmetric –Y, Open	(0,-2.5,10)	7.68E-17	-

The differences between measured and simulated PDDs especially for the first build up depths can be attributed to the measurements uncertainties which could be affected by the inherent volume of the ion chamber [21], as well as electron contaminations [22]. The maximum relative error was observed for dose profile at the farthest lateral distance of 11 cm off-axis. These negligible differences may be sourced from inaccurate vendor-supplied data or/and the non-ideal tuning of incident electron beam parameters since it is a time-consuming process.

Symmetric Physical Wedged Field

The 15˚ and 45˚ PWs mounted on Siemens Primus Linac head were simulated and validated by comparing the MC calculated and measured dose profile curves for 10 × 10 cm^2 symmetric field size. The MC calculated and measured dose profile curves for symmetric wedged field are depicted in Figure 3. Apart from the above discussed reasons, there are negligible discrepancies at off-axis distances related to the two ends of each wedges that may originate from some uncertainties surrounding the mass compositions of wedges or/and their multi part dimensions. The calculated gamma index displayed good agreement between shifted dose profiles of MC calculations and measurements.

In-line Photon fluences for open ,15˚, and 45˚ physical wedged fields with resolution of 5 mm were calculated for 10 x 10 cm^2 field size at SSD=100 cm through the analysis of phase space files using (BEAM Data Processor) BEAMDP. The curves of in-line Photon fluences for open field and physical wedged fields are presented in Figure 4. The total photon fluence inside the 15˚ and 45˚ physical wedged fields decreases to 71.6% and 27.7% of open field, respectively.

Asymmetric Physical Wedged Field

The variations of normalized dose with off-axis distance for symmetric and asymmetric of open and wedged beams were calculated and displayed in Figure 5. Table 1 displays the quantitative value of wedge factors and absorbed doses at determined points calculated for several symmetric and asymmetric open and wedged fields.

Discussion

The output factors on the central axis of symmetric wedged beams decrease to 0.687 and 0.307 for 15˚ and 45˚ PWs, respectively, that is in good agreement with the previously reported measured of 0.675 and 0.312. These agreements are also comparable with the results indicated in other studies [19, 23,24].

The photon fluence is almost uniform across the open field, while it continuously decreases from the toe to the heel region of wedged field due to more attenuation of beam at the higher thickness of heal side, compared to toe side across the photon beam width (Figure 4). As expected, the increase in PW angle increase the beam attenuation and results in a steeper dose profile. The same trend was also observed in a study conducted by Geraily et al. [25]. The presence of PWs in beam line increases the average energy of beam that is known as beam hardening effect of PWs. The average energy of photon for toe, center, and heel regions were 1.62, 1.57, and 1.62 MV for open field ; 1.85, 1.92 and 1.91 MV for 15°PW; and 2.16, 2.31 and 2.35 MV for 45° PW, respectively. As anticipated, the hardening effect of PW was found to be higher for the thicker part and increased with PW angle that is consistent with previous reported data [18, 23]. In addition, this hardening effect of wedge filter markedly affects dosimetric properties of beam. In this regard, Biglari et al. reported that variation of scatter factor (S_C) in open and wedged fields had the maximum deviation of 0.9% and 6.8% and minimum of 0.4% and 2.7% for 30° and 60° angles of wedge, respectively [26]. The results of another study performed by Mohammadkarim et al. confirmed that accurate dose delivery with externally wedged photon beams by external diode dosimeters requires the estimation of exit surface dose correction factors in various wedge angles. The deviation of off-axis wedge correction factors of the exit surface wedged fields from the central axis factor may be as large as ±10% at the evaluated depths [27]. The variation of these correction factors could be attributed to different beam modulation due to beam passing from different thickness of wedge across the beam line.

Figure 5 demonstrates that output factors for unshielded regions of asymmetric open beams are lower than symmetric open beams and steadily falloff at the nearer distances from the field edge probability due to the lack of scattered photons from the shielded regions in water phantom. The output factors markedly decrease when wedge filters are located across the incident beam (symmetric PWs) due to beam hardening effect of PW and increase the wedge angle intensify this effect [9, 28, 29]. While wedge factor is measured only on the central axis of beam for the calculation of dose distribution, the output factors decrease gradually from the toe side to the heal part of wedges owing to different attenuation of beam across the wedge. Khan attempted to formalize the output factors of symmetric and asymmetric wedged beams and discussed that the scatter factor for the asymmetric collimation are to be the same as for the symmetric collimation since they are basically a function of collimator opening [30]. Furthermore, there exist other parameters affecting output factor which must be taken into account when calculating isodose distributions and monitor unit (MU). Moreover, Niroomand-Rad et al. and Kemikler reported that wedge factor for symmetric and half-collimated asymmetric jaw setting depends on depth and field size and this dependence is a function of beam energy, as well as the design of the treatment head and PWs [31,32].

Output factors of asymmetric wedged beam are always lower than those of symmetric wedged beam, especially at adjacent distances to field edges that must be considered in the accurate calculation of dose, comparable to symmetric and asymmetric open fields. As depicted in Figure 5 and Table 1, decreased output factors especially at adjacent regions of asymmetric open and wedged field edges resulted in decreased dose profiles and consequently an unacceptable cold spot at the target volume.

Conclusion

The presence of a physical wedge across the beam line led to a decrease in photon fluence and beam hardening. The output factor for asymmetric wedged fields was found to be lower, compared to corresponding symmetric open and wedged fields, particularly at field edges. Furthermore, lack of scattering photons near the half beam edges resulted in dose falloff at these regions where overestimated by treatment planning system and led to cold spots at target volume.

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