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Multi-source modeling of flattening filter free photon beams

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In conventional clinical accelerators, a flattening filter is placed in the beamline to produce a uniform dose distribution across the treatment beam. However, the flattening filter is a major source of scatter, and it attenuates the beam intensity considerably. Hence, in IMRT treatments, the removal of the flattening filter could reduce the treatment times and the dose to organs outside the target. In this work, unflattened beams were modeled using a multiple-source model, which includes separate sub-sources for primary photons, extra-focal photons, and contamination electrons. The off-axis variation in the bremsstrahlung photon spectrum is accounted for by attenuating an initial Monte Carlo simulated spectrum with an effective material thickness at each radial distance. The extra-focal source is modeled using a Gaussian plane source located below the target. The electron contamination is modeled with a dual-Gaussian plane source located at the target. The free parameters of the model were derived from depth-dose and profile measurements by minimizing a gamma error measure between measurements and dose calculations. The objective function also includes a heuristic penalty term to constrain the parameter values into a physical range. During the optimization, a fast pencil-beam-kernel based point dose calculation method was used. Powell's direction search method was applied for the minimization. In final dose calculations, AAA algorithm (Eclipse™ Integrated Treatment Planning System) was used. The proposed procedure was applied to 6X and 18X beams measured with a Varian accelerator without the flattening filter. The agreement between measurements and dose calculations was excellent for both energies: the deviations were within 1% and 2mm for each field size. The optimized parameters indicate that the extra-focal scatter is significantly reduced in unflattened beams. The mean photon energy was also reduced significantly due to missing beam hardening from the flattening filter. Research sponsored by Varian Medical Systems Inc.

NOTES:

Introduction

The flattening filter is used in conventional linear accelerators to create a uniform dose distribution across the treatment beam at a certain depth in a water phantom. This beam shaping is performed, since the initial bremsstrahlung radiation created in the photon target has a non-uniform intensity across the treatment beam. As a drawback, however, the flattening filter is a major source of scattered radiation. It also attenuates the beam intensity considerably, increasing the number of monitor units required to deliver a certain prescription dose.

In intensity modulated radiation therapy (IMRT), an optimal fluence map is computed based on a set of dose-volume constraints for the target and critical organs. The multi-leaf collimator (MLC) leaf sequences are then optimized to realize this fluence as accurately as possible in the presence of physical leaf-motion constraints. In IMRT, it is not be necessary to have a uniform fluence across the field – the leaf sequences can be adjusted to produce similar optimal fluences as in flattened beams. The removal of the flattening filter would have two significant benefits: (1) shorter treatment times, and (2) reduced the extra-focal scatter, which may reduce the dose delivered to normal tissues and critical organs. The removal of the filter has been reported to increase the dose rate by a factor of 2.3 for 6X and 5.5 for 18X beam [1].

We propose a method for modeling flattening filter free beams using a multiple-source model and parameter derivation process originally designed for flattened beams. The method is validated with two beam data sets (6X and 18X energies) measured with a Varian Clinac 23EX having the flattening filter removed. The optimized source model parameter values for unflattened beams are also compared to the corresponding values for flattened beams with the same nominal energies.

Materials and methods

The multiple-source model

The multiple-source model used in this work includes three sub-sources: primary photon source, extra-focal photon source, and electron contamination source. The primary source models the brehmsstrahlung radiation created in the target as a result of the impinging electron beam. It also models the off-axis variation in the primary photon spectrum across the treatment beam. This variation is caused by two factors: (1) beam hardening normally occurring in the flattening filter and (2) off-axis variation in the initial bremsstrahlung spectrum. The extra-focal radiation models the photons that result from interactions in various components in the accelerator head (primary collimator, flattening filter, secondary jaws). The electron contamination source models the electrons created in photon interactions occurring in the various accelerator head components and in the air [2].

The primary photon radiation is approximated in this work with a point source located at the plane of the target. The particle spectrum of photons after the target, $S(E)$, has been simulated with the BEAMnrc [3] Monte Carlo code for each nominal energy. Realistic material and thickness information obtained for Varian accelerators were used in the simulation, and the electron beam energy was set to the accelerator nominal energy. The intensity distribution of the electron beam was a 2D Gaussian with a full width at half maximum (FWHM) value of 1.0 mm. To model the off-axis variation in the spectrum, each energy component of the initial spectrum S(E) is attenuated using the exponential attenuation law and an effective thickness d(r) for each radial distance. The effective thickness d(r) required to harden the initial spectrum is determined via an iterative process matching the mean energy of the attenuated spectrum to an optimized mean radial energy $\overline{E}(r)$ value at each radial distance. The discrete points defining the mean radial energy curve $\overline{E}(r)$ are free parameters in the model. This hardening process is applied also for flattening filter free beams, since the true energy of the beam may differ from the nominal energy used in the BEAMnrc simulation, and the bremsstrahlung radiation has a spectrum that depends slightly on the off-axis position in the beam. The variation in the beam intensity (energy fluence) across the beam is modeled with an intensity profile I(r), which is defined using discrete points that are free parameters in the model.

The extra-focal radiation is modeled using a finite-size source located at the bottom plane of the flattening filter. The extra-focal source is assumed to have a Gaussian intensity distribution. The extra-focal source models the radiation scattered mainly from the flattening filter, but also from the other accelerator components. The extra-focal energy fluence is computed by adding the rays from each source element to each destination fluence element. If a ray hits any of the collimating devices, the contribution from that ray is ignored. The extra-focal source has three free parameters: width of the Gaussian (σ_{ef}), weight with respect to the primary photon source (w_{ef}), and a mean energy ($\overline{E}_{ef}$).

The electron contamination is modeled with a finite-size dual Gaussian source located at the target plane. The electron contamination energy fluence is computed as a sum of two terms, both of which are calculated as a convolution of the primary energy fluence and a Gaussian. The widths of the Gaussians ($\sigma_{e,1}$ and $\sigma_{e,2}$) as well as their relative weights (c and 1-c) are free parameters in the model. These parameters also model the field size dependence in the electron contamination dose, since the width of the primary energy fluence to be convolved with the Gaussians varies with field size. The total energy deposited by the contaminant electrons as a function of depth is modeled by an empirical curve $c_e(z)$, which is determined from the difference between the measured PDD and calculated PDD without contaminant electrons for the largest field size.

The derivation of the parameters using an optimization based process

The free parameters of the source model $(\overline{E}(r), I(r), {}_{ef}, w_{ef}, \overline{E}_{ef,}\ {}_{e,1}, {}_{e,2}, c)$ were derived from basic beam data measurements using an automatic optimization-based process [2]. The objective function to be minimized consists of two terms: a gamma error term measuring the deviations between measurements and current dose calculations, and a heuristic penalty term constraining the parameter values to a physical range. The gamma error term is computed as a sum of the gamma errors (1%, 1mm) [4] between each measurement point in the depth doses, profiles and diagonal profiles, and the corresponding calculated curve. For example, field sizes 4x4, 10x10, 20x20, 40x40 cm^2, and profile measurement depths d_{max}, 5, 10, 20 and 30 cm can be used as input for the optimization process. The dose calculation during the optimization is performed with a fast point dose calculation method, which is based on the superposition of Monte Carlo simulated pencil beam kernels. The objective function is minimized using the Powell's direction search method, which iteratively performs a line minimization along a set of search directions [5].

The dose calculation method

In this work, the final dose calculations were performed with AAA dose calculation algorithm (version 8.0.5) in Eclipse™ Integrated Treatment Planning System, (Varian Medical Systems, Palo Alto, CA). AAA is a superposition/convolution dose calculation method, which is based on the algorithm originally developed by Ulmer *et al* [6], but the Gaussian functions have been replaced by exponential functions to better model the scatter near the borders of lateral heterogeneities. AAA divides the clinical beam into small beamlets and the patient body into a 3D matrix of divergent calculation voxels along these beamlets. For each beamlet, a poly-energetic pencil beam kernel is constructed from Monte Carlo simulated mono-energetic kernels based on the spectrum at the beamlet position. Then the dose deposition is separated into depth-directed (along the fanline) and lateral (perpendicular to the fanline) components. The depth-directed component takes into account the photon (or electron) fluence and the attenuation along the beamlet. The lateral component describes the phantom scatter perpendicular to the beamlet. The total dose is computed as a supercomposition of the doses from individual beamlets. Finally the contributions from the primary photon source, extra-focal photon source, and electron contamination source are added.

The beam data measurements

The beam data measurements were conducted at the M.D. Anderson Cancer Center (Houston, Texas) with a Varian Clinac 21EX accelerator with the flattening filter removed. Depth dose and profile measurements were made for 6X and 18X beams. A Scanditronix-Wellhöfer two dimensional (2D) phantom and OmniPro-Accept 6.1 data acquisition software were used. The depth dose measurements were made with a PPC40 parallel plate ionization chamber, and the RK chambers were used as a reference (in air) and for measurements of lateral dose profiles. All the chambers were manufactured by Scanditronix-Wellhöfer. The Varian Golden Beam data were used as a reference for flattened beams for 6X and 18X nominal energies.

Results and discussion

The source model parameters were derived using the proposed optimization process for 6X and 18X beam data sets for both flattened and unflattened beams. The resulting optimized parameter values are shown in figure 1 and in table 1. It can be seen (figure 1, left) that the mean energy on CAX of the unflattened beams is about 0.5,…,0.6 MeV lower than for the flattened beams with the same nominal energy. This is caused by missing beam hardening that normally occurs in the flattening filter. The shapes of the optimized intensity profiles for unflattened beams are radically different from the flattened beams (figure 1, right). The beam intensity (energy fluence) drops to about 50% for 6X and to 20% for 18X of the central axis value just before the beam edge. For flattened beams, on the other hand, the optimized intensity profiles are almost flat across the beam. The optimized extra-focal source parameters indicate that the scattered radiation from the beam limiting devices has reduced significantly in the unflattened beams (to 32% of the original value for 6X and to 23% for 18X). Also the effective size of the extra-focal source has increased significantly (from 32mm to 56mm for 6X). The electron contamination parameters were not significantly different between the flattened and unflattened beams (not shown). This indicates that the flattening filter is not a significant source for the contaminant electrons.

Beam	σ_{ef} (mm)	w_{ef} (%)	$\overline{E}_{ef}$ (MeV)
6X, flattened	32	3.1	0.73
6X, unflattened	56	1.0	0.51
18X, flattened	32	2.6	0.53
18X, unflattened	59	0.6	0.50

Table 1. Comparison of optimized extra-focal source parameters for 6X and 18X flattened and unflattened beams.

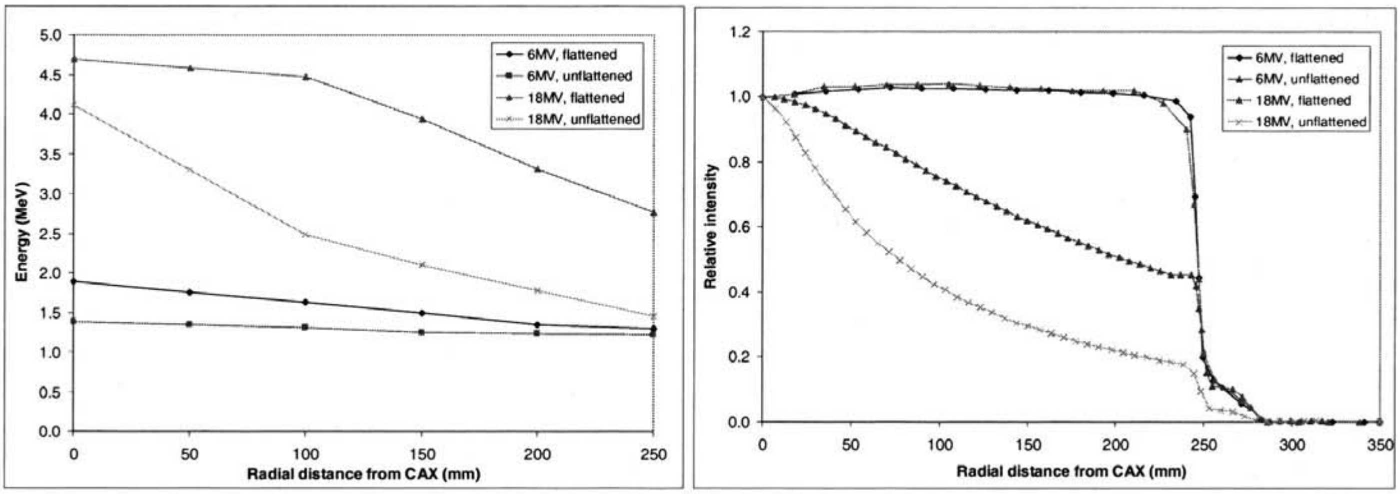

Figure 1. Comparison of optimized model parameters for 6X and 18X flattened and unflattened beams: mean radial energy curves (left), and intensity profile curves (right).

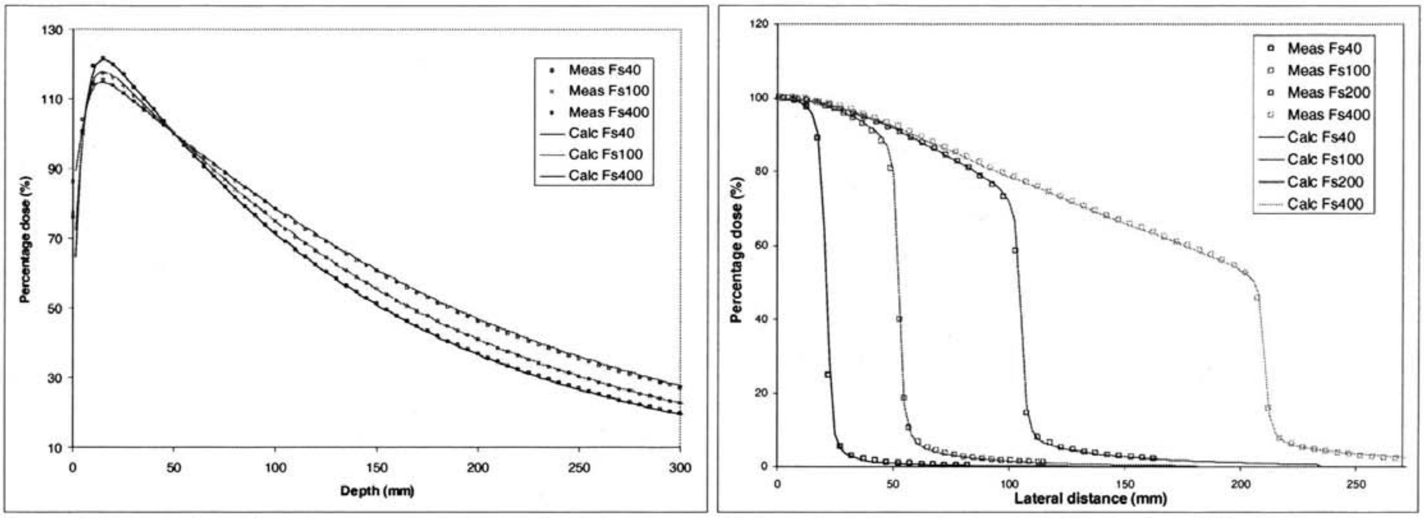

Figure 2. Comparison of measured and calculated depth dose curves (left), and profiles at 5 cm depth (right) for a 6X unflattened beam.

A comparison between measured and calculated depth dose curves and profiles is shown in figures 2 and 3 for 6X and 18X unflattened beams. The agreement between measurements and calculations is excellent for both energies. For depth dose curves, the deviations between measurements and calculations are within 1% with the exception of depths smaller than 20 mm, where the deviations are within 2mm. For profiles at 5 cm depth, the deviations are within 0.5% inside the treatment beam, and within 2mm in the beam penumbra region. Similar agreement in the profiles was observed also for other measurement depths. In order to verify the monitor unit calculation and backscatter modeling, one would need to perform measurements in absolute scale for a set of asymmetric fields, which is an issue of further studies.

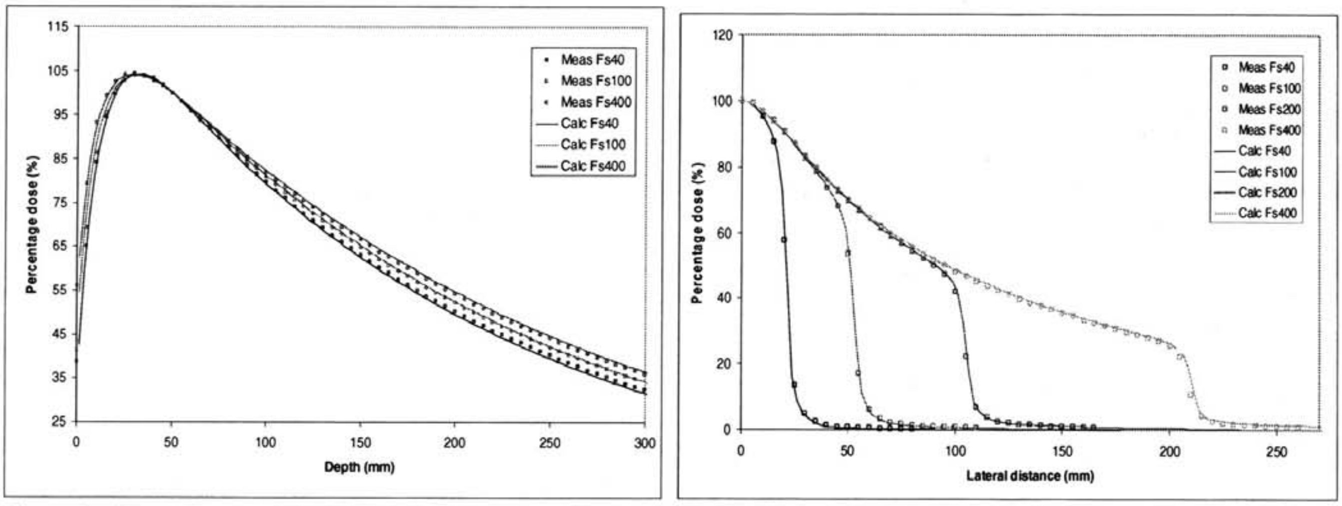

Figure 3. Comparison of measured and calculated depth dose curves (left), and profiles at 5 cm depth (right) for an 18X unflattened beam.

Conclusions

This work demonstrates that a multiple-source model and a parameter optimization process designed for standard treatment beams can be, with small modifications, successfully used to model also flattening filter free beams. Excellent agreement was obtained between measured and calculated depth dose curves and profiles for 6X and 18X unflattened beams. The optimized parameter values indicate that the extra-focal scatter from accelerator head components is significantly reduced in flattening filter free beams. The mean photon energy is also significantly smaller than in standard beams with the same nominal energy. The electron contamination is virtually identical between unflattened and flattened beams.

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