Analytical model of the binary multileaf collimator of Tomotherapy for Monte Carlo simulations

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Abstract. Helical Tomotherapy (HT) delivers intensity-modulated radiotherapy by the means of many configurations of the binary multi-leaf collimator (MLC). The aim of the present study was to devise a method, which we call the “transfer function” (TF) method, to perform the transport of particles through the MLC much faster than the time consuming Monte Carlo (MC) simulation and with no significant loss of accuracy. The TF method consists of calculating, for each photon in the phase-space file, the attenuation factor for each leaf (up to three) that the photon passes, assuming straight propagation through closed leaves, and storing these factors in a modified phase-space file. To account for the transport through the MLC in a given configuration, the weight of a photon is simply multiplied by the attenuation factors of the leaves that are intersected by the photon ray and are closed. The TF method was combined with the PENELOPE MC code, and validated with measurements for the three static field sizes available (40x5, 40x2.5 and 40x1 cm²) and for some MLC patterns. The TF method allows a large reduction in computation time, without introducing appreciable deviations from the result of full MC simulations.

1. Introduction

Helical Tomotherapy (HT) delivers intensity-modulated radiation therapy (IMRT) by the means of the simultaneous movement of the couch, the gantry and the binary multi-leaf collimator (MLC). It is generally recognized that Monte Carlo (MC) simulations provide the most accurate for dose distributions in tissue [1]. For the aforesaid treatment delivery procedures, no fast and reliable Monte Carlo (MC) modeling has been devised to date, although an extensive literature exists on MC modeling of conventional linear accelerators[2], including dynamic accessories [3]-[6]

The treatment head of HT was previously modeled using PENELOPE and commissioned with measurements [7]-[8]. The MLC is the only device in the treatment head which is moving during irradiation and which needs to be actually simulated for each individual treatment. Therefore, the transport of particles through the MLC is a critical issue regarding the speed of the simulation through the treatment head. Since the leaves are often closed during a typical treatment procedure,
straight MC simulations would spend much time tracking particles through the MLC geometry that, in many cases, have a very small probability of reaching the phantom surface.

To increase the calculation efficiency for forthcoming simulations of the helical mode, we have devised a generic analytical method, called the “transfer function” (TF) method, to transport photons through the MLC, without any significant loss of accuracy as compared with the full MC simulations. The MLC geometry was described in all detail to define the TF method, but strong approximations had to be introduced regarding the transport of photons. The accuracy of the TF method was tested by comparing dose distributions in a water phantom obtained from full MC simulations and from simulations using the TF method, for various configurations of the MLC.

Other authors already introduced approximations with a similar approach in their MC model to enable faster simulations of the MLC [3]–[6] but our model differs significantly, principally because neither modification nor approximation of the geometry of the MLC were needed, owing to the capabilities of PENELOPE and to the fact that the MLC is binary.

2. Material and methods

2.1. Geometry definition

The binary MLC of HT is composed by 64 leaves with a projected nominal thickness of 6.25 mm at the isocenter. The MLC is called “binary” because each leaf can have only two states: fully closed or wide open. Accurate MC simulations with PENELOPE of HT in the static mode were previously performed and commissioned with measurements [7]. Since the geometry and materials were fully disclosed by the manufacturer, the treatment head was reproduced in detail in the simulation, using the PENGEOM subroutine package. It was found that for a monoenergetic electron source with an energy of 5.5 MeV and a spatial Gaussian distribution with FHWM = 1.4 mm, calculations and measurements agreed to within 2% and 1 mm for the three static open fields available with HT (40x5, 40x2.5 and 40x1 cm²). The three resulting phase space files, one for each field size and recorded at a plane perpendicular to the beam and just below the jaws, could then be used for describing the transport through the MLC and stored for future developments. Moreover, the MLC geometry definition was verified for different configurations and good agreement was obtained with measurements, similar to the degree of agreement found in the commissioning. Finally, it was also observed that electron contamination in the beam was negligible, a fact that is important for the considerations that follow.

Since the full MC model reproduced accurately the measurements, results obtained from full MC simulations are regarded as reference data in the present study.

2.2. Transfer function (TF) of the MLC

The TF method is set in two steps. In the first step, the phase space file is transformed by adding calculated attenuation factors for the complete MLC geometry with all the leaves closed. The second step created a new phase space file where the MLC configuration was taken into account. This phase space file was then used for dose calculations in a water phantom.

2.2.1. Step 1: transform of the phase space file and calculation of the absorption factors. This transformation was performed by using a modified version of PENELOPE where the photons are transported along their initial direction without interacting (simple ray-tracing) through the MLC geometry with all the leaves closed and the other static parts of the MC geometry present below the phase space file (lead plate below the MLC [7]). For each photon, an attenuation coefficient (µ) is calculated by PENELOPE according to the energy of the particle and the material of the MLC (tungsten). PENELOPE also calculates the raylength (tᵢ where i is the label of the leaf) of the photon in each leaf it passes. If the photon crosses more than three leaves, the photon is disregarded (not included in the transformed phase-space file). Moreover, contaminant electrons are removed and not included in the new phase-space file. Accounting for all the photons who might cross more than three leaves would have required 64 attenuation factors and the 64 associated leaves labels, which would have resulted in a huge phase space file and a slower simulation. Since less than 0.1% of the photons cross more than three leaves, it is likely that neglecting them will not lead to significant deviations from the straight MC method.
Therefore, for each photon kept, three pairs of numbers are added at each line of the transformed phase space file. Each pair consists of the label \((i)\) of a crossed leaf and the associated attenuation coefficient, \(\exp(-\mu t_i)\). Figure 1 illustrates this procedure for the leaves 20 to 24. This first step needs to be performed only once for a given phase space file.

2.2.2. Step 2: Accounting for the MLC configuration. A new phase space file, in a plane placed just below the MLC, is generated. Each photon is assumed to move straight ahead through the MLC and its position coordinates are replaced by those of the intersection between the straight trajectory and the lower phase-space plane. It is now straightforward to account for an arbitrary MLC configuration. Let us assume that the state of each leaf (open or close) is known. It suffices to read, for each particle, the labels and the associated attenuation coefficients and toggle to one the attenuation coefficients corresponding to open leaves (no attenuation in that case). The weight of the photon is then multiplied by the adapted attenuation coefficients and the corrected weight is written into the new phase space file for future dose calculation. It is clear that the simulation time through the MLC itself is virtually zero (it requires to read 6 six variables and perform a multiplication) if one wants to calculate dose distributions in water or in a CT structure.

**Figure 1.** Schematic representation of the ray-tracing technique performed by the ray-tracing code with PENGEOM, for the leaves 20 to 24. Photons are transported along linear trajectories through the MLC geometry. When the trajectory crosses leaf number \(i\), the ray-length within this leaf \((t_i)\) is calculated and an attenuation coefficient is determined according to the energy of the particle and the material of the MLC. This is performed when one (a), two (b) or three (c) leaves are crossed, and all the determined attenuation coefficients are incorporated into the phase space file (PSF) with their associated leaf label. When more than three leaves are crossed (d), the photon is discarded.

In many aspects, the method described above is similar to the one described by Siebers et al (2002) and even more to the Chen et al (2000)’s method. However, the TF method uses the exact geometry of the MLC, which is not the case in Siebers et al (2002) even though the potential errors introduced are minimal. Moreover, and this is the major difference, the TF method takes full advantage of the “binary” property of the MLC, which simplifies greatly the problem:

- Attenuation coefficient \((\mu)\) may be precalculated
- Pathlengths are exact (no interpolation required as in Chen et al (2000)) and must be calculated only once, for only one configuration of the MLC (all leaves closed) in order to provide enough information for all the possible configurations of the MLC
- Transport through the MLC is performed only once, which avoid any additional geometric operation
Evidently, with this process we have introduced several approximations. First, the generality of the phase-space files is partially lost since contaminant electrons and widely divergent photons are discarded. Second, the scattering of photons and the production of secondary particles within closed leaves are ignored. First-Compton scattering is taken into account in Siebers et al (2002), but it was decided to neglect this phenomenon, mainly to improve speed and the simplicity, and evaluating afterwards the potential deviations from the straight MC method introduced.

The impact of the different approximations on the accuracy must be determined through comparisons of dose distributions in a water phantom obtained from full MC simulations and from simulations using the TF method, for different MLC configurations.

After calculating the phase-space file below the MLC, either with the full MC or the TF method, the dose distributions were calculated using the user code “penmain” from the PENELOPE distribution. The surface of the phantom was placed at the isocenter (source surface distance (SSD) of 85 cm). In all calculations, the dose was tallied using voxels of 2x2x2 mm³. The number of histories was such that the statistical uncertainty of the generated dose distributions was smaller than 1.5% (3σ) for the maximum dose voxel when the full MC method was employed for the open fields. The correct statistical uncertainty could only be determined in that case, since statistical information is partially lost when the TF method is used. Indeed, realistic estimations of the uncertainty is based on an efficient history by history method attributed to Salvat and described by Sempau et al [9]. Since some particles are discarded in the TF method, it is not possible to link each photon to each primary electron striking the target, which is required to perform a proper estimation of the uncertainty. One can still evaluate the statistics in a first approximation by considering that each photon is issued from a primary electron, but this will result in an underestimation of the uncertainty. Dose distributions calculated with “penmain” are expressed in units of eV/g per primary electron striking on the target. In the present work, the results obtained with the two methods are expressed in this unit, in order to enable a “fair” comparison without introducing artificial corrections due to inappropriate normalizations.

3. Results and discussion

3.1. Open fields
To check whether the transformed phase-space files retain information from the original MC phase-space files, dose distributions calculated from the full MC and the TF method corresponding to open fields (40x5, 40x2.5 and 40x1 cm²) were compared. The corresponding dose profiles were found to be in close agreement (within statistical uncertainty, not shown) for all the field sizes, as expected, since the vast majority of the photons were kept in the transformed phase-space files (more than 99.9% for a given open field). Some concern may arise regarding the depth dose distributions, because all the contaminant electrons are disregarded in the TF method. This approximation may lead to significant deviations in the build up region where electrons deposit most of their energy. However, good agreement was also observed (within statistical uncertainty) for all the open fields, as shown in the insets of figure 2 for a 40x5 cm² (a) and a 40x2.5 cm² (b) fields; for the sake of visibility, points are drawn each cm only after the build up region. This result is consistent with the fact that contamination is negligible for HT.
Figure 2. Comparison of depth-dose distributions obtained from the MC (dashed line, solid points) and the TF (open circles) methods for a 40x5 cm² field (a) and a 40x2.5 cm² field (b). Insets show a zoom on the build-up region. The depth-dose curves were calculated at SSD=85 cm. Errors bars (3σ) are plotted in the MC profiles.

3.2. Two central leaves opened
Transverse profiles and depth-dose distributions calculated with the full MC and the TF method for the two central leaves open were also analyzed. Transverse profiles are compared in figure 3. The agreement is seen to be very good, with deviations within statistical error bars (1.2 % (3σ) at maximum dose). Similar agreement is obtained for the depth-dose distributions (not shown). The agreement for doses above 10% of maximum dose is confirmed by the plot of the ratio between MC and TF, displayed as an inset in figure 3. However, for low doses, the difference can reach 50 % of the local dose (<0.6% of maximum dose) 2 cm off-axis, which is likely due to the non-simulation of the scattering by the MLC. But this occurs for very low doses and is expected to have negligible impact in clinical situations. Therefore, the phenomena that are not properly accounted for in the TF method (such as scattering and secondary particle production in the MLC) have an overall negligible effect on the dose distributions.

Figure 3. Comparison of transverse profiles resulting from the full MC (solid line, solid points) and the TF methods (open circles) for the 40x2.5 cm² static field with the two central leaves open. The profiles were calculated at SSD = 85 cm and for 1.5 cm and 5 cm depths. Errors bars (3σ) are plotted in the MC profiles. The inset shows the ratio between the full MC and the TF methods for the two depths (1.5 cm thin black line, 5 cm thick grey line).
3.3. Tongue and groove
To analyze the tongue and groove effect over the entire field, dose profiles obtained with even and odd leaves opened were added and compared for the two techniques, as illustrated in figure 4 for a reduced part of the profiles (to improve visibility of the results obtained with the two simulation modalities). The agreement is seen to be acceptable, with deviations within the statistical uncertainty of the MC results.

Figure 4. Comparison of transverse profiles calculated with the MC (solid line, solid points) and the TF methods (open circles) over 10-cm interval of the 40x2.5 cm² field with even leaves and odd leaves opened sequentially. The profiles were calculated in a water phantom at 5 cm depth and SSD = 85 cm.

3.4. Arbitrary configuration
The TF method is also able to reproduce, with similar accuracy, the dose distributions corresponding to other configurations of the MLC. Consequently, its accuracy is independent of the number of leaves that are simultaneously opened, as shown in figure 5, where deviations are again within the statistical uncertainty of the MC data.

Figure 5. Comparison of transverse profiles generated by the MC (solid line, solid points) and the TF methods (open circles) for a complicated configuration of the MLC and the 40x2.5 cm² static field. The profiles were calculated at SSD = 85 cm and 5 cm depth. Errors bars (3σ) are plotted in the MC profiles.
3.5. Fully blocked field

This test enabled the evaluation of the possible deviations introduced by the TF method in predicting attenuation and scattering by the MLC. Inter-leaf and intra-leaf leakage estimated from results of simulations with full MC and the TF method were compared. Again, overall good agreement was obtained, with deviations almost within statistical uncertainty of the MC result (figure 6), even though they are likely due to the neglected scattering in the TF method. It is also worth mentioning that the leakage for the MLC of HT is very small, with an interleaf leakage of around 0.2% of the dose of the corresponding open field at the same point and an intra-leaf leakage of around 0.1%.

![Figure 6. Comparison of transverse profiles calculated with the MC (solid line, solid points) and the TF methods (open circles) over 10-cm interval of the 40x2.5 cm² field with all the leaves closed. The profiles were calculated in a water phantom at 5 cm depth and SSD = 85 cm.](image)

4. Conclusions

The TF method was described and simulation results using this method were compared to results from corresponding full MC simulations for different configurations of the MLC. The tongue and groove effect is accurately accounted for and the leakage is also simulated correctly by the TF method. No significant deviations between the two methods were observed, even though the TF methods does yield a huge gain in computation time, since the transport through the MLC is now almost instantaneous. For instance, for one single leaf opened, the simulation of transport through the MLC is, roughly, more than 500 times faster than a full MC simulation and 60 times faster than a MC simulation with no electron transport. Therefore, the ray-tracing technique described in this study is fast, reliable and well adapted to the HT MLC design and can therefore be used for future helical calculations without any significant loss of accuracy.

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