Monte Carlo based verification of a beam model used in a treatment planning system

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Abstract. Modern treatment planning systems (TPSs) usually separate the dose modelling into a beam modelling phase, describing the beam exiting the accelerator, followed by a subsequent dose calculation in the patient. The aim of this work is to use the Monte Carlo code system EGSnrc to study the modelling of head scatter as well as the transmission through multi-leaf collimator (MLC) and diaphragms in the beam model used in a commercial TPS (MasterPlan, Nucletron B.V.). An Elekta Precise linear accelerator equipped with an MLC has been modelled in BEAMnrc, based on available information from the vendor regarding the material and geometry of the treatment head. The collimation in the MLC direction consists of leaves which are complemented with a backup diaphragm. The characteristics of the electron beam, i.e., energy and spot size, impinging on the target have been tuned to match measured data. Phase spaces from simulations of the treatment head are used to extract the scatter from, e.g., the flattening filter and the collimating structures. Similar data for the source models used in the TPS are extracted from the treatment planning system, thus a comprehensive analysis is possible. Simulations in a water phantom, with DOSXYZnrc, are also used to study the modelling of the MLC and the diaphragms by the TPS. The results from this study will be helpful to understand the limitations of the model in the TPS and provide knowledge for further improvements of the TPS source modelling.

1. Introduction
The aim of radiotherapy is to deliver a precise dose to a well-defined target volume with minimal absorbed dose to surrounding normal tissue. The outcome of the treatment is therefore dependent on the accuracy in the dose delivery both geometrically and dosimetrically. The uncertainty in the delivered dose to the patient should not be more than 3.5% (1 standard deviation) [1].

The uncertainties of the radiotherapy chain have been identified and quantified (except for volume delineation) and compiled by Ahnesjö and Aspradakis [2]. With present calibration and delivering techniques it is stated that an accuracy of 2-3% in dose calculation should be aimed at. This would lead to an overall uncertainty in the delivered dose to the patient of about 4.5 to 5%. They also state that the ultimate goal of dose calculation might be an accuracy of 1% considering future improvements.

Dose calculations for photons are today performed with dedicated computer-based treatment planning systems (TPSs) that model the dose distribution in the patient based on CT images. The majority of the commercially available three-dimensional dose calculation algorithms are based on analytical models of varying complexity with input data acquired in simple homogeneous geometries. In the future these will probably be replaced by various approaches involving Monte Carlo (MC). Independently of the base for the dose calculation, modern TPSs have to model the dose distribution
for complex beams, such as small highly modulated multi-leaf collimator (MLC) beams, to fulfil clinical requirements. To achieve high accuracy, TPSs usually separate the dose modelling into a beam modelling phase, describing the beam exiting the accelerator, followed by a subsequent dose calculation in the patient. These beam models can drive different dose engines such as analytical or MC-based.

The introduction of Monte Carlo in treatment planning for dose calculations in the patient still needs a beam modelling phase where the treatment unit is characterised. This beam model can either be analytical or MC-based. It is therefore important to study beam modelling, since this probably will be the limiting factor for the accuracy in future TPSs where the dose calculation in the patient is performed with state of the art MC simulations.

This work focuses on the beam modelling phase of the dose calculation. The Monte Carlo code system EGSnrc [3, 4] has been used to study the modelling of head scatter as well as the transmission through MLC and diaphragms in the beam model used in a commercial TPS (MasterPlan, Nucletron B.V.). An Elekta Precise linear accelerator equipped with an MLC has been modelled based on available information from the vendor regarding the material and geometry of the treatment head. Phase spaces from simulations of the treatment head are used to extract the scatter from, e.g., the flattening filter and the collimating structures. Similar data for the source models used in the TPS are extracted from the treatment planning system, thus, a comprehensive analysis is possible. Simulations in a water phantom are also used to study the modelling of the MLC and the diaphragm by the TPS. This work complements previous work where the scatter outside the direct beam was studied based on experimental measurements and compared to the TPS Helax TMS which is the forerunner of MasterPlan [5]. The results from this study will be helpful to understand the limitations of the model in the TPS and also to provide knowledge for further improvements of the TPS source modelling. The approach and results from this study may also be used to investigate beam models implemented in other TPSs.

2. Material and methods

2.1. Monte Carlo simulations

The EGSnrc user code BEAMnrc (version 2007) [6] was used to model an open 6 MV beam from an Elekta Precise accelerator based on available information from the vendor regarding the material and geometry of the treatment head. The accelerator is equipped with an MLC with 7.5 cm thick leafs which is complemented with a 3.0 cm thick backup diaphragm and perpendicular to these 7.8 cm thick diaphragms, all made of a tungsten alloy. The MLC was modelled with the BEAM-component module MLCE. The characteristics, i.e., energy and spot size, of the electron beam impinging on the target have been tuned to match measured data, i.e., central depth doses and profiles. Central depth doses and profiles were measured with an ion chamber (type RK, active volume 0.12 cm³) and a photon diode (type PFD), respectively (Scanditronix Wellhöfer AB, Uppsala Sweden), in water at a source-phantom-distance (SPD) of 90 cm.

To evaluate the source models of the TPS and to specifically pinpoint the collimating structures of the treatment head, four non-wedged fields were constructed. Table 1 presents the settings of the diaphragms X1/X2 and Y1/Y2 for the studied fields. The parameters are defined according to IEC61217 [7] and the MLC leafs and backup diaphragms are parallel to the X1/X2 direction. These fields were complemented with an open 20×20 cm² and an open 40×40 cm² field for normalization purposes.

The modelling of the collimating structures was verified against measurements for the four fields with a 2-dimensional diode array, MapCHECK™ (Sun Nuclear Corporation, USA) as well as a diamond detector (type 60003, PTW, Germany) in a water phantom. The diamond detector signal was corrected for the dose rate dependence. These measurements were performed at 5 cm depth and a SPD of 95 cm. The diode array measurements and MC simulations were normalised relative to the dose at the central axis for the open 20×20 cm² field at 5 cm depth and a SPD of 95 cm.
The simulations were divided into a treatment head simulation and a subsequent water phantom simulation. The latch utility in the nrc-codes was used to keep track of the interaction history of the particles during the treatment head simulation. This resulted in two phase spaces (phsp), one at 90 cm and one at 100 cm (i.e. at the isocentre). The phsp at the isocentre plane was analysed with BEAMDP [8] and energy fluence components corresponding to those available in the TPS were extracted.

Table 1. Description of the fields used. X1/X2 and Y1/Y2 are defined according to IEC 61217 and the MLC leafs and backup diaphragms are parallel to the X1/X2 direction.

| Field nr. | MLC X1/X2 [cm/cm] | backup d. X1/X2 [cm/cm] | Y1/Y2 [cm/cm] |
|-----------|-------------------|--------------------------|---------------|
| 1         | 9.0/10.0          | -10.0/10.0               | -10.0/10.0    |
| 2         | -10.0/10.0        | 9.0/10.0                 | -10.0/10.0    |
| 3         | 9.0/10.0          | 9.0/10.0                 | -10.0/10.0    |
| 4         | -10.0/10.0        | -10.0/10.0               | -10.0/0.0     |

The water phantom simulations were performed with a SPD of 95 cm in a Cartesian voxel grid using the DOSXYZnrc code [9]. The phantom dimension was 60×60×20 cm³. For the water phantom simulations pinpointed to the MLC leakage, i.e., fields 1 and 3 in table 1, a voxel size of 0.1×4×0.5 cm³ was used (with the smaller dimension in the direction orthogonal to the MLC movement). For the other fields a voxel size of 0.25×2×0.5 cm³ was used.

For the accelerator simulations with BEAMnrc, the transport parameters AP = Pcut = 10 keV, AE = 700 keV, and an Ecut of 711 keV were used (the latter includes the electron mass). The boundary crossing algorithm (BCA) PRESTA-I, spin effects turned on and electron-step algorithm PRESTA-II were used. For the phantom simulations with DOSXYZnrc the same parameters were used except for the electron cut-off energies which were lowered to AE = Ecut = 521 keV.

2.2. Treatment planning system
The TPS used in the study is Oncentra MasterPlan (OMP) version 1.5 SP1 (Nucletron B.V.) [10]. It incorporates a fluence-based dose calculation, where essentially a common beam model is used as source for two different in-patient dose calculation algorithms, the pencil beam and the collapsed cone algorithms. In this study the in-patient calculations were performed with the pencil beam algorithm. The beam model describes the energy fluence distribution exiting the treatment head. The parameters of the beam model are extracted from measured data (profiles, depth doses and output factors) during a radiation data handling process performed by the vendor. A detailed description of the beam model and the treatment unit characterization procedure can be found in Ahnesjö et al 2005 [11] and its references.

The TPS incorporates a feature called line dose [10]. With line dose, numerous dosimetric details can be extracted, such as normalized dose, dose components (primary, scatter), energy fluence, energy fluence components (e.g., flattening filter, wedges, and collimating structures), geometry and density information.

The four fields were constructed in the TPS and the line dose feature was used to extract total and direct energy fluence as well as the energy fluence associated with the scattering components of the treatment head, in this case flattening filter and collimating structures at isocentre. The total energy fluence and its components are normalized to the energy fluence of direct, non-modulated, and
unscattered photons in-air at isocentre. For the MC data, this normalisation level was extracted with BEAMDP for the open 40×40 cm² field.

A water phantom was created in the TPS and dose profiles at 5 cm depth with a SPD of 95 cm were extracted for the four fields using line dose. The profiles studied were in the direction orthogonal to the movement of the MLC, i.e., in the direction of Y1/Y2.

3. Results and discussion

The MC modelling of the collimating structure agrees quite well with measurements, see figure 1. The dose behind the backup diaphragm is within 3% in local dose and 0.3% relative to the central-axis dose for the 20×20 cm² field. For the Y2 diaphragm the corresponding values are about 30-50% and 0.3%. In the same geometry, the TPS overestimates the dose behind the Y diaphragms and underestimates the dose behind the X diaphragms. Furthermore the TPS does not model the MLC inter-leaf leakage.

![Figure 1](image_url)

**Figure 1.** Dose profiles along the Y direction at 5 cm depth and a SPD of 95 cm; a) behind the MLC, b) behind the backup diaphragm, c) behind the combination of MLC and backup diaphragm and d) behind the Y2 diaphragm. Black step-shaped curves represent MC, solid grey curves TPS. Dashed and dotted curves are measurements with diamond and MapCHECK™, respectively.

The normalized energy fluence extracted from TPS and MC data for the four fields at isocentre level are shown in figure 2. The normalized direct (i.e., total – head scatter) energy fluence for the maximum field of the treatment unit, in this case 40×40 cm², equals unity at isocentre.

The energy fluence is differentiated into total, direct, as well as the head scatter components associated with the flattening filter and the collimating structures. For field 4 (i.e., behind the Y
diaphragm) the agreement is fairly good for the studied components both inside and outside the primary field, see panel d in figure 2. In panel a of figure 2, showing data for field 1, (i.e. behind the MLC leaves) it is again seen that the TPS does not model the changes in energy fluence due to leakage between MLC leaves. The direct component of the TPS agrees well if the leakage is not taken into consideration. There are, however, rather large deviations for the total energy fluence due to an underestimation of the head scatter components, mainly the scatter originating from the MLC. This tendency is also seen in panel b for field 2 (i.e. behind the backup diaphragm) where the flattening filter contribution in the TPS is zero and the direct as well as the MLC scattered energy fluences are too small.

Figure 2. Normalised energy fluence profiles along the Y direction at isocentre; a) behind the MLC, b) behind the backup diaphragm, c) behind the combination of MLC and backup diaphragm and d) behind the Y2 diaphragm. Total energy fluence in black, direct in red, flattening filter in green and collimating structures in blue. Step-shaped curves represent MC and dashed curves TPS.

The differences observed in energy fluence are not entirely reflected in the water phantom comparisons, where the differences are smaller. This could be related to the fact that the TPS does not model the beam hardening effect caused by the collimating structures. The mean energy in the central part of the open 20×20 cm² field is 1.8 MeV which is increased to 2.6 MeV behind the backup diaphragm. The use of a pencil beam based on the spectrum of an open beam behind the collimating structures will result in a higher dose, since the dose per incident energy fluence decreases with increasing energy [12].
4. Conclusions
The energy fluence and dose behind MLC, backup diaphragms, diaphragms and combinations of these as modelled by the TPS has been studied with MC. The use of MC has made it feasible to study the energy fluence exiting from the accelerator and to analyse its head scatter components.

The beam model of the TPS underestimates the energy fluence behind the MLC and the backup diaphragms, and the leakage between MLC leaves is not modelled at all by the TPS. The energy fluence behind the Y diaphragms is slightly overestimated.

The differences in the resulting dose in a water phantom are slightly smaller than the one observed for the energy fluence. This is probably due to the beam hardening effect which is neglected in the TPS.

The underestimation is large if local percentages are considered, but since the dose/fluence levels are low the percentage difference relative to in-field dose/fluence is small. There are, however, situations when this underestimation could be of significance, e.g., during intensity-modulating treatment planning where a vast majority of the segments block critical structures either with MLC, backup diaphragms, diaphragms or a combination of these. With increasing complexity in treatment planning, e.g., intensity modulating, biological optimization and evaluation, the knowledge of the low dose levels to organs at risk becomes more important. The approach of this study can also be used to study beam models implemented in other TPSs as long as the suitable data can be extracted.

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References
[1] Mijnheer B J, Battermann J J and Wambersie A 1987 What degree of accuracy is required and can be achieved in photon and neutron therapy? Radiother Oncol 8 237-52
[2] Ahnesjö A and Aspradakis M M 1999 Dose calculations for external photon beams in radiotherapy Phys Med Biol 44 R99-155
[3] Kawrakow I 2000 Accurate condensed history Monte Carlo simulation of electron transport. I. EG Snrc, the new EGS4 version Med Phys 27 485-98
[4] Kawrakow I and Rogers D W O 2006 The EG Snrc code system: Monte Carlo simulation of Electron and Photon Transport NRCC Report PIRS-701.
[5] Cozzi L, Buffa F M and Fogliata A 2001 Dosimetric features of linac head and phantom scattered radiation outside the clinical photon beam: experimental measurements and comparison with treatment planning system calculations Radiother Oncol 58 193-200
[6] Rogers D W O, Ma C-M, Walters B, Ding G X, Sheikh-Bagheri D and Zhang G 2006 BEAMnrc Users Manual NRCC Report PIRS-0509A (rev K).
[7] IEC 2002 International Electrotechnical Commission, Radiotherapy Equipment – Coordinates, Movements and Scales, Report 61217 (Geneva, Switzerland: IEC)
[8] Ma C-M and Rogers D W O 2006 BEAMDP as a General-Purpose Utility NRCC Report PIRS-0509E (rev A).
[9] Walters B R B, Kawrakow I and Rogers D W O 2006 DOSXYZnrc Users Manual NRCC Report PIRS-794 (rev B).
[10] Nucletron 2006 Oncentra MasterPlan v. 1.5 SP1 Physics reference manual
[11] Ahnesjö A, Weber L, Murman A, Saxner M, Thorslund I and Traneus E 2005 Beam modelling and verification of a photon beam multisource model Med Phys 32 1722-37
[12] Ahnesjö A, Saxner M and Trepp A 1992 A pencil beam model for photon dose calculation Med Phys 19 263-73