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Dosimetric impact assessment using a general algorithm in GEANT4 simulations for a complex-shaped multileaf collimator

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ABSTRACT

Purpose: We have developed an inhouse algorithm for the multileaf collimator (MLC) geometry model construction with an appropriate accuracy for dosimetric tests. Our purpose is to build a complex type of MLC and analyze the influence of the modeling parameters on the dose calculation.
Methods: Using radiochromic films as detector the following tests were done: (I) *Density test field:* to compare measured and calculated dose distributions in order to determine the tungsten alloy physical density value. (II) *Leaf ends test field:* to verify the penumbra shape sensitivity against the discretization level set to simulate the curved leaf ends. (III) *MLC-closed field:* to obtain the value of the air gap between opposite leaves for a closed configuration which completes the modeling of the MLC leakage radiation. (IV) *Picket-fence field:* to fit the leaf tilt angle with respect of the divergent ray emerging from the source.
Results: For a 18.5 g/cm^3 density value we have obtained a maximum, minimum and mean leakage values of 0.43%, 0.36% and 0.38%, similar to the experimental ones. The best discretization level in the leaf ends field shows a 5.51 mm FWHM, very close to the measured value (5.49 mm). An air gap of 370 µm has been used in the simulation for the separation between opposite leaves. Using a 0.44° tilt angle, we found the same pattern as the experimental values.
Conclusions: Our code can reproduce complex MLC designs with a submilimetric dosimetric accuracy which implies the necessary background for dose calculation of high clinical interest small fields.

1. Introduction

A multileaf collimator (MLC) is a standard device available for clinical linear accelerators (linacs) which allows to obtain an automatic and precise beam shaping. As we know each commercial MLC has its own specific characteristics [1–7], therefore it is mandatory to take into account every detail of the MLC geometry in our Monte Carlo (MC) simulations. Following this guideline, different groups of investigation have done big efforts in order to include various MLC models in general-purpose MC codes. In the case of BEAMnrc [8] we have found component modules (CMs) which have been used for the creation of MLC geometry models. A comparison of the dosimetric results obtained with the original BEAMnrc CMs MLCQ [9] and VARMLC [10,11] highlights the fact that more accurate solutions can be developed from existing CMs. Also there have been adaptations [12,13] of new CM, such as DYNVMLC [10], which point in the same direction. Jang et al. [14] followed a different approach by proposing an MLC model, which allows to simulate various models of MLC thanks to the creation of specific regions following the MLC characteristics. PENELOPE [15] presents a precise code, calls PENGEOM, used for geometry construction process. In several MC simulations of different groups of investigation PENGEOM has been used in order to construct all the treatment head items [16,17].

In this work, we present an algorithm developed with the GEANT4 (GEometry ANd Tracking) toolkit [18–20] which allows us to create a geometry model of an MLC based on the tilt-leaf approach. The level of detail in the geometry construction is set by user from geometrical parameters provided by the vendor. As example we have modeled the 160 MLC (Siemens Healthcare, Erlangen, Germany). It constitutes a proof of goodness of the algorithm from a dosimetric point of view as one of its characteristics is that the leaf ends follow a pattern with alternated concave and convex curvatures [21,4,5]. To our knowledge, the 160 MLC had only been simulated in GEANT4 thanks to a CAD software that stored the exact position of the vertices of each leaf [21]. However our algorithm uses directly the information provided by the manufacturer to build directly the geometry model without using any external software. It has shown no versatility losses to adjust certain key parameters of

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the geometry to the reality, within the uncertainties declared by the vendor. Moreover, our tool allows the user to know all the factors involved in the MLC geometry model construction. In a CAD model it is not always straightforward to fine tune the geometry model, since the information about how the geometry is built is not easily accesible.

We also aim at appraising how the variations of some parameters characterizing the geometry model influence in dose distribution. Hence, we have done four tests to validate our MLC geometry model, based on studies about the dosimetric properties of MLCs [2,3], to accurately adjust these parameters accurately according to experimental profiles.

2. Materials and methods

2.1. Geometry construction by our inhouse algorithm

The single-focused 160 MLC includes two leaf banks with 80 leaves, each one 5 mm wide projected at the isocenter plane. It is established at a source-to-collimator distance (SCD) of 460 mm and together with the collimator jaws they can define a radiation field up to an area of $40 \times 40\ cm^2$. The 160 MLC does not present tongue-and-groove mechanism but an air gap between adjacent leaves to ensure their independent movement. This MLC design has been showed to give a performance better than the tongue-and-groove design [4,7]. As pointed out by Tacke et al. [4], all the leaves are tilted with respect to the divergence ray from the radiation source to reduce the interleaf leakage. As stated previously, the leaf ends follow a complex pattern, with a permutation of concave and convex curvatures, designed to decrease the leakage radiation between opposite leaves. Moreover, the leaf banks show a pattern of consecutive upper and lower leaves, being the upper ones closer to the source because of MLC mechanic restrictions. These aspects of the design show a real hard geometry to model, but our developed algorithm can reproduce it with the accuracy required for dosimetric tests. Essentially we want to know how the dose distribution is affected by the tongue-and-groove effect, the leaf ends or the intra- interleaf leakage radiation. In our modeling we have considered parameters of the geometry model susceptible of change, which are the leaf tilt angle and the distance between opposite leaves for a MLC-closed configuration, as the daily use of the MLC produces a mechanic wear which may change either tilt angle and leaf end position. Thus, any MLC modeled with our code can be updated in subsequent MC simulations as these slight mechanical modifications occur. Static parameters of the MLC model, such as the density of the alloy tungsten or the leaf ends are also included in the geometry construction process. Hence these features give a universal and versatile character to the algorithm.

Our algorithm discretises the four arcs which compose the leaf edge thanks to the manufacturer information, that is related to the center position and radius of each arc. Fig. 1 shows a scheme of the curve construction that can be summarized as follows:

- First of all, we define O_i positions, R_i radius and the convex or concave curvatures according to the reference system of the figure (x_L, y_L, z_L).
- P_i points are calculated solving the intersections between each pair of circumference arcs. These points are used to delimit the range of the arc angle from $\xi_{i,min}$ to $\xi_{i,max}$. ξ angle is defined with respect x_L axis thus if ξ is equal to zero and belongs to the angle range defined previously, M_i point is calculated hence we make sure that the most extremal point on x_L axis is included in the modeling.
- We define the specific angular tolerance ($\Delta\xi_{max}$) as an input, in such a way that the algorithm calculates the necessary number of points which satisfy $\Delta\xi_i < \Delta\xi_{max}$. This discretization is done for each arc delimited by P_i and/or M_i points, allowing to determine P_{ji} points. Different values for $\Delta\xi_{max}$ were put on different construction processes (Fig. 2)) to praise the importance of this parameter on the leaf ends shape.
- We construct the leaf thanks to the union of trapezoidal volumes using GEANT4 *G4Trap* class for that purpose (Fig. 3).
- The leaf is guided with respect to the diverging ray under the tilt angle specified as input.
- We place the leaf with the proper orientation, employing mathematical operations of rotation and traslation, inside the global reference system.

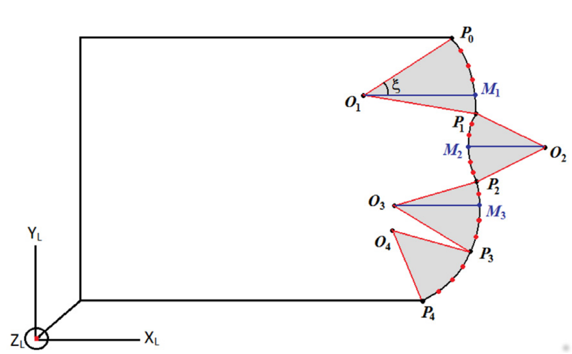

Fig. 1. Scheme of the procedure followed to discretise the arcs which compose the leaf ends.

2.2. 160 MLC dosimetric characterization

We have tested our algorithm in an Oncor Impression Plus linac (Siemens Healthcare, Erlangen, Germany) installed at the Virgen Macarena University Hospital with the 160 MLC integrated into the treatment head. For the experimental measurements GafChromic EBT3 radiochromic films (International Specialty Products, Wayne, NJ) and solid water RW3 slabs (PTW, Freiburg, Germany) were employed. The films were scanned thanks to an Epson 10000 XL (Seiko Epson Corporation, Nagano, Japan) flatbed scanner working in transmission mode, 150 dpi resolution, without color corrections. The scanned films were stored as 48-bit color images and we obtained the pixel values for each film by averaging over five scans. The dose calibration curve used was acquired previously according to a procedure described elsewhere [22]. Corrections because of the nonuniform response of the scanner were not needed as the films were centered with respect to it. Experimental uncertainties were between 2% and 3%.

To validate our MLC geometry model we used the fields described in subsections below to adjust some parameters defining our MLC geometry. For all our measurements we established 9 cm of backscatter slabs and the radiochromic film at 1.5 cm depth within the slabs. The source-to-surface distance (SSD) varied between 98.5 cm and 100 cm. As for the voxel orientation, Z axis is defined by the beam direction, X axis is defined parallel to the leaf movement and Y axis is defined perpendicular to both.

2.2.1. Density test field

An accurate knowledge of the tungsten alloy density in MC simulations is very important since a good agreement in the transmission and penumbra zones is mandatory. Checking the experimental and calculated inplane profiles, i. e. perpendicular to the leaf movement direction, at the transmission area makes possible the right fit of the leaf density. Thus the leaves were fully extended and we obtained the dose profile with a 100 cm SSD. We calculated the dose profiles relative to the dose at the central axis for a $10 \times 10\ cm^2$ with the same SSD and depth. A voxel of size