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MCNP5 Monte Carlo simulation of amorphous silicon EPID dosimetry from MLC radiation therapy treatment beams

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Abstract— **The present work is focused on a MCNP Monte Carlo (MC) simulation of a multi-leaf collimator (MLC) radiation therapy treatment unit including its corresponding Electronic Portal Imaging Device (EPID). We have developed a methodology to perform a spatial calibration of the EPID signal to obtain dose distribution using MC simulations. This calibration is based on several images acquisition and simulation considering different thicknesses of solid water slabs, using a 6 MeV photon beam and a square field size of 20 cm x 20 cm.**

The resulting relationship between the EPID response and the MC simulated dose is markedly linear. This signal to dose EPID calibration was used as a dosimetric tool to perform the validation of the MLC linear accelerator MCNP model. Simulation results and measurements agreed within 2% of dose difference. The methodology described in this paper potentially offers an optimal verification of dose received by patients under complex multi-field conformal or intensity-modulated radiation therapy (IMRT).

I. Introduction

Radiation therapy is constantly improved by new technical developments. Conformal radiotherapy and intensity-modulated radiotherapy (IMRT) techniques are an example of these optimizations. These techniques involve complex field shaping using multi-leaf collimators (MLCs) and they are increasingly used to treat tumors that in the past might have been considered too close to vital organs for radiation therapy. As a result, greater attention has to be paid to the precision and accuracy of MLC leaf positioning, as well as to the accuracy of the measurement techniques used for quality control and calibration of these devices.

Amorphous silicon electronic portal imaging devices (a-Si EPIDs) were originally developed for the purpose of patient setup verification. Nowadays, they are increasingly used as dosimeters for IMRT verification and linac quality assurance. A prerequisite for any clinical dosimetric application is a detailed and accurate geometric and dosimetric treatment verification to analyze the delivered dose to complex heterogeneous anatomical regions.

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The EPID studied in this work consist on an amorphous silicon array detector which is specially suited for patient positioning verification. We show in this paper the advantages of using this EPID as an alternative to conventional dose monitoring techniques (such as gafchcromic films, diodes and thermoluminescent dosimetry). To that, we have developed a full MC approach which provides the most accurate method for dose calculation in specific MLC clinical treatments. In this study we present the comparison between experimental measurements and a MC model of the *Elekta Precise* radiotherapy facility involving a linac with MLCs and an EPID [1], [2].

II. Methods and Materials

A. Experimental procedure

All the measurements and images acquisitions were performed with an *Elekta Sli Precise* linear accelerator available at the Hospital Clínic Universitari de València, which has also provided all the facilities and personnel necessary to obtain experimental data.

The iView GT-type EPID (*Elekta*) [3] is based on the amorphous silicon detector panel XRD 1640 (*Perkin-Elmer Optoelectronics, Fremont,* CA) with a fixed source detector distance (SDD) of 160 cm and a detection area of 46 cm x 46 cm. This system has a 1024 x 1024 pixel resolution and is composed first by a metal layer (Copper and Aluminum) as additional build-up material, in order to maximize deposited dose (i.e. obtaining the maximum image information) at the second layer constituted by the scintillator.

The experimental set-up presented in figure 1 involves the acquisition of images maintaining the gantry angle at 0◦ and using an square open field size of 20 cm x 20 cm at the isocentre, and followed by several images of different solid water blocks (from 2 cm thickness to 20 cm stepped in 2 cm increments), with a machine dose rate setting of 100 monitor units (MU), source to isocenter distance (SID) of 100 cm and source to detector distance (SDD) of 160 cm. We have selected these water equivalent blocks thickness in order to obtain a wide grey level intensities range.

In a-Si EPIDs, the incoming X-rays are converted in a phosphor screen into light which is detected by an amorphous silicon photodiode array. Each pixel from the image corresponds to the association of a photodiode with a transistor, which transmits the current generated in the photodiode to the amplifier. This current is proportional to the pixel received exposition.

Portal images were acquired in the mentioned irradiation conditions using the commercial iViewGT software with a fixed integration time of 433 ms/frame. All images were generated by integrating the frames acquired during the total radiation dose delivered. The number of frames integrated during beam delivery was estimated to range between 40 and 50, when using 100 monitor units.

Images have been exported from acquisition console to raw format *.his* and a correction filter map has been applied to each image sequence, in order to eliminate the offset noise, to apply a link offset correction (bad pixels correction) and to perform a heterogeneity detector correction.

Figure 1. Experimental procedure picture.

B. Monte Carlo EPID simulation

The MCNP version 5 [4] code system has been used to generate an accurate model of the *Elekta Precise* linear accelerator (operating with a 6 MeV photon beam) incorporating the 80 leaves of MLC and an amorphous silicon (a-Si) electronic portal imaging EPID.

The detailed geometry of the radiotherapy treatment head unit *Elekta Precise*, the solid water slabs and the EPID amorphous silicon flat-panel have been accurately implemented in the Monte Carlo model according to the manufacturer data [5].

The response of the imager in the sensitive layer of the detector was simulated in the same irradiation conditions as the experimental procedure was done.

The MCNP5 code allows to accurately registering the relative electron and photon flux and dose deposition (using the corresponding flux-to-dose conversion factors) at the flat-panel light phosphor layer by means of the FMESH tally.

The pixel resolution of the Monte Carlo EPID model was set to 1 cm x 1 cm to allow good statistical accuracy in the dose calculation.

The validation of MLC MC model was previously validated using depth dose curves in a water phantom [6], [7].

C. Calibration procedure

The resulting images experimentally acquired and simulated were spatially studied. A regional analysis has been performed in order to map the EPID signal to the MC dose as illustrated in figure 2. Both the EPID (grey level intensity) and the MC (deposited dose) images for each calibration slab thickness were analyzed using concentric squared sections with 1 cm separation. In each section, the mean of EPID Signal (S_E) and Monte Carlo dose (d_{MC}) was calculated.

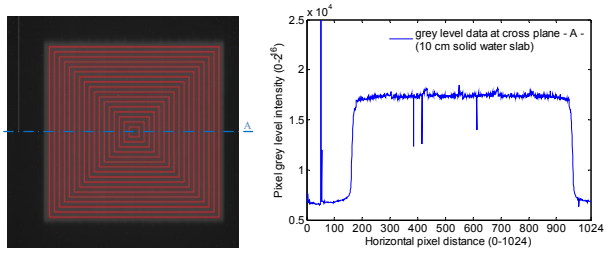

Figure 2. Concentric squared rings used for the analysis of both EPID and MC images and its pixel grey level intensity at cross line –A-.

An spatial plane calibration matrix was then developed to convert S_E into dose taking into account the dose transmission on-axis and off-axis position.

As mentioned before, in this study it has been fixed a 100 MU dose rate, nevertheless, as the response of the EPID is dose rate-dependent, alternatives calibration matrix (using the same methodology) should be perform to each dose rates settings [8].

D. MLC verification

Once the calibration method described previously was developed, it has also been applied to the verification of the MLC Monte Carlo model of the *Elekta Precise*.

During the last two decades, many different MLCs have been developed and brought in clinical routine. Among other things, these MLCs differ in the number of leaves, the leaf widths, the leaf designs, the material compositions, and the maximum field sizes allowed.

Our MLC model has been simulated on the basis of technical information provided by the manufacturer and it contains a realistic representation of the leaf design, since the leaf transmission can be an important factor when calculating the patient dose. Since such calculations are very sensitive to the detailed structure of the multileaf collimator, the 80-leaf MCL *Elekta Precise* were implemented in a geometric developed model, as shown in Figure 3.

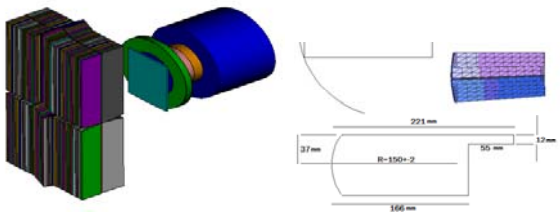

Figure 3. Linac unit head model including the MLC collimator modelled with MCNP5.

MLC material density is tungsten with a density of 17.5 g/cm^3.

The simulation of the validated model with different field sizes provides a series of phase-space files which store the particle information so that, in future simulations, these source files can be used by changing the position, when necessary, according to the gantry, table and collimator angle, significantly reducing the computing time. The phase space file was located at 54.4 cm from the source. The number of particles used in the simulations was 10^9 and the statistical uncertainty on the dose distribution was less than 2%.

Verification measurements in a water phantom were carried out using a *Scanditronix Wellhofer* chamber for a squared 10 cm x 10 cm field MLC shape using a 6 MeV photon beam.

Typical depth dose curves and dose profiles measured with the ion chamber at 10 cm depth along the horizontal water axis (SSD=100 cm) were compared with MC calculations and are shown in figure 4 and 5.

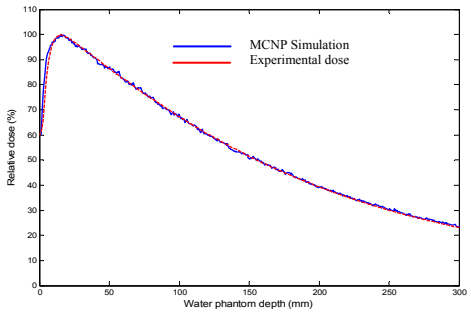

Figure 4. Depth dose curve obtained with a 6 MeV photon spectrum.

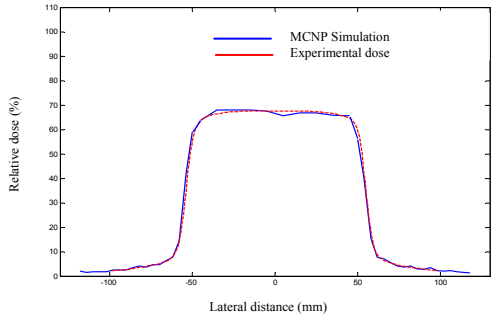

Figure 5. Profile dose at 10 cm depth with a 6 MeV photon spectrum.

The match between computations and measurements (better than 2%) shows that leaf material, and therefore also transmission properties, were accurately represented.

Nevertheless, a more complete 2D study has been carried out using the EPID images.

In order to verify our MC model further, several MLC shapes (one rhombus example is shown in this paper) were set up on the linac. The corresponding EPID images were then acquired using the same machine parameters (i.e. 6 MV, 100 MU, 160 cm SDD) as the calibration images. The leaf co-ordinates were then simulated with MCNP MC system.

The resolution of the MC EPID model was set to (1 cm × 1 cm) pixel dimension in the detector plane. S_E was converted to d_{MC} using the developed calibration matrix.

III. Results

A. Calibration Process

In this calibration procedure, the EPID signal values (S_E) (subtracted the background black image) were normalized to the open field signal. Similarly the MC doses (d_{MC}) obtained were normalized to the open field simulation dose values. The obtained results demonstrate that there is a linear dependence between EPID signal response and MC simulated dose.

The comparison between MC results and EPID image is presented. As shown in figure 6, the different slab thickness (central axis and off-axis) EPID signal S_E is well represented by a linear function of MC dose d_{MC} and follows the linear relation:

$$S_E = P \cdot d_{MC} + O \qquad (1)$$

where P is the S_E/d_{MC} slope and O is the offset resulting from the linear fit for the central 1 cm x 1cm area of figure 2 and the squared ring area at 14 cm off-axis.

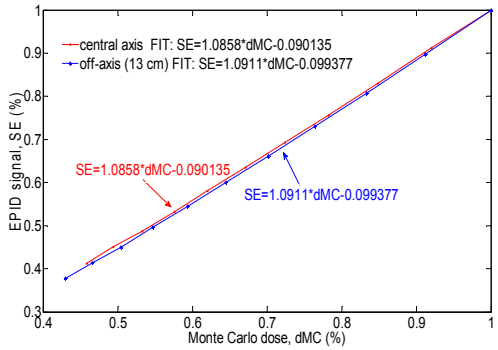

Figure 6. EPID calibration.

For the several off-axis studied, it can be seen that linear relation determine the slope gradients. The calculated linear fit gradient and offset are shown in figure 7.

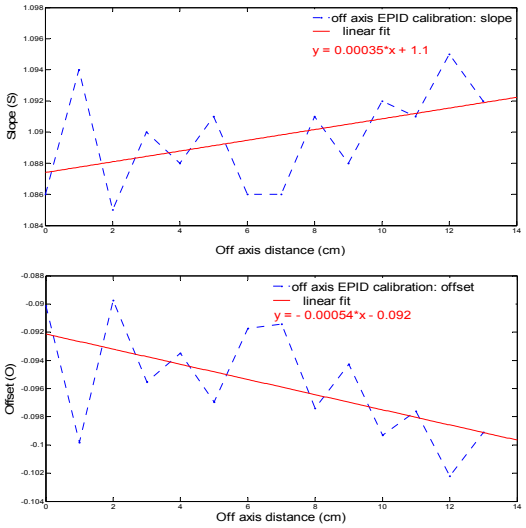

Figure 7a y 7b. Off-axis EPID calibration. (a) Slopes of the linear fits describing the relationship between SE and dMC. (b) offsets

As figure 7 displays, the linear relation is maintained off-axis, but the slope increases with distance from the central axis. Figure 7a represents the slope evolution and its linear function with the off-axis distance for the attenuation curves corresponding to the ith ring of figure 2. On the other hand, as shown in figure 7b the linear fit offset presents a soft decreasing tendency near zero values.

Using these relations the planar dose delivered to the EPID can be reconstructes from the detector signal S_E, using the appropriate values P and O composing the calibration matrix. This procedure also allows a comprehensive 2D verification of the MLC model.

B. 2D MLC validation

To perform an accurate 2D validation of the MLC MC model, an EPID image of a MLC rhombus shaped field was converted into dose using the calibration matrix described previously. To that, data were processed with MATLAB using a bi-linear interpolation algorithm.

The resulting dose dataset were compared with those obtained by simulation. To that, the complete MNCP5 simulation of the radiation treatment unit head model with the MLC rhombus field was developed. Figure 8 shows the model leaves distribution, and the dose distribution obtained at the flat panel plane using MCNP5.

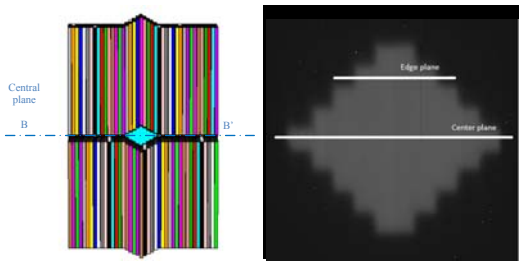

Figura 8. Configuration of the MCNP5 rhombus MLC model and its corresponding image at the EPID plane.

The MC dose profiles analyzed agree accurately with the EPID dose across the whole dose range (Figure 9). The percentage difference between MC dose and calibrated EPID dose is below 5% root mean square. This shows that the beam segment is accurately simulated and that the actual MLC leaf positions were represented in the MLC simulations with high accuracy degree.

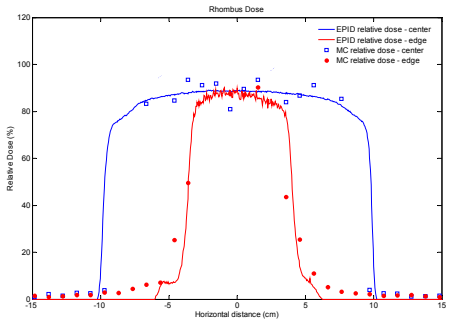

Figure 9. MC dose and calibrated EPID dose comparison.

The excellent agreement proves in this case the validity of the MC model and of the parameters being used, such as leaf-end radius, alloy composition and density.

IV. CONCLUSION

Precise MC simulation of electronic portal images can be useful for Conformal Therapy treatment verification. The accurate modeling of geometry, materials, physics particle transport all along radiation unit towards the detector system is a key issue in dosimetric verification of radiotherapy beams, since the accuracy of the results is limited by the model constraints. Moreover, the calibration of the EPID signal in terms of dose is an essential step in the correct prediction of the dose delivered to the patient.

In this study we have developed a detailed MC model of a system involving a linac with MLCs and a EPID and we have demonstrated a simple method to calibrate EPID images using the MC technique to convert the recorded signal into dose. We have shown that the square of the EPID signal is a linear function of the MC dose and that the off-axis variation can be also expressed as a linear function of the displacement from the central axis.

The simulation and measurement of EPID MLC shaped fields has provided an easy way to develop the physical and geometrical accurate MLC model. Dosimetric comparisons involving a MLC field shape have shown good agreement between simulations and measurements within 2%.

The methodology described in this paper has the potential to offer an accurate verification of dose delivery to generally heterogeneous treatment volumes, from complex multi-field or IMRT procedures using devices such as MLCs.

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