Monte Carlo characterization of a multi-leaf collimator

Author: Pau Coll Casellas
Facultat de Física, Universitat de Barcelona, Diagonal 645, 08028 Barcelona, Spain

Advisors: José M. Fernández-Varea
Departament de Física Quàntica i Astrofísica, Universitat de Barcelona

Jordi Saez Beltran and Artur Latorre Musoll
Secció de Física Mèdica, Servei d'Oncologia Radioteràpica, Hospital Clínic de Barcelona
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Abstract: Monte Carlo simulations have been done to study the dosimetric characteristics of Multi Leaf Collimators (MLCs) used to modulate the photon beam intensity in radiotherapy treatments. A set of sweeping gaps and asynchronous sweeping gaps were simulated and the absorbed dose scored in a large voxel to integrate the effect of several leaves. Two MLCs with slightly different geometrical characteristics were studied. The dose obtained for the SG was proportional to the gap distance. On the other hand, a dose reduction was obtained for the aSG tests which presented a non-linear and a linear regions. Both SG and aSG were sensitive to the fine details of the leaf design.

I. INTRODUCTION

Radiotherapy is an oncological treatment modality that uses ionizing radiation to kill cancer cells and thus shrink malignant tumours. To this end, various types of radiation qualities (type and energy) can be used, although Bremsstrahlung x-rays are the most common. While treating the patient, delivering the prescribed absorbed dose is as important as delivering it to the right place in order to minimize the amount of radiation absorbed by healthy tissues. The devices used to produce and deliver radiation to the patient are linear accelerators (LINAC) which can vary the radiation quality.

To generate an x-ray beam, electrons are accelerated towards a metal target (usually tungsten) where they collide and emit Bremsstrahlung x-rays. Two pairs of jaws (secondary collimators) trim the produced x-rays shaping the radiation field as a rectangle or a square. Next we have a multi-leaf collimator (MLC) which is used to give an arbitrary shape to the beam to prevent healthy tissues from being irradiated. As can be seen in Fig. 1, the MLC is formed by a series of tungsten alloy leaves that move independently.

To minimize the absorbed dose to the healthy tissues, intensity modulated radiation therapy (IMRT) is used. This kind of therapy relies on the use of MLCs to generate the desired beamlet intensity variations. Initially developed as a replacement for metal alloy blocks, nowadays MLCs are employed to deliver IMRT by a variety of methods [3]. To produce such intensity variations, the MLC can leave some region more time opened to radiation exposure so that the dose is higher than in regions where the MLC was either closed or opened more briefly.

Even though the leaves are independent, there is a thin air gap between them allowing them to slide. These gaps would leak radiation to the patient since photons parallel to them, could cross the MLC without interacting with it. To avoid this problem, a tongue-and-groove (TG) design

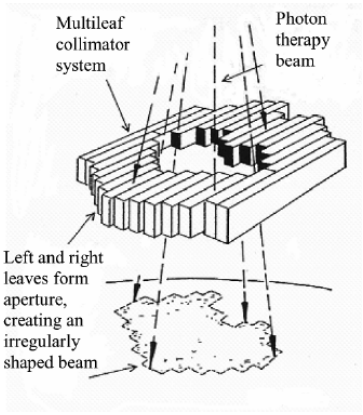
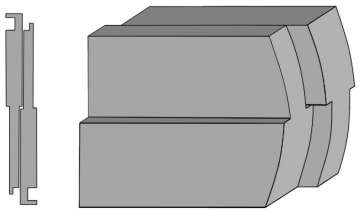


FIG. 1: Example of a MLC giving an arbitrary shape to a photon (or electron) beam. Taken from https://www.researchgate.net/figure/A-multileaf-collimator-MLC-system_fig2_220133319

is implemented, see Fig. 2. Although this layout solves the leakage between leaves, it creates a new issue. When a leaf does not have its neighbours the TG is exposed to the beam and some radiation is attenuated by it, which means that less radiation than intended is delivered to the patient.

Furthermore, if the leaf tips were straight, the behaviour of the dose reaching the patient when the leaf is just under the source or outside of the axis would be different. If we think about it, a rectangular leaf positioned at $x = 0$ would ideally block all radiation for $x > 0$ and would not block any radiation for $x < 0$. Although this behaviour is positive, the dose profile would be different when the leaf is outside of the source axis, which makes it more difficult to model. In order to have the same behaviour throughout all MLC configurations, the leafs have a rounded tip. Doing so, when the leaf is at $x = 0$, the dose profiles is not a step, and the shape at



(a) (b)

FIG. 2: Tongue and groove design for Varian LINACs. Image courtesy of Victor Hernandez.

off-axis positions ($x > 0$) would be very similar

In this study we analyze, using Monte Carlo (MC) simulations, the absorbed dose reaching the patient by different MLC configurations. The software employed to do these calculations is PRIMO and penEasy, which are built on top of the PENELOPE code.

II. MATERIALS AND METHODS

A. Photon interactions

Photons (x- and γ-rays) interact with matter in several ways which result in distinct radiation products. The main interactions are: photoelectric effect, Compton and Rayleigh scattering, and electron-positron pair production. The interaction products of first two can reach the patient but in the later ones, the photon is absorbed by the material and the outputs are electrons in the case of the photoelectric effect and electrons and positrons in the case of pair production.

The energy distributions of Bremsstrahlung x-ray beams span from close to zero up to several MeV, hence the most important interactions are photoelectric effect and Compton interactions. The former is responsible for most of the dose attenuation that happens in the MLC and the other collimators, and the latter will be the second most important component of leakage, just behind transmission.

B. Monte Carlo simulations

Monte Carlo (MC) methods are routinely used to simulate radiation transport. These techniques use stochastic methods to simulate the behaviour of physical systems. To imitate the propagation of radiation in matter, numerical sampling determines the distance between physical interactions, the type of interaction, angular deflection, energy loss and the generation of secondary particles.

The simulation is done particle by particle. This makes the results very accurate, as long as the number of simulated primery particles is large, because each and every interaction (with some exceptions) is taken into account, in opposition of other numerical methods to solve the radiation transport problem.

In medical physics, MC simulations have been used to validate IMRT planning programs, perform patient-specific Quality Assurance and in other applications. The advantage of MC is that it can simulate arbitrarily complex geometries, which can aid physicists and clinicians in understanding the limitations in the accuracy of IMRT dose algorithms, the source of dose inaccuracies, etc. [8]. The drawback of MC is the simulation time needed to get results with very small uncertainties, as each particle and the secondary particles generated by it are simulated individually, which makes a calculation that takes seconds using a dose-planning algorithm, can require up to hours or days using MC. We have to keep in mind, though, that drastic approximations are implemented in the commercial dose-planning algorithms to be able to compute absorbed dose in a volume this fast, leading to inaccuracies.

For the reasons exposed before, MC is used mainly to find discrepancies and flaws in analytical models. Even though some times the MC is only used in a segment of the total simulation (simulate the head of the accelerator using MC and then the patient dose is calculated via analytical algorithms and vice versa), in this study we will use a full MC, which means than the head and the patient dose is calculated using MC methods. This way of doing the calculations is very faithful to the reality but a lot of simulation time is needed.

C. PenEasy and PRIMO

As already mentioned, the MC simulations were carried out with penEasy and PRIMO, which are built on top of PENELOPE. The latter is a general-purpose MC code that simulates coupled electron/photon transport in a wide energy interval, arbitrary materials and non-trivial geometries [6]. PENELOPE and penEasy use a module named PENGEOM which allows to define the complex geometries of our simulation. The elaboration of this files is the most time-consuming step when preparing a simulation, even for trivial ones. Furthermore, the LINAC geometry is very complex. To simplify the process, PRIMO already incorporates the geometry of various types of LINAC which makes it suitable to study the radiation generated by them.

PRIMO also has a graphical user interface, which makes it easier to use than penEasy. It tries to replicate the Eclipse or other treatment-planning system interfaces to make it even more user-friendly to medical physicists.

When simulating radiation transport with the MC code it is possible to define a surface, usually a plane, at any location in the geometry. Particles traversing this plane are stopped and their state (*i.e.* energy, position, direction of flight, etc.) recorded in a file called phase-space file (PSF). PRIMO [4] integrates this feature by segmenting the usual simulation (from the generation of

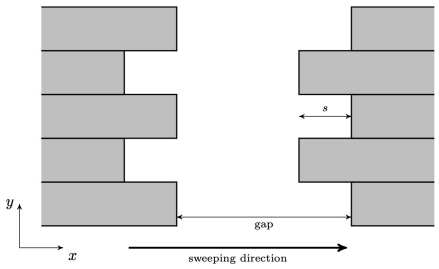


FIG. 3: Schematic representation of the asynchronous sweeping gap field. Taken from [5].

the photon beam at the target to the absorbed dose distribution in the patient) into three parts. A critical aspect when working with a PSF is its size, as a poor PSF (not many particles contained) would cause poor statistics in all subsequent simulations.

The first segment, called s1, simulates the target, the primary collimator (which removes photons directed away from the patient), the faltering filter, which in our case was removed, and other parts of the LINAC which are not important for this study. The low Bremsstrahlung cross section makes this segment the most time consuming of all the simulations. However, this part of the LINAC is common on all the radiotherapy treatments with the same radiation quality, which means that the ensuing PSF will be reusable for all the simulations in our study. The second segment (s2) corresponds to the patient-dependent part of the LINAC, which encompasses the jaws (they set the field size which in our case, for all the configurations it will be a 10×10 cm^2 field) and the MLC. We will focus on different MLC configurations so that we will not be able to reuse this segment. Finally, the last segment s3 is the geometric region corresponding to the patient or phantom. The absorbed dose is estimated in the structures defined by the simulation.

In this study, a very rich PSF was provided by Jordi Saez and Artur Latorre (Hospital Clínic de Barcelona). The MLC configuration is different in each simulation, hence it is calculated at the end of s1. The file contains information of almost 1.14×10^9 particles, most of them photons.

D. Multileaf collimator configurations

The simulations that were performed are called sweeping gaps (SGs), which means that a small gap is left open between pairs of leaves, and this gap moves from one end of the field to the other. We will also study asynchronous sweeping gaps (aSGs) which they maintain a set gap distance, but adjacent leaves are shifted a distance s as can be seen in Fig. 3 [5]. The aim of these configurations is to highlight the TG effect mentioned in the introduction. The distance traveled by the center of the gap is 12 cm.

Two models of MLC were used in the study. One was a Varian Millennium 120 and the other was a Varian HD120. The most important difference between these models is that in the Millennium, the inner leaf width is 5 mm while the HD120 has a inner leaf width of 2.5 mm [2], and thus TG effects will be more relevant. Moreover, the height of the leaves is different: the Millennium 120 leaves measure 67 mm while the HD120 ones measure 69 mm. But since space is needed for the screw that retracts and takes out the leaf, the effective heights are smaller, 61 mm for the Millennium and 68 mm for the HD120. Furthermore, the radius of the rounded leaf end is also different. In the case of the Millennium, the radius is 80 mm while in the HD120 the radius is 160 mm. This means than the HD120 dose profile is more similar to a straight leaf end.

Another very important factor in the simulations is choosing the phantom geometry. In our case, the phantom (place where we will tally the absorbed dose) is a body of water. The aim of this study is to obtain the absorbed dose at the center of the phantom's surface. To do so, adopted big voxels to integrate the dose throughout multiple leaves. Since the MLC leaves are arranged along the x axis, our geometry will be along the y axis. Taking this into consideration, each voxel has the following dimensions: $x = 1$ cm, $y = 2$ cm and $z = 1$ cm. In this way, the dose will be accumulated between four leaves when simulating a Millennium collimator and eight leaves for the HD120.

The configurations selected for the SG simulations were: g05, g10, g20 and g30, where the number indicates the gap distance in millimeters. On the other hand, for aSG the gap was constant at g20 and we chose the following configurations: s00, s01, s02, s05, s10, s15 and s20, where s is the shifted distance in millimeters.

The absorbed dose depends on several factors and thus its hard to monitor how much is leaving the LINAC to be delivered to the patient. In order to do so, a pseudo-variable was defined by radiotherapists although other alternatives were also viable (like the filament current). The unit is called monitor units (MU) and it measures the output dose from a LINAC. If we think about a traditional radionucleide, the MU would be equivalent to time of exposure, meaning that more time implies more dose.

III. RESULTS AND DISCUSSION

A. Absorbed dose as a function of gap

In order to study the dose in the central voxel of the water phantom, the simulations were launched as discussed above, and the results are shown in Fig. 4. We can imagine than the simulation process consists in three phases for our voxel. Initially the voxel is blocked by the MLC and the radiation that reaches it is mainly due transmission of this component [1, 3]. This will happen until the rounded leaf end arrives, as more photons will

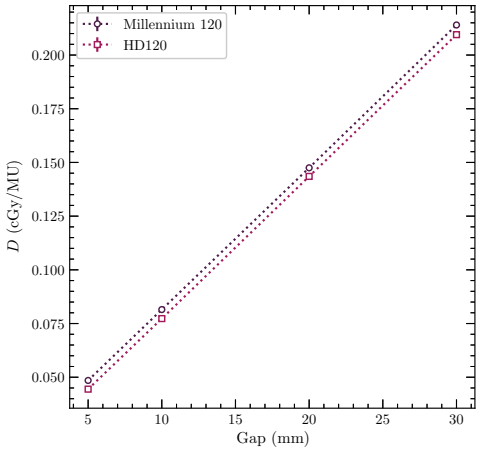


FIG. 4: Absorbed dose on a SG as a function of the gap distance.

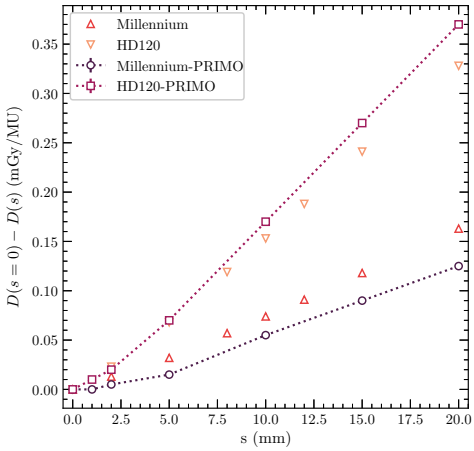


FIG. 5: Absorbed dose as a function of the parameter s. Millennium and HD120 points are experimental measures while Millennium-PRIMO and HD120-PRIMO are simulation results.

be able to cross the MLC and thus more dose will be absorbed. Lastly, the voxel is inside the gap and so photons will reach it without attenuation. When the simulation continues, the previous scene will happen again but reversed. Having this into account, we can affirm than the calculated dose will have 3 components,

$$D = D_{Tr} + D_{RL} + D_G, \tag{1}$$

where D_{Tr}, D_{RL} and D_G are the absorbed doses due to transmission, rounded leaf end and gap, respectively.

D_{Tr} will be much lower than the other 2 components and we can neglect it as concluded in [1]. Furthermore, D_G will be the same for both MLC, as the time exposed to the open gap is the same. Therefore, we can verify that the difference between absorbed doses will be due to differences in D_{RL}. The leaf end has a radius of 16 cm for the HD120 and a radius of 8 cm for the Millennium 120, which means that the leaf tip section will be longer in the Millennium MLC and thus more dose will be measured.

The linear behaviour is due to the fact that the gap distance is proportional to D_G. This dose component is the main component and thus the absorbed dose increases linearly. Furthermore, D_{Tr} and D_{RL} remain constant independently of the gap.

B. Absorbed dose as a function of the parameter s

As explained before, this calculations were done fixing a gap distance and changing the s parameter, which is related on the shifted distance between adjacent leaves.

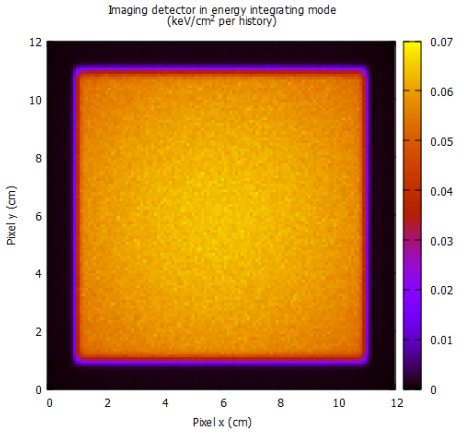
Conceptually, we can distinguish two sections in MLC leaves: the central part and the TG. When we change s, a tongue from one leaf slides this set distance above the adjacent groove. This way, the central section is not affected by the shift and thus differences in the absorbed dose, will be due to the TG.

This way, subtracting each measure to the measure where $s = 0$, only the TG dose contribution is left.

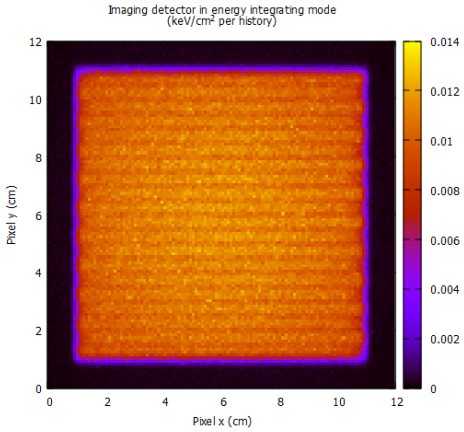
In Fig. 5 we see the results of the simulations as well as experimental measures done under the same conditions. First we will analyze the experimental data. Two different behaviours can be observed: for $s >$ 5 mm we find a linear behaviour while for lower values of s, the difference still increments with it tough it doesn't do it linearly. If we do a linear regression for the $s > 5$ mm section, we get the following slopes: $m_{Mil} = 0.009$ mGy/MU/mm and $m_{HD120} = 0.017$ mGy/MU/mm . We see that $m_{HD120} \approx 2m_{Mil}$. Since the HD120 leaves are half the width of the Millennium leaves, our voxel samples twice as many TG regions. Thus, we expected to find that the slope m for the HD120 should double that of the Millennium.

Using PRIMO simulations, we can see that the behaviour is correct though it does not reproduce exactly the experimental results, as the slope of the linear section for the HD120 is more than double the slope for the Millennium. This discrepancy deserves further investigation to understand the origin of the differences found.

Finally, in Fig. 6 we present a dose map of radiation arriving to the phantom for different configurations of g20s00 and g20s10. This were taken using the Pixel Image tally built in penEasy. [7] In the g20s00 image we can see that the dose map looks like a Gaussian function. This is due to the fact that the PSF at s1 was made without flattening filter. Apart from that, no other anomalies can be seen. On the other hand, the g20s10 image presents a clear horizontal line pattern. As discussed previously, the TG exposed to the radiation attenuates



(a) MLC configuration: g20s00



(b) MLC configuration: g20s10

FIG. 6: Dose map reaching the patient when using different MLC configurations.

part of the radiation and thus the pattern in figure 6b emerges. Looking at the images we can confirm than the lack of radiation measured when we increment the s parameter is due to this TG effect.

IV. CONCLUSIONS

The properties of absorbed dose using different MLC configurations have been studied using MC simulations. Firstly, we see that for a SG, dose is proportional to gap distance. Furthermore, we conclude that the discrepancies between doses seen for the millenium and HD120 MLCs are due to the latter having a bigger radius of rounded leaf end and thus a shorter leaf tip.

When studying the impact of the TG doing aSG simulations, two different behaviours can be seen for $s < 5$ and $s > 5$. For the lower values of s, the difference of dose increases but without a linear behaviour. This changes when $s > 5$ as a linear behaviour can be seen. Furthermore in the experimental measures show than for Millennium MLC this effect is half of the effect for HD120. This is due to integrating half of the leaves in the same space. Finally, the results calculated with PRIMO show this behaviour qualitatively though they don't reproduce the fact that for HD120 these effects are the double. This discrepancies may be due to some simplifications done by the software in order to speed up the simulations but further studies would be required to know what is causing them.

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