Heterogeneities in lung dosimetry: MC, AAA and Acuros calculations

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Abstract: Stereotactic Body Radiation Therapy is a widespread therapy that aims to ablate a tumor by delivering high-dose distributions in few fractions. One of its main applications can be found in Early Stage Small Cell Lung Cancer where it has been proven to be a good alternative to surgery for those cases tumor that can not be surgically removed. The aim of this final degree project is to study and compare the absorbed dose distributions computed with Monte Carlo simulations and two commercial treatment-planning algorithms, namely AAA and Acuros. A comparison with a measurement using radiochromic film dosimetry was also performed. The uncertainties of the simulations as well as those intrinsic to the film do not allow us to reach a conclusion about the improvements of one calculation algorithm with respect to the other.

I. INTRODUCTION

Stereotactic Body Radiation Therapy (SBRT) refers to a hypofractioned, high dose per session radiotherapy technique used to control early-stage non-operable cancers in locations such as the thoracic cavities. To understand the radiobiological rationale for SBRT, we must define the Biologically Effective Dose (BED), "a measure of the true biological dose delivered by a particular combination of dose per fraction and total dose to a particular tissue" [1]. With a higher number of fractions, for the same total absorbed dose and the same tissue, a higher BED is achieved.

As a higher BED is achieved, it becomes essential to preserve healthy tissues in order to avoid future complications such as secondary cancers derived from the irradiation of organs at risk. It is then of capital importance to maximize tumor coverage while reducing the absorbed dose to critical structures.

SBRT was developed as a consequence of the technological improvements that allow to better conform the absorbed dose delivered to the patient [2, 3]. For instance, image guidance techniques, patient immobilization or the integration of treatment simulations.

The aim of this TFG is to study and compare, within the SBRT context, the results of total dose absorbed in lung considering the respiratory motion (which implies small variations in the tumor position) obtained by two commercial algorithms incorporated in the Eclipse Treatment System, with Monte Carlo (MC) simulations and experimental measurements.

II. MATERIALS AND METHODS

A. Experimental setup

To carry out the dose distribution measurements, we used radichromic film dosimetry in a QUASAR Multi-Purpose Body Phantom. This phantom is an acrylic body that contains a wood insert which, in turn, contains a polyethylene sphere. The latter two simulate the lung and the tumor, respectively, and have very similar electronic densities to these tissues. We employed a VARIAN TrueBeam linear accelerator at the *Hospital de la Santa Creu i Sant Pau*, selecting the 6 MV x-ray beam. We performed an irradiation with a single 3×3 cm^2 photon field and a Source-to-Surface Distance (SSD) of 92.5 cm. The isocenter of the tumor is at 100 cm of the source.

1. *Effect of respiratory motion*

When treating tumors in thoracic, abdominal and pelvic regions the respiratory motion may produce significant variations in the dose absorbed by the tumor and the surrounding tissues [4]. As a first approximation to respiratory motion management, we used the QUASAR Respiratory Motion Phantom (Fig. 1), a programmable breathing and tumor motion simulator that acts moving the implant that simulates the lung in the QUASAR with respect to the photon source, thus displacing the polyethylene sphere contained in it. We programmed it to work following a sinusoidal function with an amplitude of 1 cm. An irradiation was done using this technology, and a complimentary one was carried out with the static QUASAR and the square beam perfectly centered in the isocenter of the tumor.

2. *Radiochromic film*

Film dosimetry offers unbeatable characteristics regarding spatial resolution [5]. Its functioning is based on the partial polymerization of the active substance present in the surface of the film when exposed to ionizing radiation, which leads to the darkening of the polymer. This darkening increases with absorbed dose.

In our study, the film was placed between the two halves of the lung implant (two semi-cylinders assembled together). The polyethylene sphere used to simulate the

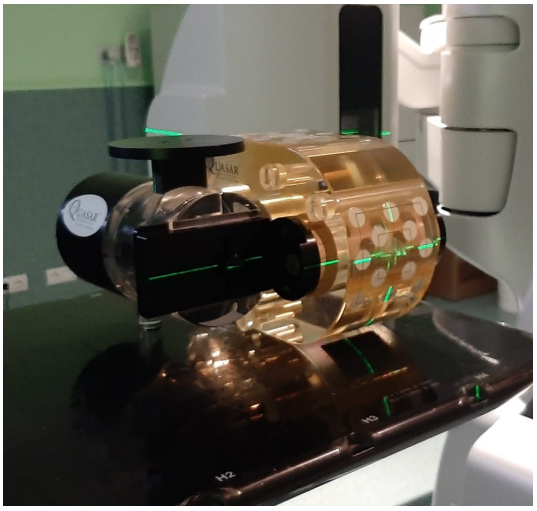

FIG. 1: Experimental setup of the QUASAR Respiratory Motion Phantom.

tumour also consists of two semi-spheres, so that the film could be placed also in between. With this setup, we were able to obtain the dose absorbed by lung and tumor in their sagittal plane.

To analyse the radiochromic film, a standard protocol was followed. We used an Epson Expression 10000 XL scan in transmission mode to obtain the data with the dose-response curves previously generated by calibrating the films production lot. Due to the post irradiation coloration process that the film suffers, we left a 24 h delay between the irradiation and the scanning. The analysis of the collected data was carried out with the FilmQA Pro software. Along with the irradiated film, we scanned simultaneously an unirradiated one as well as another film that had been irradiatiated at reference conditions, in order to adapt the dose-response function for the conditions applying to this particular scan.

B. Treatment-Planning System Algorithms

To calculate the dose distribution in the lung we employed a Treatment-Planning System (TPS) [6]. In our case, we used the Eclipse Treatment System (Varian Medical Systems) which incorporates two dose distribution calculation algorithms [7].

AAA— The Analytical Anisotropic Algorithm (AAA) [8, 9] is a convolution-superposition-based photon beam dose computation algorithm. It superposes the absorbed dose deposited by a primary photon source, a secondary one, and electron contamination.

Acuros— Acuros [10] solves the Linear Boltzmann Transport Equation which describes the transport of neutral and charged particles in a medium. It accounts better for the effects of heterogeneities in the calculated absorbed dose and it is much faster than MC simulations.

C. Monte Carlo simulations

The MC simulation of radiation transport recreates in a computer the propagation and interaction of ionizing radiation in matter by numerically sampling the distance between physical interactions, the kind of interaction, the angular deflection and/or energy loss and the generation of secondary radiation. There are several MC codes available. In this study, we adopted PENELOPE/penEasy. PENELOPE is a software package for the MC calculation of coupled electron/photon transport, developed as a set of Fortran subroutines. It allows the user to work with complex geometries and arbitrary materials. In turn, penEasy is a structured main program for PENELOPE. The user has to provide an input file that will serve as the configuration of the simulation, no further programming being required.

To run our simulations we need four types of files: A *.geo* file, that will serve as the geometry definition of our system, one or more *.mat* files, with the material(s) of our geometry (the user may need more than one material to accurately define its geometry, as it is our case), a *.in* file that will be our configuration (input) file, and finally a *.exe* file, our executable.

1. *Geometry definition*

PENELOPE includes the PENGEOM library that handles quadric geometries. We adopt the reduced form of quadric functions, defined as

$$\Phi(\vec{r}) = I_1\, x^2 + I_2\, y^2 + I_3\, z^2 + I_4\, z + I_5 = 0,$$

where the indices I_i take values -1, 0, $+1$. Three transformations are allowed in order to generate arbitrary quadrics: scaling, rotation and translation. These functions are versatile enough to represent many geometries present in real-life problems.

To define any geometry, an inside-out strategy is recommended. That is, the geometry will be created from the inner parts to the outer ones. We start defining the minimum number of surfaces that is needed to define a body delimited by them. In the input file, each body will be linked to a *.mat* file (see below).

In our study we have simulated the QUASAR Multi-Purpose Body Phantom geometry, simplifying some parts of the geometry that only introduce second-order corrections due to laterally-scattered electrons (Fig. 2). We have also included a body that serves to delimit a square photon field equal to that of the experimental part of the project. The complete geometry involves 11 surfaces and 6 bodies.

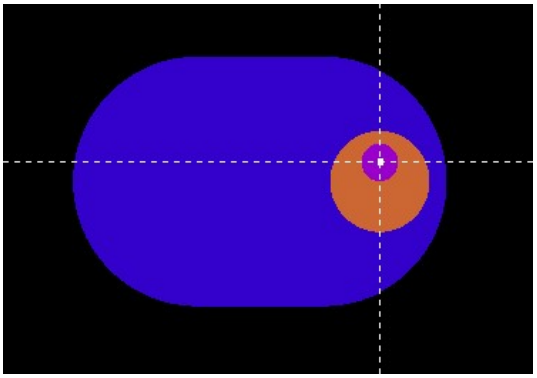

FIG. 2: Simulated geometry of the QUASAR Multi Purpose Body Phantom, as rendered by the `gview2d` viewer.

2. Material files

Material files are generated with the `material.exe` preprocessor for the various materials associated to the bodies defined in the geometry file. These *.mat* files contain tables of cross sections for the interaction models implemented in PENELOPE. In our study, we must generate four such files that will recreate these materials' interaction properties, namely acrylic, polyethylene, lung (inflated) and air.

3. Input file

The input file contains the information needed to control the simulation. On the one hand, all the parameters regarding the radiation beam: type of particles and their energy, the type of source used and its characteristics, cut-off energies (used to perform more efficient simulations) as well as simulation parameters such as the desired number of histories. Each history follows the trajectory of a primary particle and the secondary ones produced in the interactions suffered in the geometry. On the other hand, the input file links the geometry and material file(s) so that the main program is able to simulate with the cross sections pertaining to each material.

The adopted source of particles is a 6 MV photon energy spectrum from reference [11]. A total number of the order of $7 \cdot 10^8$ histories was simulated. This value is carefully selected so as to achieve statistical (type A) uncertainties around 1.5%. The selected cut-off energies were 10 keV for photons and 200 keV for electrons. This allows a notable reduction of the computing time without compromising the quality of the results.

We performed a total of 11 simulations with variations of the tumor position in the x-axis of 2 mm, obtaining dose distributions in lung from -1 cm to 1 cm in the x-axis in 2 mm steps.

D. Gamma analysis

Gamma analysis is a technique widely employed in medical physics to quantitatively evaluate and compare calculated and measured absorbed dose distributions [12]. The first thing one must establish is an acceptance criterion. Here we chose 2%/2mm for the TPS/Radiochromic film comparison and 3%/3mm for the TPS/MC one. This type of analysis unifies dose-difference and distance to agreement (DTA). In a space composed of dose and physical distance, the acceptance criterion defines an ellipsoidal surface and, more specifically, its major axes. The origin is the point where we perform the analysis. The gamma index is calculated as the radial distance between the measurement and the calculation points. Whenever gamma > 1, the calculation does not meet the acceptance criterion.

III. RESULTS

A. Comparison of radiochromic films with TPS calculations

In the first place we made a comparison between the absorbed dose distributions computed with AAA and Acuros and measured with the radiochromic film. In order to obtain quantitative results, we used the FilmQA Pro software, which is capable of doing a gamma analysis between two dose maps. Previously, a fitting of the images had to be carried out by means of the adjustment of the lateral dose profiles. Once a maximum resemblance between these curves had been established, we defined a region of interest of the superposed images to obtain its gamma index. This step was important to avoid the comparison of the calibration films (the unirradiated and the known-dose irradiated ones) with the dose map exported from the TPS.

We obtained a 98.8% gamma pass rate for the AAA-based calculation (Fig. 3, left) and a 99.4% for the Acuros-based calculation (Fig. 3, right). Although a higher percentage for Acuros due to its better account of heterogeneities would seem logic, the uncertainty in the image positioning is large enough to conclude that there are no substantial differences between calculations when compared to an actual irradiation.

B. Comparison of MC simulations with TPS calculations

A Python script, taken from reference [13], was used to do the gamma analysis between the MC simulations and TPS calculations. The results from both calculations have been treated and represented in the form of 2D matrices using MATLAB. We generated a total of 11 dose distributions in the case of MC simulations.

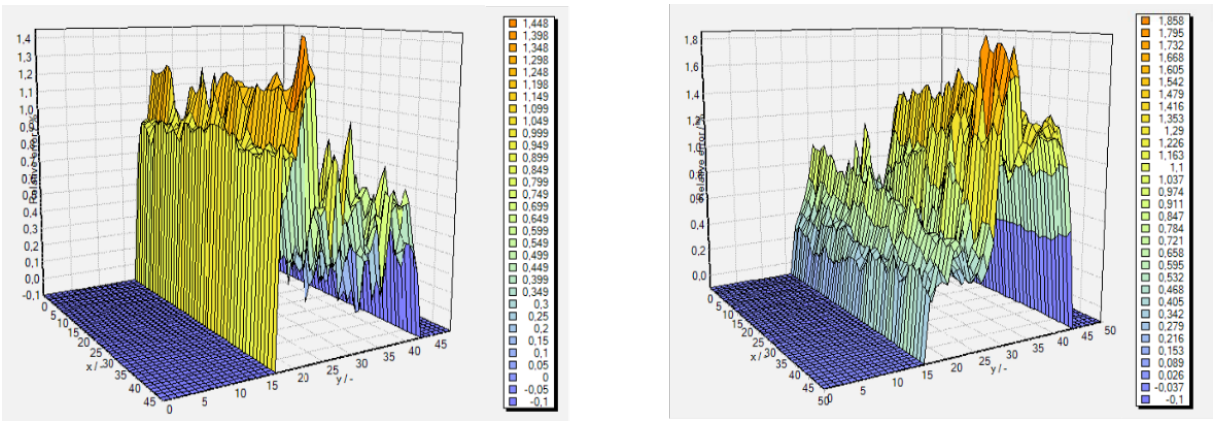

FIG. 3: Relative error between the TPS calculation and the radiochromic film dose distribution in the x and y axes as obtained by the FilmQA software. The used TPS algorithms are AAA (left) and Acuros (right). A 10% of the maximum dose has been set as a threshold.

In order to obtain a single matrix, we assigned a weight to each of the simulations that represents a single tumor position and summed the 11 weighted matrices. These weights are specific for a sinusoidal breathing of 1 cm amplitude.

As the MC results of the absorbed dose were in (keV/g)/history units, and the ones from the TPS, in Gy, a relative dose comparison has been carried out. Both dose distributions have been normalized to a point in the center of each of the distributions.

We have plotted the relative dose distributions for MC, AAA and Acuros in Fig. 4. We can see an artifact in the MC simulation caused by tissue heterogeneities. These changes in density between the tumor and the lung are not taken well into account when we voxelize our geometry and only one of the two bordering densities is assigned to the voxel. This, and the 1.5% uncertainty of the simulations were taken into account while analysing our results, where we adopted a lesser strict gamma acceptance criterion for the MC/TPS comparison (3%/3mm) than the one used for the TPS/Radiochromic film one (2%/2mm). Additionally, a low dose threshold of 10% was established when computing the gamma pass rate to minimize the impact of low dose regions in the analysis.

We have also plotted the probability density of the gamma index values (Fig. 5) and calculated the gamma pass rate by summing the gamma indexes < 1, and dividing by the total number of gamma indexes computed from the distributions. In the case of the MC/AAA comparison, a gamma pass rate of 99.97% has been obtained, and in the case of the MC/Acuros comparison, the pass rate is 99.98%.

IV. CONCLUSIONS

When working with radiochromic films, there are several uncertainties intrinsic to the experimentation and data analysis. Better results in our global gamma pass rate have been obtained by Acuros when comparing to the film, but the difference between both algorithms is small enough to be inconclusive.

Although Acuros should better account for heterogeneities than AAA, it can be seen that, with the level of uncertainty reached by MC simulations (around 1.5%), the difference between the results is not conclusive on which algorithm is better.

If we had increased substantially the CPU time of the Monte Carlo simulations, we could reach levels of statistical (type A) uncertainties low enough to get potentially conclusive results. However, the available hardware became a limitation in this case, and we compromised a lot of simulation time for a somewhat greater uncertainty.

Lacking further results with smaller uncertainties, it seems reasonable to think that radiochromic film dosimetry offers a good compromise between absorbed dose fitting to the TPS calculations and time dedicated to the measurements and results analysis.

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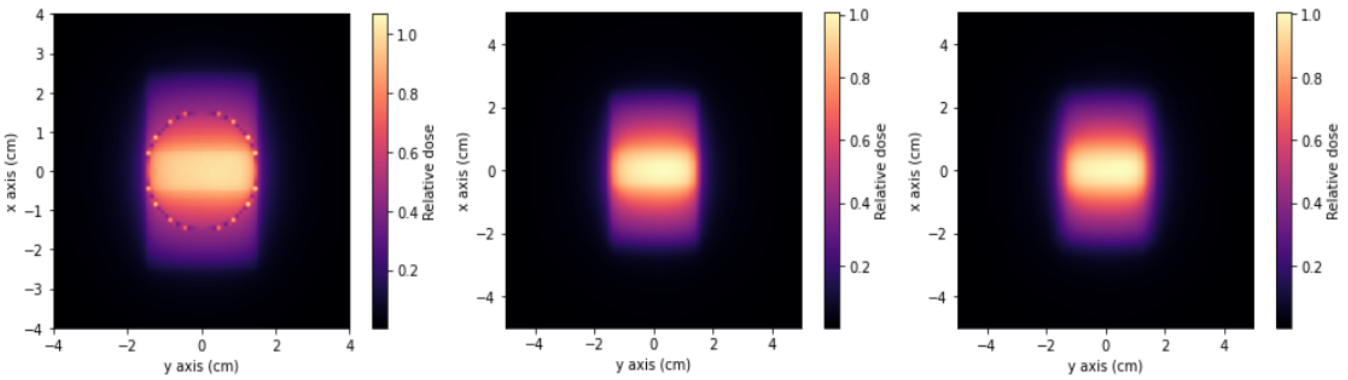

FIG. 4: Normalized dose distributions for the MC simulation (left), AAA (middle) and Acuros (right) calculations with respiratory motion.

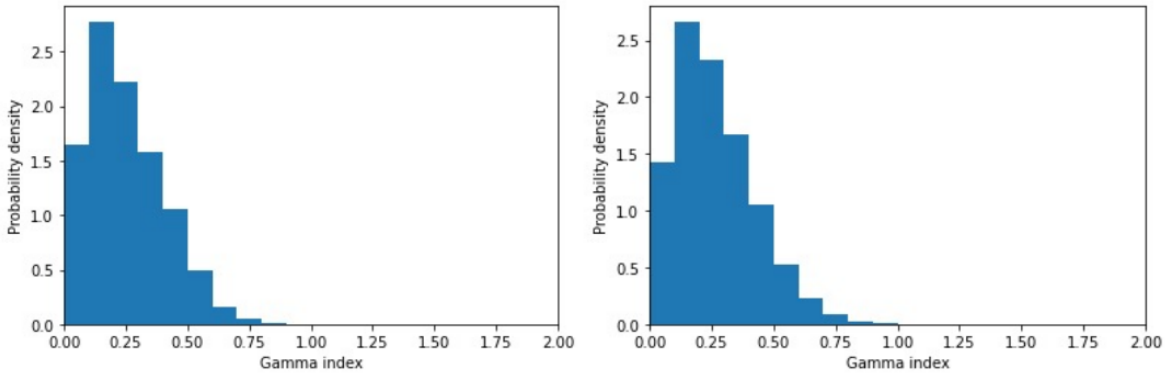

FIG. 5: Probability density of the gamma indexes for MC/AAA (left) and MC/Acuros (right) comparisons.

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