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Monte Carlo simulation on heterogeneous phantom and physical dose calculation on heterogeneous organ

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Abstract

Surgery, chemotherapy and radiotherapy are now the common cancer treatment techniques. In radiation therapy, lung cancer is associated with local control rates very low. The difficulty of this type of treatment is to irradiate relatively radio resistant lung lesions very radio-sensitive. Thus, the issue of adequate therapeutic doses is often limited by the size of the target volume in order to keep the risk of complications to an acceptable level. Radiotherapy of lung tumors is sully by many uncertainties that must be considerate by the safety margins, implying an increase in the size of the target volume. The challenge is to implement methods to reduce uncertainties, and therefore the size of the target volumes. In addition, the protontherapy may better spare the healthy tissues relative to the X-ray radiotherapy.It is necessary to carry out the study of the impact of heterogeneity on the position of the Bragg peak and the absorbed dose in the target volume to be able to perform processing in protontherapy. For this we used the simulation in different phantoms based on Geant4 code to better appreciate the need of this therapy.

Keywords: Monte Carlo simulation, heterogeneous, physical dose.

1. Introduction

Radiotherapy has been in an important evolutionary process for about 30 years. It underwent a revolution, as long as current practices differ from the first established bases. Computerization is the main source since it is found in all phases of diagnosis, imaging, preparation, processing and validation. Lung cancer is the leading cause of cancer death, requires special attention given its incidence and induced mortality rate. Radiotherapy of a tumor located in the thorax is one of the most complex situations because it brings together all the greatest dosimetric difficulties and has very variable shapes and positions which require very personalized design studies. They are in contact with tissues of different densities. They often undergo changes in form and volume during processing. The position and size of the target volume within the thorax condition the entire planning ie the number and orientation of the beams, the margins in all directions and the beam qualities Photons or proton to use[1, 2].

Protontherapy is a type of radiotherapy that involves irradiating tumors with a particle beam while sparing the surrounding healthy tissue as much as possible. Cells are destroyed as a result of damage caused by direct DNA irradiation. Protontherapy uses protons as projectiles instead of photons or electrons used in conventional radiotherapy [1]. The main asset of protons lies in their particular ballistics. In contrast to the photon beams, where maximum energy deposition from the first centimeters at the patient's inlet decreases with depth, charged ions such as protons deposit their maximum energy at the end of their path while maintaining a minimum dose deposited at the inlet called Bragg Peak, Figure 1[3].

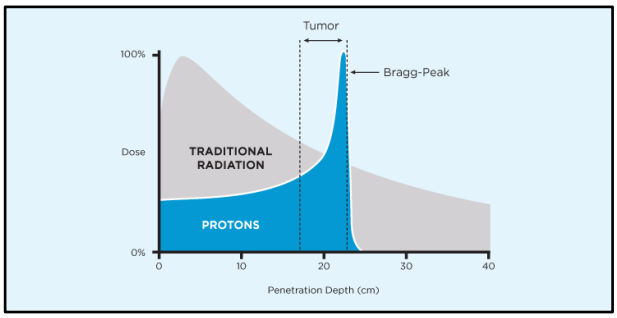

Figure 1. The difference between traditional radiation (photons) and protons beam (Bragg Peak).

In 1946 the application of high-energy beams to radiotherapy was demonstrated for the first time when Robert Wilson [4] gave details of the physical properties of the accelerated protons specially depth dose (In terms of armor). This work came after so many years from the investigations of William Bragg and Kleeman in 1905 on the Bragg peak, which revealed the deposition of the proton energy in the matter. According to them, one can even spread this peak in depth during the process of shaping the beam to create a modulated Bragg peak and perfectly conform to the tumor in depth [5]. The construction of a cyclotron at the Berkley Radiation Laboratory in the USA enabled verification by experimental studies carried out by Tobias in 1952, in order to confirm what was announced in the theories of

Wilson, Bragg and Kleeman [6]. In 1958, the Upssala center in Sweden constructed the first Synchrotron, examined the biological properties of the 185 MeV proton energy and produced the first proton beam dedicated to stereotactic treatment without sparing the physio-biological consequences [7]. In 1960, the neurosurgeon Kjellberg "Massachusetts General Hospital" (MGH) Boston developed the treatment of arterial venous malformations [8]. In parallel, Goitein and Suit worked on the possibility of treatment of deep tumors thanks to the dual diffusion system [9]. In 1974, the first patient with pelvic sarcoma was treated with fractional proton therapy 2Gy/fraction [10]. [11] Presented a theory on the stopping power of ions in matter. Extensively, the improvement of this theory by Chen and Quivey resulted in fractionation of the 2Gy/session treatment dose. They showed the importance of relative biological efficiency and the oxygenation ratio in the target volume [12].

Popularity of Monte Carlo (MC) techniques in the field of medical physics is increasing rapidly in recent years. This is specifically the case for proton therapy. MC simulations are an essential tool for the design and commissioning of novel clinical facilities, allowing a detailed description of the beam line and the delivery system. They are also widely used for bunker design, shielding, and radiation protection.

MC calculations are a valuable tool for the commissioning of Treatment Planning Systems (TPSs). Furthermore, MC codes can represent a unique instrument for validation, and possibly the improvement, of analytical TPS's. In situations where experimental validation is unavailable and/or analytical methods are inadequate; MC simulation allows patient-specific dose calculation. Aspects where MC techniques can be more effective compared to traditional, analytical methods may be summarized as follows:

MC methods take into account more realistically the composition of the human body, with a possible advantage over the water-equivalent approach typically used in analytical TPS's.

These methods naturally include mixed field description and three-dimensional spread of the particle fluency, reliably describing the transport, and the interaction of the primary beam and of the secondary particles.

2. Experimental part: RX Radiation therapy

The aim of this part is using clinical case; we have chosen one patient for curator treatment who was the subject of this retrospective study. He was selected for stage and volume of the tumor. The treatment parameters for the chosen patient are listed in Table 1 He has undergone 3DCT simulation using immobilization device (headrest and thermoformed mask medical solutions) with *General Electric optima Radiation Therapy CT scanner*. Scans covered the entire chest volume part. Then, CT data imaging were generated using the TPS Eclipse (*soma version 11.3 by Varian Medical System*). Gross tumor volume (GTV) was contoured by the treating radiation oncologist from CT datasets. For treatment plan, it was generated accounting for treatment uncertainties in RC3D plan which was developed using the Eclipse (*Version 11.3Varian Medical System, California, USA*) Treatment Planning System (TPS) with 6 MV, AAA (*Analytical Anisotropic Algorithm, Varian Medical System, California, USA*) the dose distributions were computed. In the RC3D radiotherapy planning, after contouring all normal structures and critical organs, 5 fields treatment technique was used for the smallest volume PTV with 60Gy. Beam arrangements at 45°, 90°, 180°, 225°, 270°, angles or orientations were used. The prescribed dose was normalized to 100% at the isocenter, and 95% isodose surface covering the PTV. Dose Volume Histograms (DVH) was used to evaluate treatment plan including PTV, Organs At Risks (OAR) with conformity index (CI) defined below:(CI, ideal value = 1), and in particular points of DVHs [13-19].

$$CI = V_{IR}/V_T \qquad (1)$$

Conformation Index represents Tumoral Volume covered by reference isodose.

- V_{IR}: Volume of reference Isodose.
- V_T: Tumoral Volume,

Table1: Conformity index in PTV 40Gy and PTV 60Gy by RX 6MV beam treatment

	Volume (cm^3)	IC
ISODOSE 95% 40GY (38Gy)	3931.05	0.34
ISODOSE 95% 60GY (57Gy)	2031.18	0.24

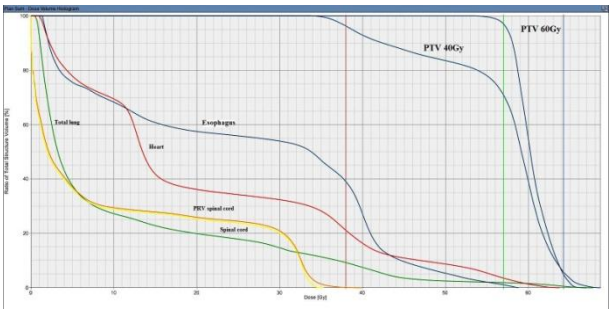

Figure 1. DVHs curves of dose distributions in lung irradiation with 60Gy. PTV 60Gy is represented in bleu 1, in bleu 2: PTV 40Gy, in blue 3: esophagus, in yellow: spinal cord, in brown: PRV spinal cord, in green: total lung and heart in red.

The results calculated in Figure 2 were represented foreach organ in the diagrammatic representation Figure 3(*a*).

We can observe that the mean dose in different OARs is significantly important. The values of this dose attend their maximum for the liver with more than 85% of the total dose.

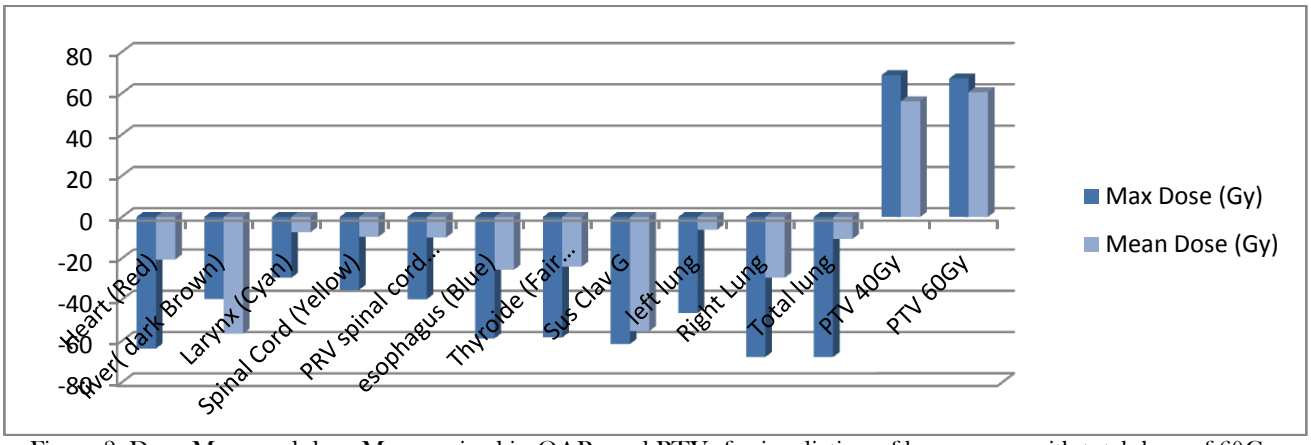

Figure 3. Dose Mean and dose Max received in OARs and PTVs for irradiation of lung cancer with total dose of 60Gy.

3. Simulation part

In this work, we have used the Geant4 (GEometry ANd Tracking 4) [15, 17-25], a software toolkit that is used to simulate the interaction of particles in matter and has been widely used in various fields from high-energy physics (HEP) to nuclear physics and medicine.
Geant4 takes into account the particle interaction physics using theoretical models or experimental cross-section data. Therefore, it is considered to be the most accurate method by which to calculate the dose in radiotherapy. Monte Carlo simulations can be helpful in the design of treatment facilities, improvement of treatment plans, and quality assurance of ongoing treatments, and verification of the Geant4 validity for use in dose calculations. Geant4 simulations are currently considered in medical physics as a powerful tool to design and optimize calculation treatment. It has been used extensively at the Massachusetts General Hospital in Boston for proton therapy applications using passive spreading techniques [26].

3.1. homogenous phantom

We used C++ code to write program which allows the interaction of proton beam in water, the phantom has rectangular shape with (10, 10, 30) cm size and 1g/cm^3 of density for 1000 events. All results were represented in ROOT version 5. Figure 4. Shows phantom in parent volume and the interaction of proton beam in water.

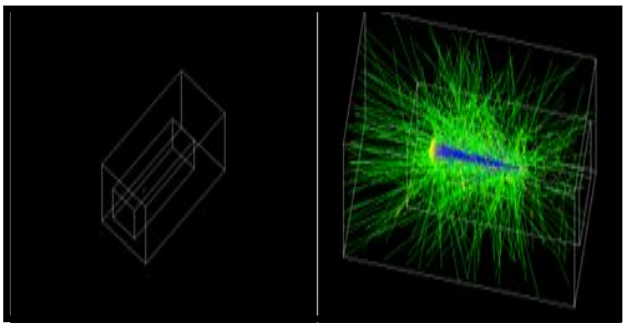

Figure 4. (left) Mother volume containing water phantom, (right) interaction of proton beam in water phantom

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The dose in entries about 20% not important, which will coincidence with soft tissues in patient; we can observe that the maxima of dose attend 150 mm of depth.

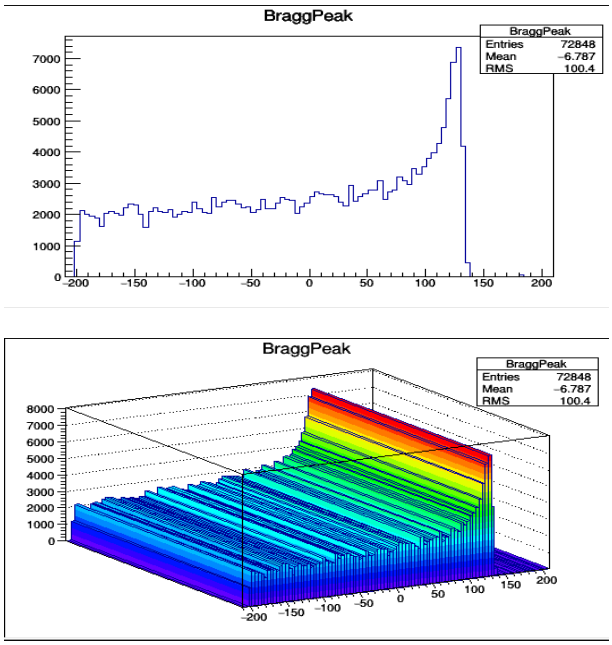

Figure 5. (a)Depth-dose profiles (Bragg Peak) generated from the interaction of scenario 1, the depth of deposit dose is in 150 mm in water with mean energy of 79 MeV, (b) 3D projection of the Bragg Peak.

3.2. Heterogeneous phantom

The configuration of transverse phantom was designed with density variations, using four different media: soft tissue, cortical bone, lung and water with densities of, 1.08, 1.90, 0.26, 1.0 g/cm^3 and with thicknesses of 20, 10, 50, and 70 mm respectively. Energy proton beam used for this simulation is 230 MeV, for 1000 events. Figure 6 presents the position of layers material in phantom and screen shot of the interactions.

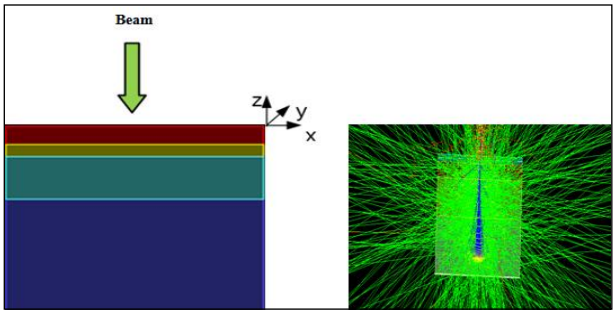

Figure 6. Schematic representation of the heterogeneous configuration used: The different materials are represented by different colors; in red: soft tissues, in yellow: cortical bone, in blue: lung, and in dark blue: water, (left). Screen shot of the interactions of proton beam in the phantom (right).

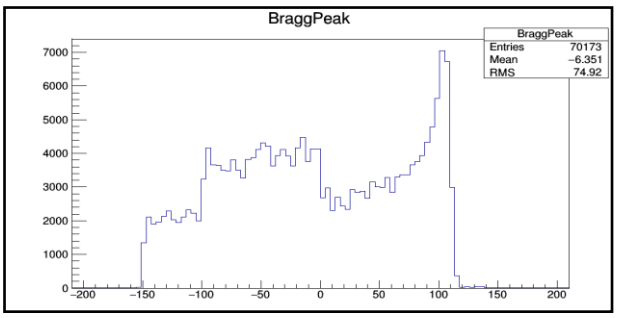

Figure 7. Bragg peak generated from the interaction of scenario 2. All depths less than zero represent proton beam interactions before phantom, which are neglected. The maxima of deposited dose attend 118 mm and the energy in entries is 70 MeV.

Figure 7 represents the variation of absorbed dose bythe periphery in different layers density. We can see: direct proportion between dose and material densities, direct proportion between energy deposited and depth dose.

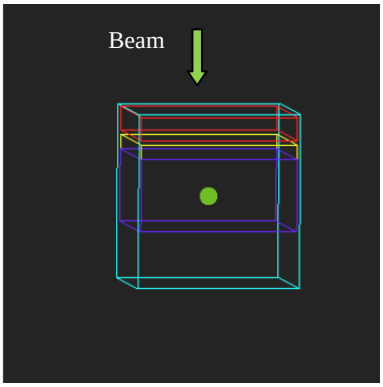

Figure 8. Schematic representation of the heterogeneous configuration used: The different materials are represented by different colors; in red: soft tissues, in yellow: cortical bone, in dark blue: lung, and in blue: water and in green spherical ball.

To determine the effect of the target size, we used the protons beam of 230MeV in the same heterogeneous phantom (soft tissue, cortical bone, lung and water). We added a ball of 2mm radius and 0.26g/cm^{3}as density (lung density) as it shown in figure 8.

We obtained, as results, the distributions in figure 9.

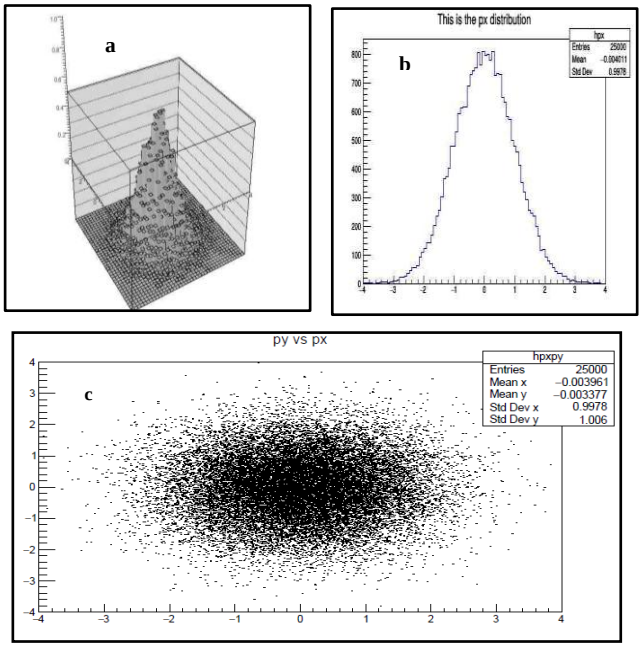

Figure 9. Dose distribution in spherical ball obtained by 230MeV protons beam (a): the maximum of dose deposit is concentrated on the center (b): the variation of 96% dose is between [−2, +2] (c): Top view.

4. Interpretation

More than 10% of dose distributions in water and in heterogeneous environment are calculated in bones, however, they are less in soft tissues. This step is very important to evaluate the difference in term of depth, the dose gaps in calculation algorithm are due to the nature of saved dose (water or heterogeneity).

We compare our results to those of M. L. Grevillot, 2011 [20], and we can see that we have similar results, the maximum of deposited dose in water is around 150 mm and it is less than 120 mm in heterogeneous phantom, for both. The loss of 30 mm of depth results from the absorption by cortical bones and other tissues. The differences between the two doses engines are clinically acceptable. These differences show the necessity of evaluate TPS dose calculation algorithms with Monte Carlo code.

To determine the size effect and introduce the uncertainty we have to more understand how Geant4 treat hadronic process.

In heavy particles with high energy (>100MeV), the hadronic processes describe the interactions between incident proton and the target nuclei. There is no strict boundary between the different nucleon-nucleon collision processes, but four main types of process depending on the energy and the impact parameter beam can be

observed. At low energies, collisions lead to elastic or inelastic scattering in peripherical collisions and incomplete fusion in central collisions. At intermediate energies (our case), the collisions lead to a fragmentation of the system into several lighter fragments or nucleons in the central collisions and into a participating part and a spectator part for the peripheral collisions.In Geant4, the inelastic fusion, inelastic scattering and fragmentation processed are included in the inelastic process type. These inelastic processes had three main steps: Cascade step where the incident particle interacts strongly with the target and produces secondary particles; Preequilibrium step (thermalization process) where the excited target nucleus switches into equilibrated state by emitting excitations and light nuclei and De-excitation step where the residues evaporate nucleons [27].
To approve the results it is recommended that at least 97% of distribut;ion must be between [–3ò, +3ò] (ò is standard deviation). From figure 9 (b), we can see that our results are satisfactory and it is concentrated between [–3, +3] with the value of Std Dev of 0.9978.

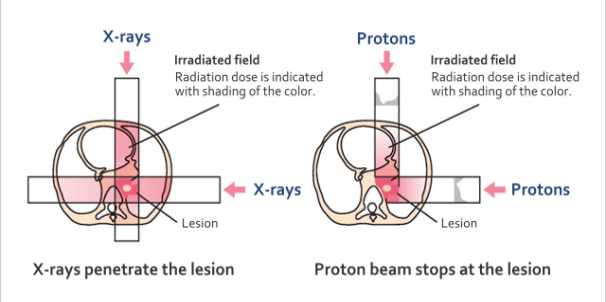

Figure 10.Schematic representation of high dose in OARs in XR treatment and the advantage of proton beam [28].

5. Conclusion

Protontherapy helps to save healthy cells around tumors. Indeed, protons offer an additional quality of irradiation compared to photons. The protons stop in the matter. This stop is defined by the energy of the incident particle. Photons, meanwhile, are only gradually absorbed and deposit energy well beyond the cancer cells. The contribution of proton therapy compared to the RC3D can be discussed only according to the tumor locations. Protontherapy today mainly deals with tumors of the eye, chondromes and chondrosarcomas of the base of the skull. It is used in adults, but also to treat tumors in children. Our goal is to add this proton treatment technique for pulmonary cancer since, from the simulation results; we can see their effectiveness in heterogeneous tissues Figure 10.
The purpose of this study is to valorize the use of Proton in therapy of lung cancer. The presence of heterogeneous tissue in lung cancer makes irradiation especially vulnerable to patient setup and range uncertainties. Controlling heterogeneity is too important for lung cancer that we can accomplish just with MC simulation.The emplacement and the volume of the tumor influent on the estimation. The high energy is beneficial to increase dose in tumor till 230 MeV.The physical dose to water occurs for the PTV, for which Geant4 predicts lower contributions of high doses.

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