LIP-STUDENTS-23-3

Radiobiological Phantom Characterization

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Abstract. The irradiation of any biological system generates a succession of processes, and their effects are the main concern in any radiobiological study. To perform experiments on biological models, the creation of a system that allows us to perform the desired measurements and that is also reproducible, easy to assemble and fast to set up is especially important. A phantom for the irradiation of cells at radiotherapy clinical facilities was designed and its characterization is necessary. This work is focused on the validation of the phantom using Monte Carlo simulations and resourcing to TOPAS, a Geant4-based Monte Carlo tool.

KEYWORDS: TOPAS, Phantom, Electrons, Photons, Monte Carlo, Radiotherapy

1 Introduction

1.1 Radiotherapy

Radiotherapy (RT) is a treatment where high-energy ionizing radiation is used to destroy certain cells and tissues and it is mostly used in the treatment of cancer patients. The most common type of RT is external beam radiotherapy (EBRT), where a commercial medical linear accelerator shoots high-energy beams aimed at a specific area of the patient's body, damaging the genetic material of the cancer cells. This high-energy ionizing radiation can have the form of high-energy photons, as well as other particles such as electrons or protons.

To simulate a clinical irradiation procedure, dosimetry phantoms are used. These are devices with similar absorption and scattering characteristics as human tissue, capable of dose measurements at specific points during or after the irradiation. The phantom used was designed to be easy to assemble, fast to set up, adaptable to different studies and that allows for precise dosimetry measurements. Inside the phantom there is usually some biological material that is prepared on microplates.

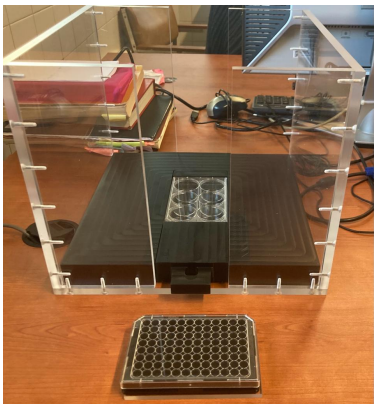

Figure 1. Real phantom simulated in the internship.

The ionization produced by high-energy photons is due to two different interactions with the tissue [2]. In the photoelectric effect, a photon collides with an electron and disappears, transferring most of its energy as kinetic energy for the electron that irradiates the surrounding atoms and molecules. On the other hand, in the Compton effect, a photon transfers only part of its energy to a free electron and is scattered with a certain angle. In this case, the incident photon's energy is much higher than that of the free electron. There is also another interaction known as pair-production which is predominant for photon energies higher than the ones used in this internship.

Meanwhile, electron absorption is directly influenced by the depth of the organ or tumor, since electrons are constantly absorbed by human tissue before they reach the desired location in the human body. They are mostly used in the treatment of superficial tumors.

1.2 Overview of TOPAS

TOol for PArticle Simulation is a software designed specifically for medical applications because it allows the user to assemble simulations with Geant4 without having to write any code. In other words, it is extremely user-friendly and it has a simple input that can be used by anyone without coding background in Geant4 Monte Carlo simulations [3].

2 Simulations

2.1 Assembly of the Phantom Setup in TOPAS

The phantom was designed to be used in studies where cell culture lines are irradiated. It consists of a box that can support all of the slabs of tissue equivalent material present at most hospitals (usually called solid water) which can be easily swapped when needed to test different scenarios because of the gaps in its frame. In its center, a drawer is placed where a microplate can be attached.

The implementation of the phantom was relatively quick since TOPAS allows the use of computer-aided designs like the one of the phantom that needed to be characterized since it was built on SolidWorks (figure 2).

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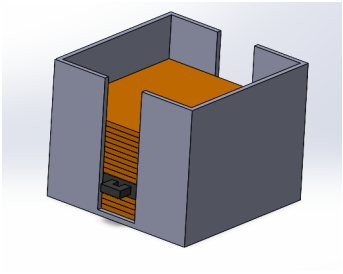


Figure 2. 3D representation of the phantom used on the SolidWorks interface.

The phantom is made of PMMA, a synthetic polymer that is similar to water, which allows for a good approximation of human tissue. The purple volume on figure 3 was used to represent where the biological material will be placed during the simulations as well as during the irradiation [1].

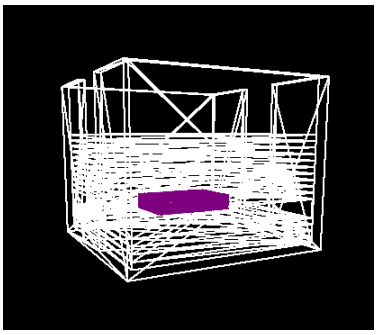


Figure 3. 3D representation of the phantom in TOPAS.

The microplates tested were a simplified version of the Greiner Bio-One 6-well and 96-well microplates [1], which consists of a polystyrene slab with the wells embed in it and an air layer of 0.1 cm in the bottom of the slab. The wells have the same sizes as the ones described on the costumer drawings of each plate in the Greiner Bio-One website, with an air column above and a thin water cylinder for scoring below. Each water component was scored in terms of depth and quadrant dose distributions. An average dose deposited in each well was calculated using the depth dose distribution. Their model implementation on TOPAS is represented on figure 4.

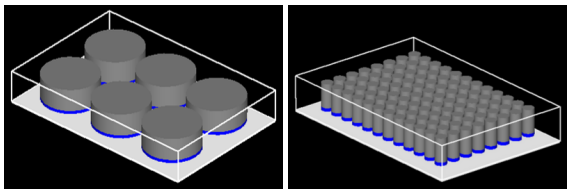


Figure 4. On the left, the 6-well microplate. On the right, the 96-well microplate.

TsJaws, a special component of the TOPAS software, was used to collimate the beam into a surface field of 10x10 cm^2. The collimator is made out of tungsten. The complete setup with the collimator and the phantom with the microplates inside is shown on figure 5.

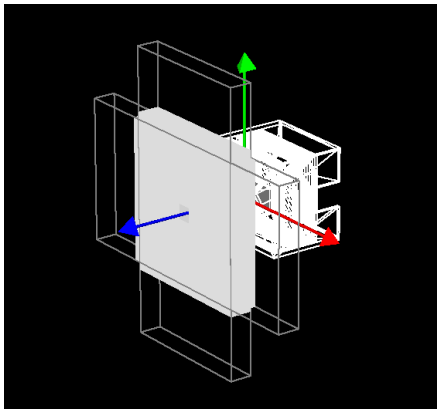


Figure 5. Complete setup on TOPAS with the collimator and the phantom with a microplate inside in the right position. The red, green and blue axis represent the x, y and z axis, respectively.

2.2 Beam Profiles

Two beam profiles were tested throughout the simulations, a pencil beam with a cylindrical shape, and a cone beam that also shoots particles at an angle relative to the z-axis, axis from where the beam will be fired at 50 cm from the phantom [4].

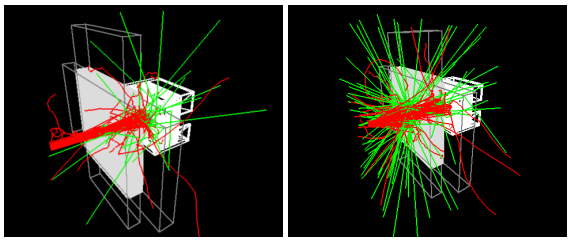


Figure 6. On the left, the pencil beam. On the right, the cone beam.

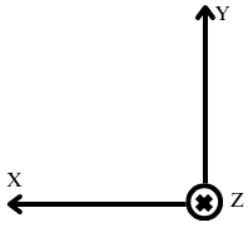
The beams will be comprised of two types of particles, electrons and photons, with energies of either 6 or 12 MeV. The secondary radiation of the photons (X-ray after bremsstrahlung) was not be accounted for since a monoenergetic beam was used.

3 Results

Before going through with the results, it is important for the reader to understand how each microplate was analyzed and the conditions of the simulations. Each one of them was comprised of 10^6 events and the "g4emlivermore" package was chosen for its useful data on how particles interact in medical physics.

With TOPAS, it was possible to score how the dose was distributed in depth and also in the quadrants of each

well. The well and quadrant numeration considered from now on was the following:



Well 1	Well 2	Well 3
Well 4	Well 5	Well 6

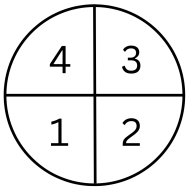


Figure 7. Well and quadrant distribution. The axis serves as the perspective from which the microplate on the setup is being observed (so the beam is coming from the inside to the outside of the paper).

This means that the second and fifth wells will be the ones at the center of the microplate.

For simplification, the 96 wells of the other microplate were grouped into 6 groups of 16 wells, each group located on the same locations of the wells from the 6-well microplate.

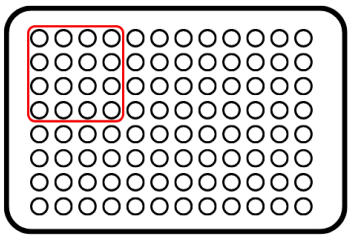


Figure 8. Grouping of the 96-well microplate. The red line represents a group of wells, in this case, on the same position of the first well of the 6-well microplate.

3.1 Pencil vs. Cone

The differences between the pencil and the cone beam were essential to this characterization. Since the real experiment will be done with a photon beam, the focus was shifted only to those results.

For both microplates, the depth dose profile was analyzed for the 6 and 12 MeV photon beam for both beam shapes.

With the pencil beam, a higher dose is deposited on the second and fifth wells (established earlier as the center wells) as ilustrated on figures 9 and 10.

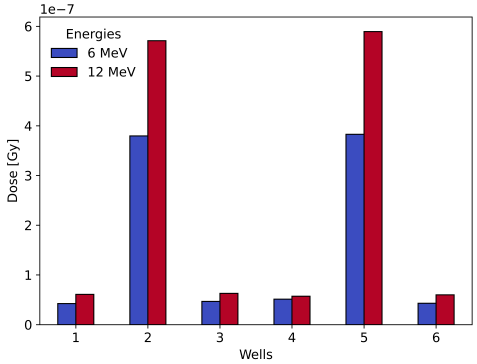


Figure 9. Pencil photon beam (6 wells).

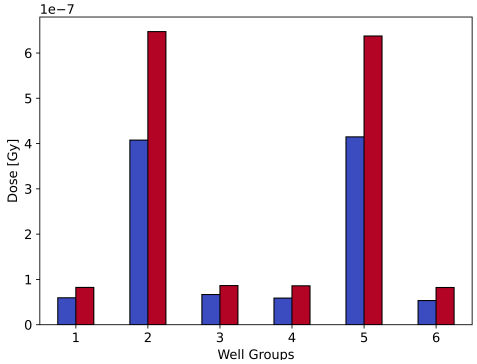


Figure 10. Pencil photon beam (96 wells).

On the other hand, the dose deposited by the cone beam with the same energies is more dispersed throughout all the wells (see figure 11 and 12). This difference is due to the fact that the pencil beam is very narrow and focused beam, i.e. it has a small cross-sectional area, which means that area hit on the target will be smaller and centralized. Whilst, on the cone beam, the spread is wider which leads to a larger area of the target covered by the particles.

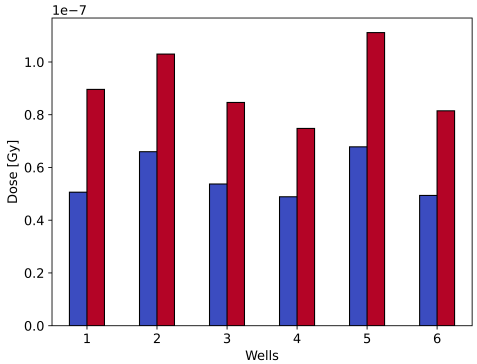


Figure 11. Cone photon beam (6 wells).

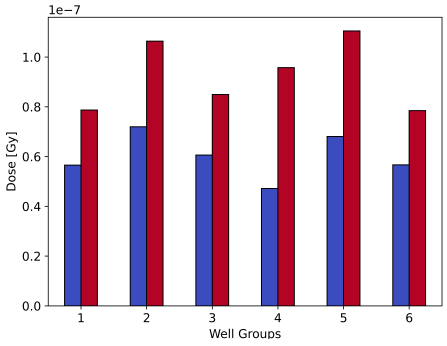


Figure 12. Cone photon beam (96 wells).

Besides analyzing the depth dose profile, it was also possible to analyze how the dose was distributed per quadrant of each well. This allowed for a more meticulous description of how the dose is distributed. For the pencil beam (figure 13), what was observed was that the bottom of the second well and the top of the fifth well (which are the fractions of these wells that are closer to the center of the microplate), receive a higher dose than the other halves of these wells. For the wells on the side, the same applies, but this time it was the left half of the right-side wells and the right half of left-side of the wells that got the higher dose when compared to the other half.

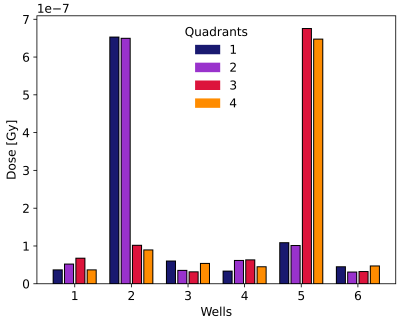


Figure 13. Dose distribution per quadrant with a 6 MeV photon pencil beam.

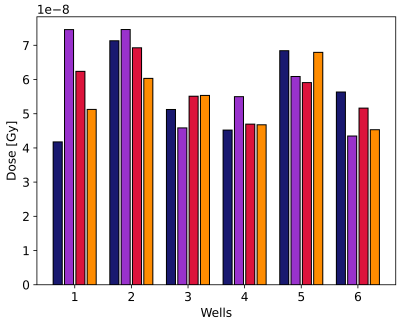


Figure 14. Dose distribution per quadrant with a 6 MeV photon cone beam.

On the other hand, the homogeneity that the cone beam provides is still visible since each quadrant receives a dose close to the others (see figure 14). This difference is again related to how the different beams irradiate their targets.

A 2D representation is helpful to check this result. This is represented on figure 15.

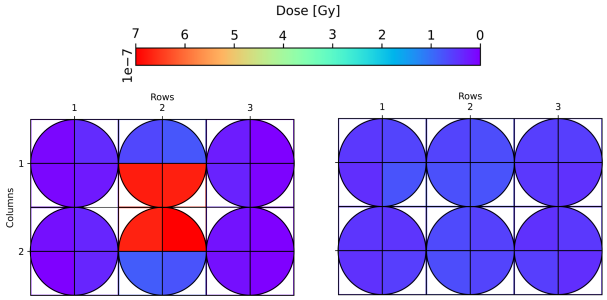


Figure 15. On the left, the well scoring with the pencil beam. On the right, the well scoring with the cone beam.

3.2 Photons vs. Electrons

For both microplates, it was possible to compare the doses deposited by the photon and the electron beams for both energies. The photons and electrons will always be represented as green and as red, respectively, in order to match the colors TOPAS assigns to both particles.

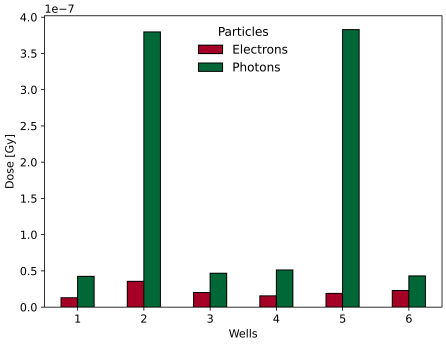


Figure 16. 6 MeV pencil beam (6 wells).

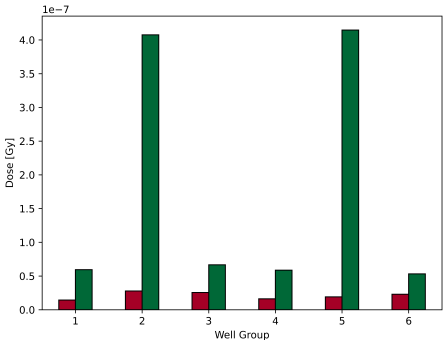


Figure 17. 6 MeV pencil beam (96 wells).

Observing the average dose distribution comparison between the two energy beams, it is possible to observe that for the lower energy, 6 MeV (figures 16 and 17), the dose deposited by the photons is relatively higher than that deposited by the electrons, though when we increase the energy to 12 MeV, the opposite happens (figures 18 and 19).

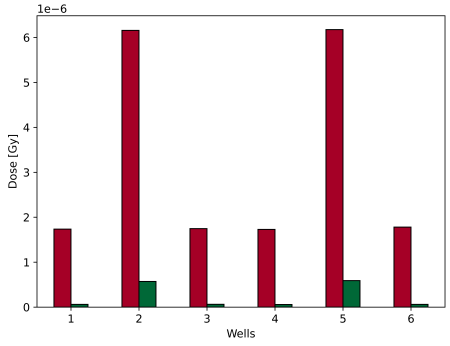


Figure 18. 12 MeV pencil beam (6 wells).

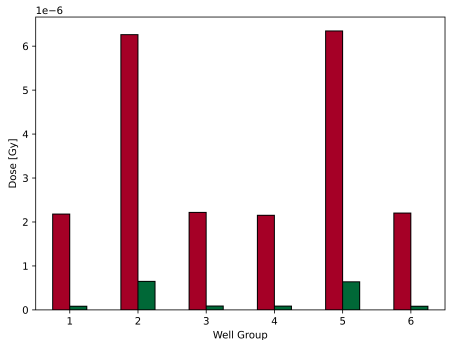


Figure 19. 12 MeV pencil beam (96 wells).

This is due to the fact that electrons lose energy as they pass through a medium, in this case water, because they suffer multiple scattering, due to Coulomb force interactions between the incident electrons and the nuclei of the material. So, as the electron beam traverses the patient, its mean energy decreases. The typical energy loss for a therapy electron beam, averaged over its entire range, is about 2 MeV/cm in water and water-like tissues [2]. So for lower energies, such as 6 MeV, having to go through 5 cm of PMMA means that the electrons that reach the wells are not as energetic as they were in the beginning. Adding to that, the X-ray production (bremsstrahlung) through radiation is much more efficient for higher energy electrons, which explains the radical increase in dose deposited in each well for the 12 MeV electron beam.

4 Conclusions

In sum, the desired characterization of this phantom was successful and provided important insights. It was concluded that for the pencil beam, the photons' dose is relatively deposited towards the center of the microplates, scoring much higher doses for the center wells than to the others on the side. Even for the center wells, it was observed that their quadrants were scored differently according to how close they were to the center; the closer they were, the higher was the dose. The same happened to the other wells.

On the opposite hand, the cone beam showed a more homogeneous distribution for all the wells, creating a more evenly spread out dose, although lower than that of the pencil beam's center wells, but higher than the outside wells when using the same initial energy values.

It was also relevant to discuss the discrepancy between the results of the photon and the electron beam for different energies since it provided insight as to how electrons behave when in contact with water.

It was significant to analyze how different values of energy affect how electrons are absorbed or scattered when passing through simulated tissue and how they are better suited for low depth radiotherapy since they need rather large energies to pass through all the tissue and reach the desired location on the human body. The differences in the photons were also noticeable since at higher energies, the dose they deposit is not as high as that of the electrons. This happens because as we increase the energy, the Compton effect starts to become the dominant phenomenon and because of that, not all the energy of the photon is transferred to the scattered electron, which is what happened when the photoelectric effect was dominant.

Following this work, it would be important to compare our results, the simulated data, to those obtained experimentally. Other future implementations and analysis could be the use of X-ray produced by photons from Bremsstrahlung, or the use of a phase-space with all the data for the beam already imbedded into the file, which TOPAS can read.

Acknowledgments

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Another great thanks to the NUC-RIA group, especially to its coordinator, Professor Daniel Galaviz, from whom I was able to learn a lot. My time there was largely fruitful.

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