GEANT4 Study of Proton–Body Interactions

J.A. López1*, S.S. Romero González1, O. Hernández Rodríguez1, J. Holmes2 and R. Alarcon2

1Physics Department, University of Texas at El Paso, El Paso, Texas, 79968 USA
2Physics Department, Arizona State University, Tempe, Arizona, 85281 USA

*jorgelopez@utep.edu (Corresponding Author)

ARTICLE INFORMATION

Received: September 18, 2020
Accepted: January 09, 2021
Published Online: February 10, 2021

Keywords:
Proton therapy, Gamma rays, GEANT4

ABSTRACT

Proton therapy uses a beam of protons to destroy cancer cells. A problem of the method is the determination of what part of the body the protons are hitting during the irradiation. In a previous study we determine that by capturing the gamma rays produced during the irradiation one can determine the location of the proton-body interaction, in this work we investigate if by examining the gamma rays produced it is possible to determine the body part that produced the gamma rays by the proton collision. This study uses GEANT4 computer simulations of interactions of proton-tissue, proton-brain, proton-bone, etc., which produce gamma rays, to determine the characteristics of the gamma rays produced. We then analyze the characteristics of the gamma rays to find signatures that could be used to determine the source of the rays. In particular, we study the distribution of gamma ray energies, their full-width half-maximum, energy resolution, maximum height, and total number of counts. This study concludes that it is possible to use the gamma ray spectra to determine what body part produced it.

1. Introduction

Proton therapy uses a beam of protons to irradiate diseased tissue. An advantage of proton therapy over other types of treatments is the ability of the protons to deposit energy in a narrow range minimizing irradiation to healthy cells.

Calibrating the proton energy allows to deposit energy in a certain range known as the Bragg peak [1]. Figure 1 (A) shows a typical spread-out Bragg peak (SOBP) of a proton beam produced by twelve Bragg peaks (blue lines) at different energies [2], compared to the X-ray range. Typically, proton beams have energies in the range of 70 to 250 MeV [4].

Figure 1: (A) Spread of x-ray radiation compared to proton radiation. The spread-out Bragg peak (SOBP) is actually produced by several Bragg peaks (blue lines) at different energies [2]. (B) Proton interaction mechanisms: (a) proton-electron interactions, (b) deflection of proton by the nucleus Coulomb field, (c) proton-nucleus collision [3].
In spite of this, it is impossible to know where exactly is the proton hitting. If information about the location of the target being hit by the proton beam were available, one could then fine-tune the beam energy during the irradiation for a better focus. As explained in [5, 6], it is conceivable to use the gamma rays produced during the proton-target interaction to determine the location of the proton-tissue interaction and, as an extension, it may also be possible to determine the type of target being hit by looking at the characteristics of the gamma rays being produced. This is the ultimate goal of this study, namely, to determine the type of target being irradiated by inspecting the gamma rays produced.

The gamma ray produced in proton-nucleus collisions are expected to be more or less intense depending on the density of the body being irradiated. The intensity of the gamma rays produced in different parts of the body is then expected to vary, and thus could be used as a signal to identify the organ being irradiated. The specific goal of this work is to characterize the gamma rays produced by the different body parts when irradiated by a proton beam.

Here we use the package Geant4 to simulate the proton-body interactions, and by varying the parameters of the simulation (beam energy, geometry, body part, etc.) thousands of simulations will produce gamma rays with varying energies and intensity. These characteristics of the gamma rays produced will be used to try to distinguish among the various targets.

This work is born in support to the project of Arizona State University [7] to develop an out-of-the-body gamma ray detectors that can help determine the location of the proton-tissue interactions during proton therapy. Next we discuss the interactions of protons with body parts and the production of gamma rays, the setup of the GEANT4 simulation, the analysis of the gammas produced, and the result of the simulations.

2. Physics of Proton Therapy

Protons interact with the tissue at the atomic level through the reactions shown in Figure 1 (B). Out of those three types of reactions, only direct collisions of protons and nucleus produce gamma ray, which can be detected outside the body during the irradiation. Although gamma rays can interact with matter in various ways (i.e. Mössbauer Effect, Coherent Scattering, Pair Production, Photoelectric Effect and Compton Effect [8]), most of the time such interactions do not occur and the rays simply travel through the body freely in a straight line.

The particles that intervene in proton therapy are the electrons, protons and neutrons, as well as x rays and gamma rays; these particles constitute an “ionizing radiation”, for their ability to remove electrons from matter through which they propagate. Protons can interact with nuclei and produce gamma rays in several manners, identifying nuclei as A, B, C, etc. excited nuclei as A*, B*, etc., protons as p, and gamma rays as γ, these interactions are:

- Radiative capture: \( p + A \rightarrow B^* \rightarrow B + \gamma \), such as \( p + ^{27}\text{Al} \rightarrow ^{28}\text{Si} + \gamma \).
- Inelastic scattering: \( p + A \rightarrow A^* \rightarrow A + \gamma \), such as \( p + ^{27}\text{Al} \rightarrow p + ^{26}\text{Al} + \gamma \).
- Rearrangement collisions: \( p + A \rightarrow C^* \rightarrow C + \gamma \), such as \( p + ^{27}\text{Al} \rightarrow ^{4}\text{He} + ^{24}\text{Mg} + \gamma \).

The gamma rays are emitted with energies in the few MeVs. The proton-nucleus interactions produce gammas by bremsstrahlung and by resonant reactions at specific energies; a gamma yield at resonant energies is known as a “Lewis Peak”. Figure 2 shows a gamma ray spectrum produced in proton-water reactions with the resonant peaks clearly visible, and Table 1 lists the seven prominent energies of gammas produced in proton irradiation of a water target along with characteristics of the peaks to be explained below.

![Gamma ray spectra of water and the reactions producing the peaks.](image)

**Figure 2:** Gamma ray spectra of water and the reactions producing the peaks.

**Table 1:** Characteristic gamma ray energies produced in proton-water reactions.

| ENERGIES (keV) | FWHM (keV) | R% Max. height | Area   |
|---------------|------------|----------------|--------|
| 2000          | 75.3       | 3.765          | 973.21 | 78009.44799 |
| 2310          | 74.98      | 3.245887       | 1784.6 | 142440.0084 |
| 2800          | 160.42     | 5.729286       | 453.01 | 77359.19944 |
| 3680          | 118.11     | 3.209511       | 541.94 | 68137.0838 |
| 4440          | 165.65     | 3.730856       | 2394.25 | 422188.6971 |
| 5200          | 153.08     | 1.030484       | 638.29 | 43410.68055 |
| 6200          | 63.89      | 1.030484       | 638.29 | 43410.68055 |

3. GEANT4 Simulation

Geant4 is a Monte Carlo platform designed by CERN to simulate particle interactions [9]. The simulation is a series of “events” in which protons collide with the medium (body...
parts) and produce gamma rays, which are allowed to travel unperturbed. Outside the medium, the energy and direction of the gamma rays is analyzed through CERN’s interface ROOT. The simulations include a “world”, a proton beam, and a “water phantom” representing both the target and the counter. The simulations were performed with different target materials composed of different body compounds (tissue, blood, bone, brain, etc.), created with GEANT4’s material database [10]. Proton energies used were 60 MeV, 80 MeV and 120 MeV. The simulations were computed in a personal computer with Intel i7 processors and each run lasted up to 20 minutes. Altogether close to one billion runs were simulated. Figure 3 shows the world (large external cube), protons (blue lines) hitting the water phantom (inside cube), producing gamma rays (green lines) and electrons (red lines).

4. Results

The energy spectra were obtained with ROOT, further analysis includes a Gaussian fit of the resonant peaks, the areas under the peaks, the full width half maximum (FWHM), the maximum number of counts, and the peak resolution. The media studied were water, MS20 tissue, lung, brain, bone, blood, tissue, muscle with sucrose and without sucrose, muscle striated ICRU, and muscle skeletal ICRP. Histograms contain 10,000,000 events of proton colliding with the targets. Figure 4 shows typical spectra obtained for water, MS20 Tissue, brain and bone.

Next, the observed spectra were compared on a peak-by-peak basis. For this, the seven most prominent peaks of the water spectrum (2.0 MeV, 2.31 MeV, 2.8 MeV, 3.68 MeV, 4.44 MeV, 5.2 MeV, 6.1 MeV) were characterized by fitting them with a Gaussian curve: $Y = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{[E - E_0]^2}{2\sigma^2}}$, where $Y$ is the gamma count, $E_0$ is the mean energy of the peak, and $\sigma$ is the standard deviation, all obtained with the software package Origin. Furthermore, the energy resolution (R) of each peak is the FWHM expressed as a percentage of the mean energy, $R = \text{FWHM} \times 100/E_0$; R is important for the design of the detector, scintillation counting equipment in nuclear medicine typically have resolutions of less than 10%. Figure 5 shows the comparison of water and tissue peaks and Gaussian fits, Table 2 shows the number of gamma rays produced in each of the seven peaks of the nine target materials at the selected energies, and compared to water in percentages.
Figure 5: Example of comparison of water and tissue peaks and Gaussian fits.

Table 2. Integration peaks of body materials normalized respect to water.

| MATERIAL                        | 2.00 MeV | 2.31 MeV | 2.80 MeV | 3.68 MeV | 4.44 MeV | 5.20 MeV | 6.10 MeV |
|---------------------------------|----------|----------|----------|----------|----------|----------|----------|
| WATER                           | 7572     | 12759    | 10500    | 7604     | 16463    | 8598     | 10177    |
| WATER NORMALIZED (N)            | 100%     | 100%     | 100%     | 100%     | 100%     | 100%     | 100%     |
| TISSUE                          | 8483     | 12444    | 6568     | 6613     | 8822     | 8113     | 5438     |
| TISSUE N                        | 112.03%  | 97%      | 62.55%   | 86.97%   | 53.59%   | 94.3%    | 53.43%   |
| BONE                            | 20189    | 24968    | 12523    | 9314     | 19004    | 9906     | 7623     |
| BONE N                          | 266.63%  | 195.69%  | 119.27%  | 122.49%  | 115.43%  | 115.21%  | 74.90%   |
| BLOOD                           | 8132     | 13517    | 10503    | 7781     | 15812    | 8790     | 9707     |
| BLOOD N                         | 107.40%  | 105.94%  | 100.03%  | 102.33%  | 96.05%   | 102.23%  | 95.38%   |
| BRAIN                           | 8399     | 13431    | 10173    | 7737     | 15412    | 8670     | 9410     |
| BRAIN N                         | 110.92%  | 105.27%  | 96.8%    | 101.75%  | 93.62%   | 100.84%  | 92.46%   |
| LUNG                            | 8338     | 13299    | 10646    | 7757     | 15977    | 8806     | 9797     |
| LUNG N                          | 110.12%  | 104.23%  | 101.39%  | 102.01%  | 97.05%   | 102.42%  | 96.27%   |
| MS20 TISSUE                     | 11486    | 16675    | 9168     | 7967     | 13996    | 11478    | 9157     |
| MS20 TISSUE N                   | 151.69%  | 130.69%  | 87.31%   | 104.77%  | 81.37%   | 135.50%  | 89.98%   |
| MUSCLE STRIATED ICRU            | 8072     | 12990    | 10081    | 7643     | 15216    | 8693     | 9507     |
| MUSCLE STRIATED ICRU N          | 106.60%  | 101.81%  | 96.01%   | 100.51%  | 92.43%   | 101.1%   | 93.42%   |
| MUSCLE WITHOUT SUCROSE          | 7606     | 12649    | 9997     | 7650     | 15359    | 8525     | 9379     |
| MUSCLE WITHOUT SUCROSE N        | 100.45%  | 99.14%   | 95.21%   | 100.60%  | 93.29%   | 99.15%   | 92.16%   |

In summary, we present some of the most interesting features observed in the hundreds of peaks studied.

• For the peak at 3.68 MeV the lung’s area is less than water’s by 30%, and for the peak at 2.3 MeV the difference is around 15%. These two points are promising signatures to distinguish between lung and water.

• For the peak at 3.68 MeV the tissue’s FWHM is bigger than water’s by more than 300%, and for the 5.2 MeV peak is around 400% greater.

• There is a pronounced difference in the values of Max Height for blood, water, or tissue and, thus, it is possible to distinguish between these materials at some energies.

• Tissue differs in area by 30% with respect to water or lung at the 2 MeV peak, by 75% at the 2.3 MeV peak, and by about 150% at the 3.68 MeV peak.

• Water, tissue and MS20-tissue have similar spectra, but at the energy of 3.68 MeV muscle (of any kind) yields less gammas than water.
• R for water, tissue and MS20-tissue present major differences at 3.68 MeV, where R for MS20-tissue it is greater by 100% than water. This is due to the fact that tissue nor MS20-Tissue does not present a peak at such energy.

• At 2 MeV, MS20-tissue and normal tissue differ from water by about 50% at the same energies. The comparisons of the seven peaks of some of the targets are presented in Table 3; results labelled as NA (Not Applicable) indicate that the Gaussian fit was not accurate.

Table 3: Peak comparison of water and body materials.

|        | Xc(ENERGIES KeV) | FWHM(KeV) | R%   | MAX HIGH | INTEGRATION OF PEAKS |
|--------|-----------------|-----------|------|----------|-----------------------|
| WATER  |                 |           |      |          |                       |
| 2000   | 75.3            | 3.76      | 973.21 | 78009.44 |
| 2310   | 74.98           | 3.24      | 1784.6 | 142440.00 |
| 2800   | 160.42          | 5.72      | 453.01 | 77359.19  |
| 3680   | 118.11          | 3.20      | 541.94 | 68137.08  |
| 4440   | 165.65          | 3.73      | 2394.25 | 422188.69 |
| 5200   | 153.08          | 2.94      | 1249.27 | 203573.11 |
| 6200   | 63.89           | 1.03      | 638.29 | 43410.68  |
| TISSUE |                 |           |      |          |                       |
| 2000   | 69.92           | 3.49      | 1403.39 | 104454.09 |
| 2310   | 78.2            | 3.38      | 482.41 | 40157.68 |
| 2800   | NA              | NA        | 510   | NA       |
| 3680   | NA              | NA        | 331.46 | NA       |
| 4440   | 109.65          | 2.46      | 1843.41 | 215167.28 |
| 5200   | NA              | NA        | 199.06 | NA       |
| 6200   | 24.37           | 0.39      | 152.57 | 3957.95  |
| LUNG   |                 |           |      |          |                       |
| 2000   | 77.33           | 3.86      | 984.83 | 81069.02 |
| 2310   | 69.22           | 2.99      | 1604.75 | 118245.50 |
| 2800   | NA              | NA        | 456.83 | NA       |
| 3680   | 84.01           | 2.28      | 520.12 | 46513.62 |
| 4440   | 166.43          | 3.74      | 2290.39 | 405776.33 |
| 5200   | 158.35          | 3.04      | 1109.59 | 187036.45 |
| 6200   | 63.42           | 1.02      | 587.55 | 39665.84 |
| BRAIN  |                 |           |      |          |                       |
| 2000   | 69.13           | 3.45      | 1013.94 | 74614.71 |
| 2310   | 71.13           | 3.07      | 1478.34 | 111936.77 |
| 2800   | 130.23          | 4.65      | 461.76 | 64013.71 |
| 3680   | 84.55           | 2.29      | 483.38 | 43505.87 |
| 4440   | 162.24          | 3.65      | 2240.09 | 386873.57 |
| 5200   | 157.6           | 3.03      | 1004.05 | 168444.64 |
| 6200   | 71.22           | 1.14      | 533.56 | 40451.15 |
| BONE   |                 |           |      |          |                       |
| 2000   | 50.85           | 2.54      | 2133.85 | 115504.92 |
| 2310   | 55.19           | 2.39      | 1203.1 | 70681.83 |
| 2800   | 42.87           | 1.53      | 1544.02 | 70461.53 |
| 3680   | 15.98           | 0.43      | 981.73 | 16699.92 |
| 4440   | 110.92          | 2.49      | 1846.09 | 217975.85 |
| 5200   | 113.08          | 2.17      | 384.52 | 46286.08 |
| 6200   | 34.78           | 0.56      | 169.11 | 6261.01 |
Conclusions
The goal of this study was to determine the type of target being irradiated by inspecting the gamma rays produced in proton therapy. We performed GEANT4 simulations of proton-body interactions and studied the gamma rays produced in such interactions. The analysis was performed for 10 body materials, namely, MS20 tissue, lung, brain, bone, blood, tissue, muscle with sucrose and without sucrose, muscle striated ICRU, and muscle skeletal ICRP. The gamma ray peaks studied were those at the energies of the seven main gamma peaks produced in proton-water collisions, at energies 2.0, 2.3, 2.8, 3.68, 4.44, 5.2, and 6.1 MeV. Characterizing such peaks, a comparison between the peaks produced by different body parts was performed.

Part of the results are shown in Table 3, and they show that indeed it is possible to use the gamma rays emitted at certain energies to identify the target that produced the rays by proton collision. Although this study is a good start, there are limitations related to the sensibility of the gamma ray detectors to be used, and further studies are necessary.

Innovations and Contributions
The main innovation and contribution of this article is to introduce a way to identify the target (body part) being hit by the proton beam in proton therapy.

Acknowledgements
J.A.L. acknowledges support from UTEP’s BUILDING SCHOLARS Program. This work was part of the M.S. thesis of O. Hernández Rodríguez [11].

References
[1] K.A. Camphausen and R.C. Lawrence, Cancer Management: A Multidisciplinary Approach. In: *Principles of Radiation Therapy*, edited by R. Pazdur, L.D. Wagman, K.A. Camphausen and W.J. Hoskins, 11th ed., Cmp. United Business Media, 2009.
[2] W.P. Levin, H. Kooy, J.S. Loeffler and T.F. DeLaney, British Journal of Cancer 93, 849 (2005). https://doi.org/10.1038/sj.bjc.6602754
[3] W.D. Newhauser and R. Zhang, Phys. Med. Biol. 60, R155 (2015). https://doi.org/10.1088/0031-9155/60/8/R155
[4] J. Metz, Differences between protons and X-rays. Abramson Cancer Center of the University of Pennsylvania, 2006. Retrieved on February 04, 2018 from http://www.oncolink.org/treatment/article.cfm?c=9&cs=70&cid=210.
[5] J.A. López, S.S. Romero Gonzalez, O. Hernández Rodríguez, J. Holmes and R. Alarcon, Journal of Nuclear Physics Material Sciences Radiation and Applications 7, 217 (2020). https://doi.org/10.1541/jnp.2020.7.2028
[6] S.S. Romero Gonzalez, M.S. Thesis, University of Texas at El Paso, 2018. Retrieved on September 14, 2020 from https://scholarworks.utep.edu/dissertations/AAI10822888/.
[7] R. Alarcon, D. Blyth, E. Galyaev, J. Holmes, L. Ice, G. Randall, M. Bues and M. Fatyga, Int. J. Modern Physics: Conference Series 44, 1660217 (2016). https://doi.org/10.1142/S2010194516602179.
[8] Basics physics of nuclear medicine/interaction of radiation with matter. Retrieved on September 14, 2020 from https://en.wikibooks.org/wiki/Basics_Physics_of_Nuclear_Medicine/Interaction_of_Radiation_with_Matter.
[9] Geant4 Collaboration. Introduction to Geant4. Retrieved on September 13, 2020 from http://geant4-userdoc.web.cern.ch/geant4-userdoc/UsersGuides/IntroductionToGeant4/html/index.html
[10] http://www.sixiangguo.net/code/geant4/AppDevelop/apas06.html. Accessed 13 September, 2020.
[11] O. Hernández Rodríguez, M.S. Thesis, University of Texas at El Paso, 2018. Retrieved on September 14, 2020 from https://scholarworks.utep.edu/dissertations/AAI10823026/.
