Cumhuriyet Science Journal

e-ISSN: 2587-246X
ISSN: 2587-2680

Cumhuriyet Sci. J., 42(3) (2021) 688-693
http://dx.doi.org/10.17776/csj.935566

Measurement of out of field doses in brain proton therapy with GATE simulations

Melisa SÖNMEZ [1] ***,Sinan KUDAY*** [2] *

[1]*Istanbul Aydın University, Health Science Institute, Medical Physics, 34295, Istanbul / Turkey*
[2]*Ankara University, Physics Department, Tandogan, 06100, Ankara / Turkey*

Abstract

Proton therapy as one of the radiotherapy applications, aims to treat the tumor by using the accelerated proton particle. High radiation dose distributions delivered to the tumor tissue, is characterized with Bragg curves, while the radiation in the tissues surrounding the tumor is expected to be as low as possible. In our study, proton treatment of the tumor volume placed in the brain created by GATE software was simulated. The absorbed doses in other organs created by GATE software during treatment were determined using DoseActor and TLEDoseActor algorithms. Nuclear interactions of the accelerated proton with the nucleus of the target atom make the target atom reactive and cause secondary radiation. Similar to the TLEDoseActor algorithm, NTLE algorithm was used to determine the doses caused by neutrons from these secondary radiations. With the algorithms used, out-of-field doses and secondary doses for proton beams at 250 MeV energy were determined. It is important to determine the secondary radiations caused by the interaction of the proton with the tissue and to determine the doses out of the field. These results may be helpful in determining and preventing secondary cancer formation in proton therapy in clinical applications.

Article info

History:
Received:10.05.2021
Accepted:22.06.2021

Keywords:
Geant4,
DoseActor,
TLE,
Radiotherapy.

1. Introduction

Proton therapy is the application of radiotherapy, which allows proton, one of the particles that make up the atom, to be used in the treatment of cancer. The basic principle of radiotherapy applications is to provide high doses to the tumor while minimizing the radiation dose that healthy tissues will receive. While the deep dose characteristics of protons increase tumor doses, the quality of life is improved by maintaining healthy tissues and providing local control of the tumor. [1] Considering the clinical advantages of proton therapy compared to traditional photon radiotherapy, their publications in the literature in this field are increasing. Although protons are considered to have clinical superiority in many types of cancers such as pediatric cancer, ocular melanoma, head and neck cancers, studies are limited to small research. [2] One of the most important reasons for this is that it is inadequate in number due to the cost and cost of proton therapy centers. When protons move through tissue, accelerated protons interact with atomic electrons, while high-energy protons can cause nuclear interactions in atomic nuclei. The nucleus, which becomes reactive by nuclear interactions, allows secondary radiation in the form of smaller fragmentation and gamma release.[3] From these secondary radiations, neutrons in particular can cause extraterrestrial doses in healthy tissues located away from the treatment area. The likelihood of radiation-related tumor formation in organs other than the treatment area is less likely than tumor formation in organs close to the target volume. [4] Secondary radiation can cause cancer to recur in patients undergoing treatment. Therefore, it is important to calculate out-of-field doses caused by secondary radiation. [5]

The draft of the article is as follows: in the next section we describe the anthropomorphic phantom simulation installation, GATE software, algorithms used to calculate out-of-field doses and their calculations. In the findings section, we give the dose values obtained by GATE software, brain and out-of-field dose distributions and end our work with the result and interpretation part.

*Corresponding author. e-mail address: melisasonmez1@stu.aydin.edu.tr

2. Materials and Methods

2.1. Anthropomorphic phantom preparation with GATE v.9.8

GATE is a simulation application that enables visualization using the Geant4 toolkit, which simulates interactions between particles and matter. [6] Shaping the simulation is done through simple macros to learn. It has a wide range of studies that can be used in many researches such as improving image quality in imaging and determining radiation doses taken in radiotherapy.

In the coordinate system, the World volume, which we have determined to be 2.1 m at the x, y and z coordinates, is created. It is created using MIRD female phantom data defined in skull, brain, tumor, thyroid, lungs, heart, breast, liver, spleen, kidneys, stomach and pancreatic GATE [7]. Excluding phantom as out-of-area doses are studied especially in the external environment where staff can be exposed calculation of doses has also been targeted. Global geometries are therefore placed outside the phantom. 4 spherical water-filled geometries are placed outside the MIRD phantom. 250 MeV proton energy has been selected as the typical upper energy limit for treatments in this area.The global tumor volume placed inside the brain is irradiated by a bundle of protons created by 100K accelerated protons in 250 MeV proton beam. Pen beam scanning method (PBS) was used for irradiation with proton. Different resource types can be defined in GATE. With the PBS source, the tumor is irradiated with ultra-narrow proton beams. With the PlanDescription file, parameters such as particle energy, patient position, and treatment head position are determined, while the SourceDescription file determines the source information for each pen beam source location and direction. Secondary radiation production in the treatment head is prevented by using the pencil beam scanning (PBS) method. Secondary radiation in irradiations using PBS method occurs as a result of nuclear interactions in patient tissues. DoseActor and TLEDoseActor are placed in all geometries for the calculation of out-of-field doses. DoseActor and TLEDoseActor algorithms will be mentioned in chapter 2.2.

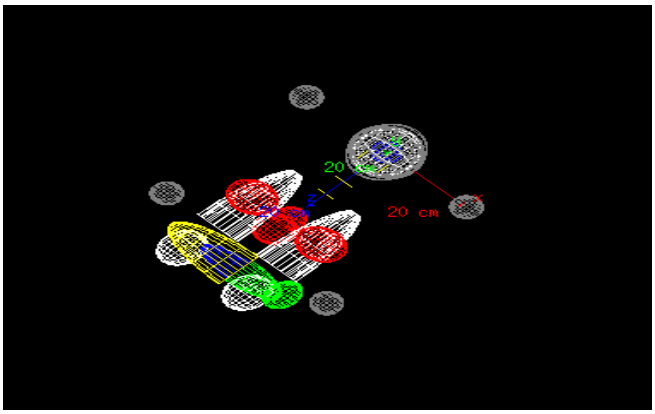

Figure 1. Image from phantom prepared in GATE

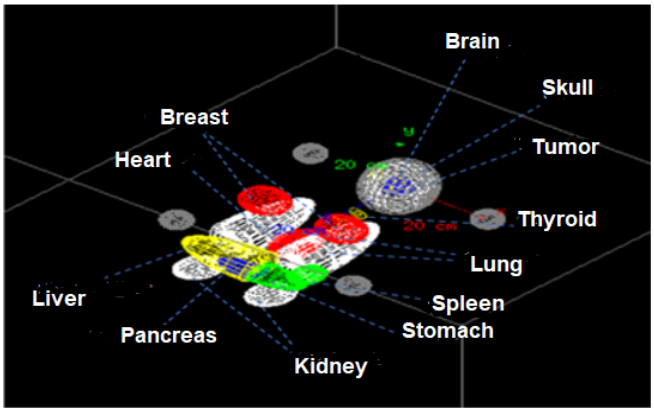

Figure 2. Representation of organs in phantom prepared in GATE

2.2 Description of DoseActor and TLEDoseActor algorithms

In the simulation, the source was selected as a proton particle with energy of 250 MeV and irradiation was performed by pencil beam scanning method (PBS). In GATE, actors are tools that record a lot of information, such as doses accumulated and particles accumulated as a result of interactions in simulation. In our study, we used two of these actors, DoseActor and TLEDoseActors. We placed these actors in all the organs we created and determined the doses and secondary doses accumulated in the organs. We filtered neutrons within both algorithms with the help of dose values we received from DoseActor and TLEDoseActor algorithms for each organ, as well as particle filters that we added to these algorithms. In algorithms, care should be taken that the step length is not too large compared to the voxel. Along this line, the position determined for the actor to hold the information can be chosen randomly. In our study, it was chosen as (post) because it is suitable for calculating out-of-area doses. We have received a total of 4 separate data from both algorithms in two ways,

total doses and neutron doses. We viewed and calculated the analysis of all data using ROOT. [8]

During the analysis phase, the dose absorbed in an area of GATE can be calculated by the DoseActor algorithm. The DoseActor algorithm is placed at the desired volume. The volume in which DoseActor is placed is divided into three-dimensional vocsels and calculated by the energies left in the vocsel by the particles passing through the vocsels. This algorithm can calculate the absorbed dose volumetrically or mass ively. [9]

Volume-weighted algorithm is given in Equation 1.

$$D_{dosel} = \sum \frac{V_i}{V_{dosel}} \times D_i = \sum \frac{V_i}{V_{dosel}} \times \frac{E_i}{m_i} = \sum \frac{E_i}{V_{dosel} \cdot \rho_i} \quad (1)$$

The energy stored in the dosel volume is calculated by dividing the total energy in the region to which DoseActor is connected by E_i, Dosel volume (V_{dosel}) and density of the region (ρ_i).

Similarly, the mass-weighted algorithm is given in Equation 2.

$$D_{dosel} = \sum \frac{m_i}{m_{dosel}} \times D_i = \sum \frac{m_i}{m_{dosel}} \times \frac{E_i}{m_i} = \sum \frac{E_i}{m_{dosel}} = \frac{E_{dosel}}{m_{dosel}} \quad (2)$$

The energy stored in the dosel volume is calculated by dividing the dosel energy E_{dosel} by dosel mass m_{dosel}.

Similar to the DoseActor method, GATE uses the TLEDoseActor algorithm to determine photons with energies below approximately 1 MeV of energy. [10] With this algorithm, photon flux is shown in Equation 3 by determining the number of trace length (L) left by photons entering voxel volume (V):

$$\phi = \frac{L}{V} \quad (3)$$

The dose absorbed based on flux and trace length is shown in Equation 4:

$$D = \phi . E . \frac{\mu_{en}}{\rho} \quad (4)$$

Here ϕ is photon flux, E is the energy of photons, and $\frac{\mu_{en}}{\rho}$ is the mass energy absorption coefficient.

3. Results and Discussion

Total dose values absorbed for 11 different organ structures and 4 spherical geometries created and photon and neutron doses resulting from interaction of high-energy protons with target volume are given in Table 1. In addition to the absorcited doses in our study, the percentage of doses absorbed in organs and spherical geometries was determined and 77.26 % of the total dose was absorbed in the tumor as expected. %16.3 of the absorded dose is absorbed by the brain and 6.33 % by the skull. Percentages of doses in non-field organs remain below %1. In our study, it is seen that bragg peak, which is defined as the characteristic dose curve of proton, indicates the highest doses to the tumor, while doses in out-of-field organs are quite low compared to traditional photon radiotherapy. [11] In addition to the total absorbed doses, doses resulting from photons and neutrons produced as a result of nuclear interactions during the irradiation of the brain tumor are given in Table 1.

Clinically, the treatment of a brain tumor is planned to be treated with approximately 1.8 Gy absorbed radiation daily, depending on the tumor size, only 5 days a week for approximately 6-7 weeks. In line with this planning, it is aimed to give approximately 60 Gy doses to the tumor at the end of the treatment. [12] In our simulation study, when the tumor dose of the patient is calculated to be 60 Gy at the end of the treatment based on the absorption dose values given in the DoseActor total dose column, the total doses that the brain and skull will absorb are 12.74 Gy and 4.94 Gy respectively, while the total doses absorbed in other organs range from 0.3 mGy to 38.4 mGy. In our study, neutron and photon doses that contributed to these total absorbed doses were calculated and it was observed that the doses of neutrons absorbed in the organs were formed in the kidneys with at least 0.07 μGy and in the skull with a maximum of 921.9 μGy. These values are seen to be very low in the formation of secondary cancer of proton therapy.

TLEDoseActor algorithm, it was possible to calculate the dose by absorption of low-energy photons in the tissue. At the end of the treatment process, photon doses of the skull, brain and tumor ranged from 65mGy to 397mGy, while in remote organs outside the treatment area, these doses were calculated to be as low as 7.62 μGy.

Table 1. DoseActor and TLEDoseActor algorithms for dose values absorbed in organs (250 MeV)

PROTON BEAM				
	DoseActor		TLE DoseActor	
	Total dose (Gy)	Neutron dose (Gy)	Total dose (Gy)	NTLE dose (Gy)
Skull	1,24511 e-05	2,58111 e-09	9,99404 e-07	1,39916 e-07
Brain	3,21134 e-05	1,94425 e-09	7,36327 e-07	1,0308578 e-07
Tumor	1,51157 e-04	4,2541 e-09	1,64756 e-07	2,306584 e-08
Thyroid	1,32034 e-08	6,98735 e-10	5,09889 e-10	7,138446 e-11
Lung	6,98735 e-09	8,2216 e-12	2,08297 e-11	2,916158 e-12
Liver	4,8393 e-09	4,44157 e-11	2,57861 e-09	3,610054 e-10
Breast	9,69003 e-07	1,96138 e-10	8,1 e-09	1,134 e-09
Stomach	1,04147 e-09	1,76101 e-11	4,97604 e-10	6,966456 e-11
Heart	2,12196 e-09	5,38965 e-11	3,6467 e-10	5,10538 e-11
Kidney	1,61768 e-09	2,2062 e-12	5,09065 e-10	7,12691 e-11
Pancreas	5,25745 e-09	3,44521 e-12	9,4511 e-10	8,41123 e-11
Sphere 1	5,16413 e-09	1,98501 e-11	1,48072 e-09	2,073008 e-10
Sphere 2	9,79271 e-09	3,28908 e-11	3,8489 e-10	5,38846 e-11
Sphere 3	1,07722 e-09	1,80002 e-11	4,01108 e-10	5,615512 e-11
Sphere 4	5,32978 e-09	3,52746 e-11	2,74903 e-09	3,848642 e-10
Total	1,96625 e-04	9,89946 e-09	1,918 e-06	2,67534 e-07

With this study, we calculated the total doses absorbed by tumor and other organs with DoseActor algorithm using accelerated proton beams in the irradiation of the brain tumor, neutron doses that contribute to the total dose absorbed in the organs using particle filter in the DoseActor algorithm. Using particle filtering in the TLE algorithm, we filtered neutrons defined as NTLE. NTLE was used to determine neutrons that are part of the secondary dose. [13] Figures 3 and 4 show particle and dose distributions in brain tissue and out off-field global dosimetry.

TLE and NTLE algorithms as in actual measurements does not depend on the absorbed dose. This is experimental algorithms are being developed. On the tumor, the protons sent directly The direct interaction with the absorption is the dominant interaction. On the other hand dose in the tumor, since off-field doses were taken into account is outside the scope of the study. As a result; TLE and NTLE algorithms in calculating the dose amount in the directly affected tissue alone unusable result.

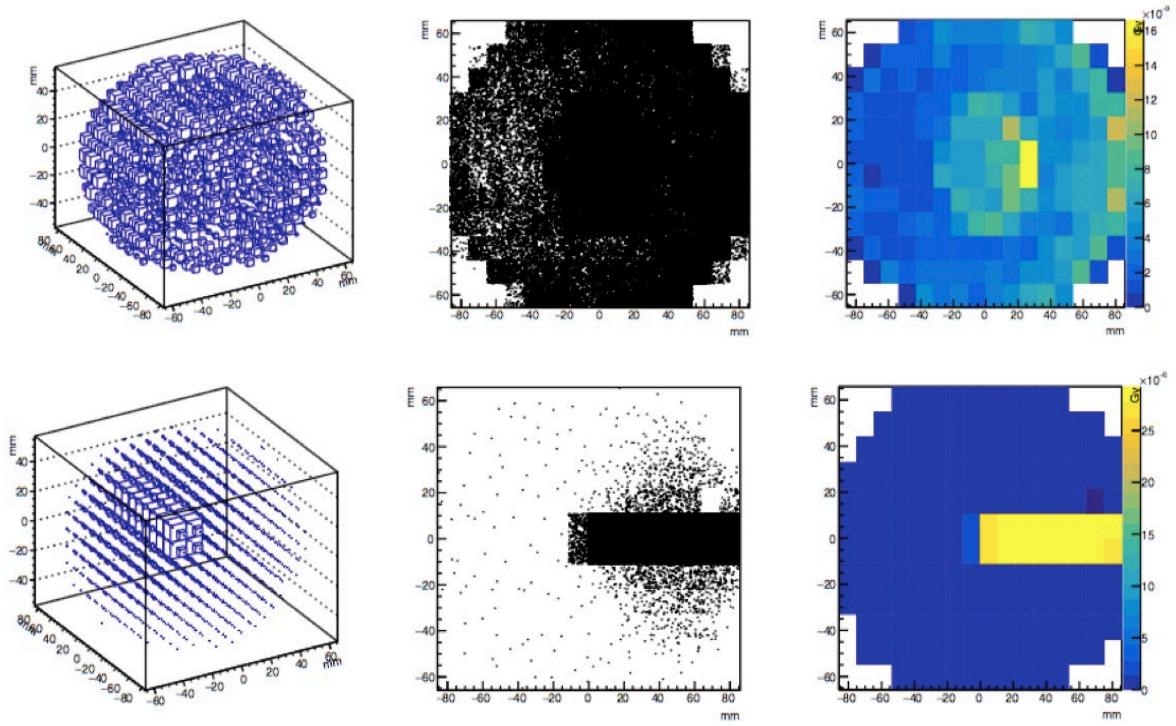

Figure 3. Measured by simulation in brain tissue; 3B particle distribution (left), 2B particle distribution (centre) dose distribution (right) TLE algorithm (top) and DoseActor algorithm (bottom) dose data

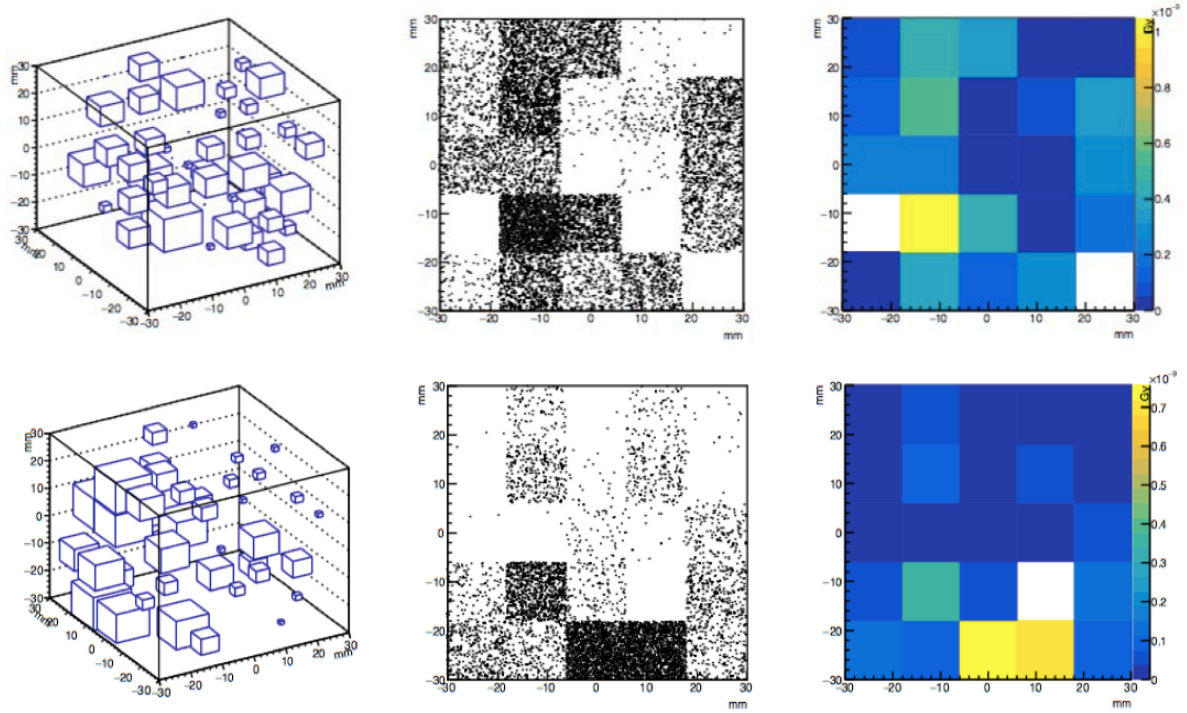

Figure 4. Measured by simulation in the out-of-field dosimeter (Sphere 4); 3B particle distribution (left), 2B particle distribution (centre) dose distribution (right) TLE algorithm (top) and DoseActor algorithm (bottom) dose data

4. Conclusion

As in this study, it is very important to determine the characteristic dose distributions and out-of-field doses of proton in proton treatment applications in GATE software. The treatment of complex brain tumors becomes possible with protons after surgical procedure or without the need for surgical procedure. However, it

is very important to determine the out-of-field doses exposed to protect healthy tissues in the patient and to minimize the exposure of radiation-powered health workers to radiation. In general dose calculations, the proton therapy (N)TLE and DoseActor algorithms calculated doseactor chi-square value $13{,}6767.10^{-6}$, TLEDoseActor ki-squared value $18{,}6570.10^{-6}$ and no significant difference was seen according to the comparison of %5 alpha value. It has been observed that the TLE algorithm determines particle distributions and scattered secondary particles with higher precision. This result is however, statistically, (N)TLE and Doseactor algorithms are both applicable in dose calculations to issue similar results that justified by our simulation data. Note that it is critical to determine out-of-field doses so that doses taken in proton therapy do not lead to secondary cancers and other diseases in the long term.

Conflicts of interest

As the authors of this study, we have no conflict of interest.

References

[1] Mohan R., Grosshans D., Proton therapy - Present and future, *Advanced Drug Delivery Reviews*, 109 (2017) 26-44.

[2] Riley B., Peaking ınto the future with proton therapy, *Journal of Radiology Nursing*, 26(4) (2007) 115-120.

[3] Didi A., Dekhissi H., Sebihi R., Krim M., & Mohamed R. M., Calculate primary and secondary dose in proton therapy using 200 and 250 MeV proton beam energy, *The Physics of the Atomic Nucleus and Elementary Particles*, 74 (2019) 364-368.

[4] Ardenfors O., Dasu A., Lillhök J., Persson L., Gudowska I., Out-of-field doses from secondary radiation produced in proton therapy and the associated risk of radiation-induced cancer from a brain tumor treatment, *Physica Medica*, 53 (2018) 129-136.

[5] Jia S. B., Hadizadeh M. H., Mowlavi A. A., Loushab M. E., Evaluation of energy deposition and secondary particle production in proton therapy of brain using a slab head phantom, *Reports of Practical Oncology & Radiotherapy*, 19(6) (2014) 376-384.

[6] Slimani F. A. A., Hamdi M., Bentourkia M., G4DARI: Geant4/GATE based Monte Carlo simulation interface for dosimetry calculation in radiotherapy, *Computerized Medical Imaging and Graphics*, 67 (2018) 30-39.

[7] Snyder W. S., Ford M. R., Warner G. G., MIRD Pamphlet No. 5 Revised, Estimates of absorbed fractions for monoenergetic photon sources uniformly distributed in various organs of a heterogeneous phantom, *Journal of Nuclear Medicine*, 3 (1969) 5-52.

[8] Rene Brun and Fons Rademakers, ROOT-An Object Oriented Data Analysis Framework, Proceedings AIHENP'96 Workshop, Lausanne, Sep. 1996, Nucl. Inst.&Meth. In Phys. Res. A 389 (1997) 81-86. See also [root.cern.ch/] (http://root.cern.ch/).

[9] Sarrut D., Bardies M., Boussion N., Freud N., Jan S., Letang J. M., Loudos G., Maigne L., Marcatili S., Mauxion T., Papadimitroulas P., Perrot Y., Pietrzyk U., Robert C., Schaart D. R., Visvikis D., Buvat I., A review of the use and potential of the GATE Monte Carlo simulation code for radiation therapy and dosimetry applications, *Medical Physi*cs, 41(6) (2014).

[10] Baldacci F., Mittone A., Bravin A., Coan P., Delaire F., Ferrero C., Gasilov S., Letang J. M., Sarrut D., Smekens F., Freud N., A track length estimator method for dose calculations in low-energy X-ray irradiations: implementation, properties and performance, *Zeitschrift für Medizinische Physik*, 25(1) (2015) 36-47.

[11] Riley B., Peaking Into the Future Wıth Proton Therapy, *Journal of Radiology Nursing*, 26(4) (2007) 115-120.

[12] Liu H., Chang J. Y., Proton therapy in clinical practice, *Chinese Journal of Cancer*, 30(5) (2011) 315-326.

[13] Elazhar H., Deschler T., Letang J. M., Nourreddine A., Arbor N., Neutron track lenght estimatör for GATE Monte Carlo dose calculation in radiotherapy, *Physics In Medicine and Biology*, 63(12) (2018).