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Original Research

Gate/Geant4 Dose Distribution Simulation with Carbon-12 Ion Source in Water

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ABSTRACT

In this study, radiotherapy simulations were studied using Carbon-12 (^{12}C) ion source. For this purpose, radiation dose distribution in water was investigated by bombarding water with ^{12}C ions in different energies. As energies of ^{12}C ions were increased, the maximum dose region occurred in more depth. Then, water was bombarded with ^{12}C by placing different materials on the surface of the water, and radiation dose distribution in water was studied. The thickness of material placed in front of the surface of water changed the location of maximum radiation dose region. This trend provided the opportunity to be able to create a maximum dose region of what we wanted in water by using a mono-energetic source. For derivation of dose distribution, Gate/Geant4 program was used.

KEYWORDS Simulation, Absorbed dose, Carbon ion, Gate.

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INTRODUCTION

Cancer is really a serious disease problem of current century with harmful impacts on humankind life.[1] In this case, considerable efforts have been always performing to solve such complicated unsolved problem.[2-5] For more than 40 % of cancerous patients, a 5-year tumor control could be reached meaning that the patients will be cured free of tumors after 5 years.[6] Generally, 12 % of these patients would take radiotherapy treatments, in which proton and heavy-ion treatments in tumor therapy have gotten more attentions in developed countries.[7] Proton and carbon ion treatment devices have been undergoing fast development in recent years with increasing numbers of patients under such treatment.[8] Currently, Monte Carlo (MC) simulation has been seen an important approach to obtain accurate radiotherapy parameters.[9] Water is considered as a kind of matter approximated to body tissue; hence, a simulation that Carbon-12 (^{12}C) ion beam was incident on water phantom within this work.[10] A computer-based simulation is indeed a model of physical system with simplified version of reality to make sense the ideas.[11] MC simulation is now a much-used scientific tool for solving the problems by assistance of many available simulation programs.[12] Among which, Geant4 Application for Emission Tomography (GATE) has been introduced as one of the most reliable and flexible simulation programs.[13] Radiation therapy is a process of destroying cancer cells as much as possible using a particle beam or ion beam focusing on the cancerous tissue.[14] The most important goal of this process is to ensure that the healthy cells around the cancerous area would be remained safe by very low level of exposure to the radiation dose in contrast with the targeted cancer cells with the highest possible level of exposure to the radiation dose.[15] Several attempts have been dedicated to such problem by developing novel therapeutic protocols to increase non-invasive methodologies for cancer therapy purposes.[16-18] In this regard, the main advantage of ion-based therapy instead of photon-based is the inverse dose profile with increasing energy deposition with penetration depth up to a sharp maximum at the end of particle range, the Bragg peak.[6] In 1946, Robert Wilson, with Berkeley cyclotron, recognized the potential of ion-like protons or carbon for tumor therapy providing favorable depth-dose distribution in a direct consequence of the interaction mechanism of heavy charged particles with the penetrated material different from that of electromagnetic radiation.[6] Within the therapeutic energy range, heavy charged particles would interact predominantly with the target electrons and the interaction strength would be directly correlated with the interaction time. At high projectile energies, the interaction time would be shorter with lower energy transfer to the target. By slowing down the particles close to the end of their range, the interaction time becomes larger with the maximum value of energy transfer.[6] Such details were visually exhibited in Fig. 1 for protons, carbon ions, and photons depending on the penetration depth of measured radiation dose.

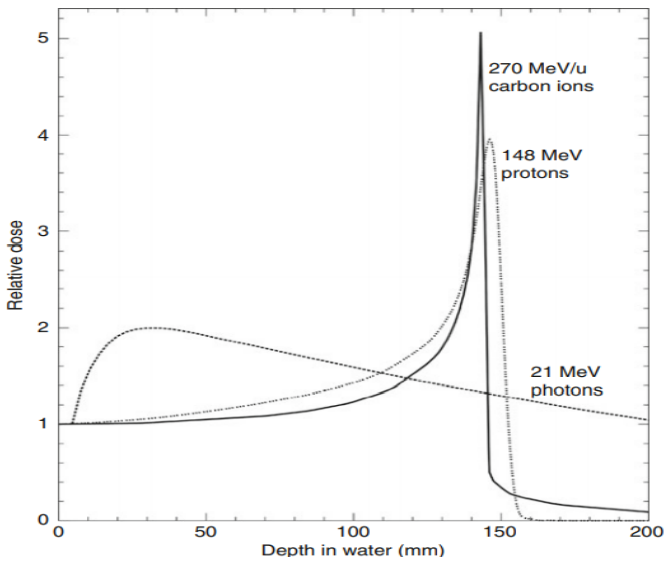

Fig. 1: The measured dose as a function of penetration depth is compared for photons, protons, and carbon ions.[6]

The energy loss as a function of particle energy and atomic number could be given in the Bethe-Bloch formula (Bethe 1930, Bloch 1933) indicated by eq. (1).[6]

$$\frac{dE}{dx} = -\frac{4\pi e e^4 Z_{eff}^2 N}{m_e v^2} \times \left[ln \frac{2m_e v^2}{I(1-\beta^2)} \right] + relativistic\ terms \quad (1)$$

Describing the components of eq. (1), *m*: the electron mass, *v*: the projectile velocity, *N*: the density of electrons of the target material, *e*: the elementary charge, *I*: the mean ionization potential, Z_{eff}: the effective charge interacting with the target electrons.[6]

MATERIALS & METHODS

In this study, GATE was used for performing simulation processes. GATE has been developed by the OpenGate collaboration as a community-driven initiative with an ability that every user could access the source code proposing new features.[13] GATE has been dedicated to numerical simulations in medical imaging and radiotherapy.[19] GATE is an application based on the GEANT4 toolkit: GEANT4 manages the kernel simulating interactions between particles and matter, and GATE provides additional high-level features to facilitate the design of GEANT4 based simulations.[13] At the end of the simulation, root files will be generated. ROOT is also an open-source data analysis framework used by high-energy physics.[20] Everything about simulation in GATE should be written in a script file with mac as a suffix. The script file included several aspects: source and particle management, defining geometry and material, setting up the physics, and actor management.[6]

RESULTS & DISCUSSION

Simulation Geometry and Absorbed Dose Distribution

To extract the absorbed dose distribution in the water environment bombarded with carbon ions, the experimental setup in Fig. 2 was designed. The water phantom was chosen in cubic shape with each side length of 180 mm for $l_{1x} = l_{1y} = l_{1z}$. The carbon ion source was selected as squared, and the carbon ion drop to each region on the water phantom, the size of the source was the same as the water phantom. The distance between the carbon ion source and the water phantom was 210 mm. By using carbon ions at different energies, the dose amounts stored in water were obtained. The physics processes of this simulation were used to default settings of particle radiotherapy in GATE. Particle dose distribution were recorded by the DoseActors in GATE. DoseActor stored the absorbed dose in an interested volume. The dose actor had to be attached to the volume of interest in GATE macros.

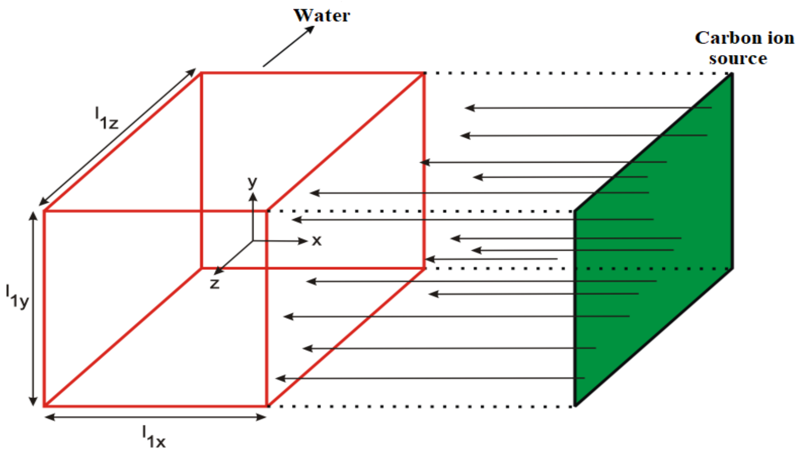

Fig. 2: Water bombarded with Carbon-12 ions.

The water environment was bombarded with Carbon-12 ions with different energies and the dose distributions in the water environment were examined. In this paper, the absorbed dose is unit was gray (1 Gy = 1 J/kg). Absorbed dose distribution in water was shown in Fig. 3, in which the Bragg peak formed in the water went deeper by increasing the energy of carbon ion. The position of formed Bragg peak was in agreement with that of obtained by earlier study of Ou et al.[10]

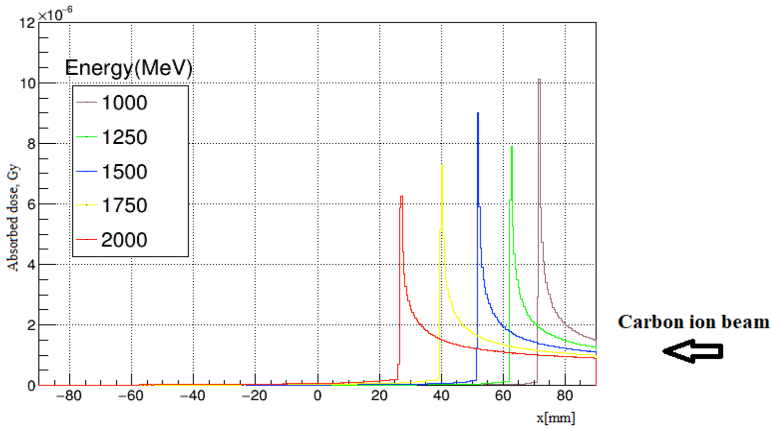

Fig. 3: Absorbed dose distribution in water for different beam energies.

Effect of Placing Material in Front of Water on Dose Distribution

Different materials were placed between the water environment and the source to examine the effect of the material placed between the water environment and the source on the dose distribution in the water environment. These materials were those of combination of elements of III V main groups, in which earlier studies indicated even nanostructure formations of such combinations.[21-25] The III-V combinations of this work included boron nitride (BN), aluminum nitride (AlN), gallium nitride (GaN), and indium nitride (InN). The elements of group III were all showing similar chemical properties by the same number of electrons in the final orbit of atomic valance shell. In this way, material selections enabled the material changes to be systematically examined, in which all of them were combinations of group III atoms and N atom. Moreover, the thermal expansion coefficients of III-N materials would be supposed to be quite low. This feature made the expansion amount of material negligible during the bombardment, making the dose distribution in the water environment almost independent of the temperature change of the material placed between the water environment and the source. In this way, the position of Bragg peak formed in the water was almost not affected by the temperature change of material placed between the water environment and the source. This feature made the mentioned materials important in terms of radiotherapy applications. The simulation setup was arranged as follows to observe how the Bragg peak would be changed when the material was placed between the water phantom and the source. The setup given in Fig. 4 showed the material thickness of l_{2x}.

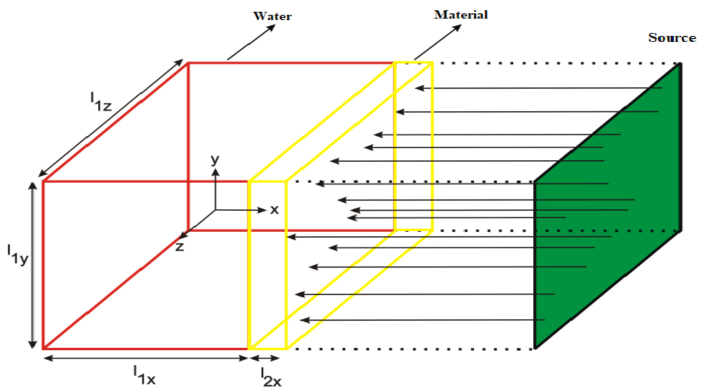

Fig. 4: Simulation design to examine the material effect on dose distribution.

The effect of material thickness on the maximum dose distribution was investigated by changing the material thickness. The mass densities of these materials were summarized in Table 1.

Table 1: Mass density values of the used materials.

Material	Density (g/cm^3)(T=300K)
AlN	3.255
BN	3.487
GaN	6.150
InN	6.810

The Bragg peak and dose distribution graphs were given in Fig. 5 when bombarded with a 2000 MeV energy carbon ion source in different material thicknesses.

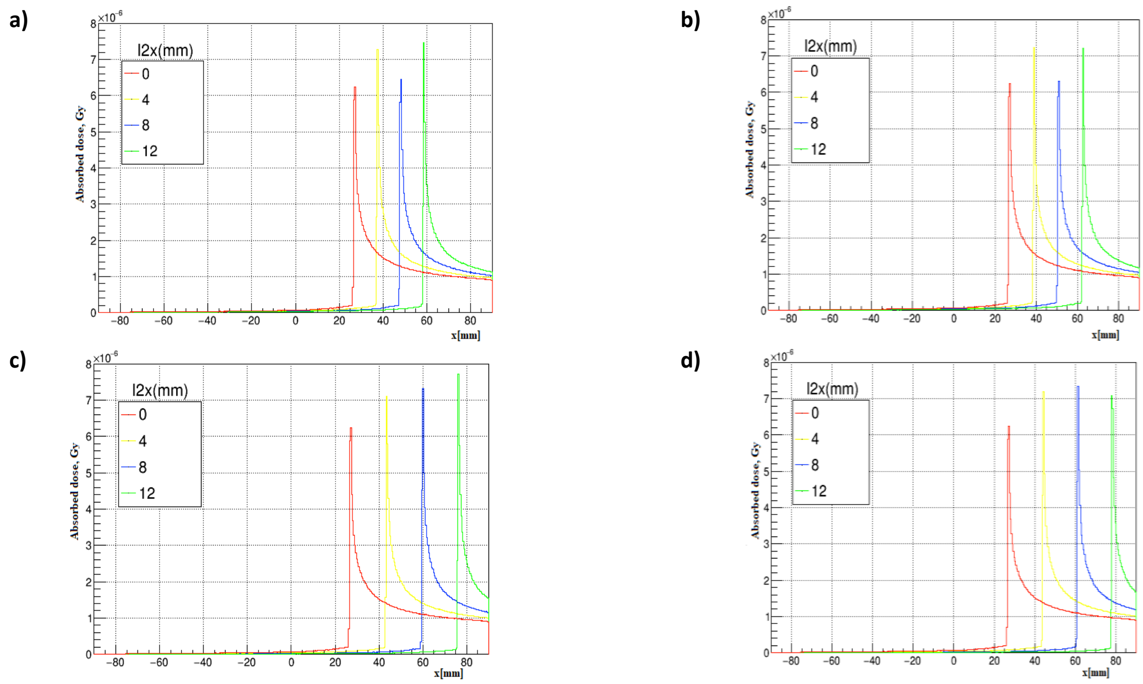

Fig. 5: Dose distribution with 2000 MeV energy source with a) AlN, b) BN, c) GaN, and d) InN materials for various thicknesses.

In cases where materials of different thicknesses were placed in front of the ion source, the dose distribution in water was given in Fig. 6. As could be seen from Table 1, since the densities of AlN and BN were close to each other, it was seen that the Bragg peak was formed at the same point. When GaN and InN, with higher densities, were used, the Bragg peak occurred further. Absorbed dose amounts were also close to each other. Moreover, by increasing the source energy and material thickness, the change in the dose distribution was examined as shown in Fig. 6.

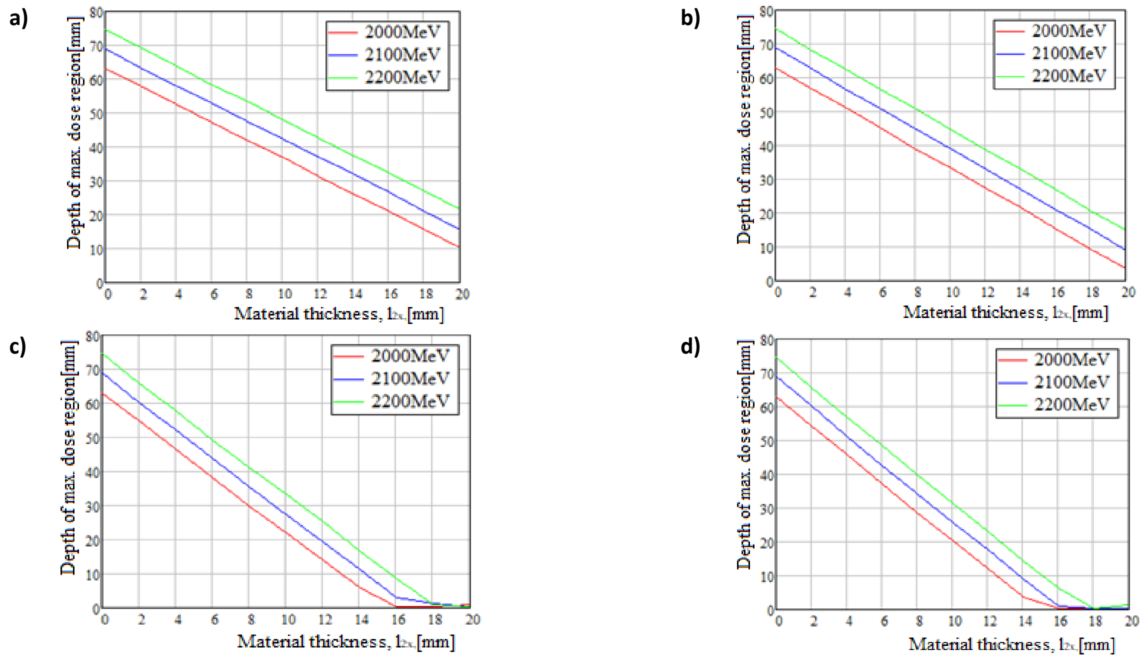

Fig. 6: The effect of material thickness on the depth of the maximum dose zone for a) AlN, b) BN, c) GaN, and d) InN materials.

CONCLUSION

In this study, the maximum dose distribution in the water phantom was investigated using the carbon ion source. When the material was placed between the source and the phantom, the thickness of the material could be changed and the location of the maximum dose zone formed in the phantom could be changed. It was shown that the location of the maximum dose zone formed was also dependent on the material density. Furthermore, the change of the maximum dose region by increasing the thickness of the material was investigated with different source energy. Knowing the material thickness when the zero maximum dose was important in shielding to protect from radiation. As a result, it was shown that the maximum dose zone could be created at the desired location by placing the material between the source and the phantom.

DISCLOSURE STATEMENT

The author(s) did not report any potential conflict of interest.

REFERENCES

1. Sedrak MS, Freedman RA, Cohen HJ, Muss HB, Jatoi A, Klepin HD, et al. Older adult participation in cancer clinical trials: a systematic review of barriers and interventions. CA: A Cancer Journal for Clinicians. 2021;71:78-92.
2. Farahbakhsh Z, Zamani MR, Rafienia M, Gülseren O, Mirzaei M. In silico activity of AS1411 aptamer against nucleolin of cancer cells. Iranian Journal of Blood and Cancer. 2020;12:95-100.
3. Mirzaei M, Gulseren O, Rafienia M, Zare A. Nanocarbon-assisted biosensor for diagnosis of exhaled biomarkers of lung cancer: DFT approach. Eurasian Chemical Communications. 2021;3:154-161.
4. Mirzaei M, Gülseren O, Hadipour N. DFT explorations of quadrupole coupling constants for planar 5-fluorouracil pairs. Computational and Theoretical Chemistry. 2016;1090:67-73.
5. Kakaei A, Mirzaei M. Cyclophosphamide@ CNT: in silico exploration of nano drug delivery system. Lab-in-Silico. 2021;2:9-14.
6. Kraft G, Weber U. Tumor therapy with ion beams. Handbook of Particle Detection and Imaging. 2012:1179-1205.
7. Peukert D, Kempson I, Douglass M, Bezak E. Metallic nanoparticle radiosensitisation of ion radiotherapy: a review. Physica Medica. 2018;47:121-128.

8. Rackwitz T, Debus J. Clinical applications of proton and carbon ion therapy. Seminars in Oncology. 2019;46:226-232.
9. Andreo P. Monte Carlo simulations in radiotherapy dosimetry. Radiation Oncology. 2018;13:1-5.
10. Ou HF, Zhang B, Zhao SJ. Gate/Geant4-based Monte Carlo simulation for calculation of dose distribution of 400 MeV/u carbon ion beam and fragments in water. Nuclear Science and Techniques. 2016;27:1-7.
11. Mirzaei M. Making sense the ideas in silico. Lab-in-Silico. 2020;1:31-32.
12. Harrison RL. Simulation of medical imaging systems: emission and transmission tomography. Handbook of Particle Detection and Imaging. 2012:1095-1124.
13. Sarrut D, Bardiès M, Boussion N, Freud N, Jan S, Létang JM, et al. A review of the use and potential of the GATE Monte Carlo simulation code for radiation therapy and dosimetry applications. Medical Physics. 2014;41:064301.
14. Tchelebi LT, Lehrer EJ, Trifiletti DM, Sharma NK, Gusani NJ, Crane CH, Zaorsky NG. Conventionally fractionated radiation therapy versus stereotactic body radiation therapy for locally advanced pancreatic cancer (CRiSP): an international systematic review and meta-analysis. Cancer. 2020;126:2120-2131.
15. Zhao Q, Liu Y, Zhang Y, Meng L, Wei J, Wang B, Wang H, Xin Y, Dong L, Jiang X. Role and toxicity of radiation therapy in neuroblastoma patients: a literature review. Critical Reviews in Oncology/Hematology. 2020;149:102924.
16. Chen X, Gole J, Gore A, He Q, Lu M, Min J, et al. Non-invasive early detection of cancer four years before conventional diagnosis using a blood test. Nature Communications. 2020;11:1-10.
17. Son S, Kim JH, Wang X, Zhang C, Yoon SA, Shin J, et al. Multifunctional sonosensitizers in sonodynamic cancer therapy. Chemical Society Reviews. 2020;49:3244-3261.
18. Yaraghi A, Ozkendir OM, Mirzaei M. DFT studies of 5-fluorouracil tautomers on a silicon graphene nanosheet. Superlattices and Microstructures. 2015;85:784-788.
19. Jan S, Santin G, Strul D, Staelens S, Assie K, Autret D, et al. GATE: a simulation toolkit for PET and SPECT. Physics in Medicine & Biology. 2004;49:4543.
20. Antcheva I, Ballintijn M, Bellenot B, Biskup M, Brun R, Buncic N, et al. ROOT-A C++ framework for petabyte data storage, statistical analysis and visualization. Computer Physics Communications. 2009;180:2499-2512.
21. Giahi M, Mirzaei M, Meskinfam M, Yousefi M. Density functional studies of the fluorine-terminated boron nitride nanotubes through computations of quadrupole coupling constants. Computational and Theoretical Chemistry. 2011;977:29-33.
22. Bodaghi A, Mirzaei M, Seif A, Giahi M. A computational NMR study on zigzag aluminum nitride nanotubes. Physica E. 2008;41:209-212.
23. Sun C, Wu F, Wallis DJ, Shen MH, Yuan F, Yang J, et al. Gallium nitride: a versatile compound semiconductor as novel piezoelectric film for acoustic tweezer in manipulation of cancer cells. IEEE Transactions on Electron Devices. 2020;67:3355-3361.
24. Pécz B, Nicotra G, Giannazzo F, Yakimova R, Koos A, Kakanakova-Georgieva A. Indium nitride at the 2D limit. Advanced Materials. 2021;33:2006660.
25. Rai A, Noor S, Ahmad SI, Alajmi MF, Hussain A, Abbas H, Hasan GM. Recent advances and implication of bioengineered nanomaterials in cancer theranostics. Medicina. 2021;57:91.

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