Estimation of the Radioactivity Produced in Patient Tissue during Carbon Ion Therapy

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Abstract

Nuclear interactions of the projectile carbon ion in biological soft tissue for cancer treatment purpose are studied. Elastic interaction of carbon ion with carbon, oxygen and nitrogen nuclei existing in soft tissue leads to beam divergence especially in Bragg peak region, where the carbon ion is slowing down. Monte Carlo simulation shows the amount of carbon ion beam divergence in soft tissue. For carbon ion beam with 2.4 GeV energy and 2mm diameter, at 85mm penetration depth the beam spreads out to 4mm diameter. Non-elastic interactions are modeled as well. Such interactions are important due to secondary radiation produced in patient's body. The product particles include positrons and neutrons, being important in therapeutic dose verification with PET imaging and extra dose in the hospital ambient, respectively. Computer code ALICE produces reaction cross sections that might be used to roughly estimate the neutron and positron yield. Computer code ALICE was used to assess the cross section and yield of products from carbon nuclei interaction with soft tissue.

Keywords: Carbon ion therapy, Induced activity, Nuclear reaction

1. Introduction

Application of charged particle such as proton and carbon ion is being developed for treatment of cancerous tumors (Khoroshkov & Minakova, 1998). This is due to eligibility of such particles in tailoring radiation dose distribution to geometrical shape of tumor and capability of carbon ion in damage of radio-resistant tumors (Schardt 2007). Unlike photons, charged particles have a finite range in matter with little scattering. The increase of energy loss with decreasing velocity is characteristic of all ions. Charged particles slow down as they travel through matter as a result of electromagnetic interactions, including Coulomb scattering. The slower they move, the more efficient they are at ionizing atoms in their path and more likely they are to interact with atomic nuclei. It means that the highest radiation dose is delivered at points in the body at which the charged particles stop, while the dose elsewhere is low. Hence the rate of energy loss increases sharply near the end of its range, culminating in a peak, the so called Bragg peak. The depth of the Bragg peak in the body depends precisely on the initial energy of charged particles.

Carbon ion with higher LET than proton is more efficient in destroying tumors resisting against radiation therapy. Thus carbon ion therapy has become a matter of interest over past few years (Khoroshkov & Minakova 1998, Schardt 2007).

Verification of dose delivery to the tumor is possible by taking advantage of the property of positrons in producing 511 keV annihilation gamma photons (Parodi 2008). A similar technique as PET imaging might be utilized to track the charged particle beam down to the tumor by making the image of its trail of positron emitters. Nuclear interactions along the track of charged particles in the patients body leads to production of sufficient amount of positrons, which makes possible the use of PET imaging technique for the purpose of tracking the beam down to the tumor. The production yield of some positron emitter nuclide such as ^{11}C and ^{10}C has been studied using GEANT4 computer code (Pshenichnov et al 2006), but in present work a complete list of nuclear reactions that produces positron emitter nuclides would be presented.

Another product of nuclear interaction inside the living tissue is neutron (Chaudhri 2001). Due to absorbed dose by the patient and radiotherapy personnel, it is important to estimate neutron yield in therapy with charged particles (Schardt et al 2006). There have been some experiments in measurement of neutron yield, but computational results are scarce (Khoroshkov 1998, Schardt 2007, Schardt et al 2006)

2. Computation method

Computer code ALICE has already been successfully used to estimate the nuclear interaction products and their respective cross sections as function of the energy of projectile particle (Abbas 2006, Kiraly 2008, Kettern 2004). For medical radioisotope production purposes, the projectile is usually proton, deuteron, or alpha particle. In this work, the projectile is considered ^{12}C ion which is used for treatment of deep-seated cancer tumors. The interaction is assumed to happen between ^{12}C and the most abundant nucleus in fat and muscle tissue, that is ^{16}O , ^{12}C , ^{14}N and ^{1}H . Many radioactive and stable isotopes may be produced in interaction between carbon ion beam and biological soft tissue. The complete list of possible reactions used is shown below. A similar problem has been considered for the case when the impinging beam is proton (Kettern 2004).

Cross section of nuclear interaction usually increases as the ion slows down. In carbon ion therapy, usually the energy of carbon ion beam is 2-4 GeV (Khoroshkov 1998, Schardt 2007). In the present work carbon ion beam is considered to pass through healthy tissue and then enter into the tumor with much lower energy. Thus, the kinetic energy of carbon ion beam is considered in the range of 7-100 MeV. This is in accord with ALICE code abilities. On the other hand this energy range appears to be in Bragg Peak of carbon ion, happening inside the tumor.

Approximate values of cross section are indicated in table 1. Bearing in mind the composition of soft tissue as $C_5H_{40}O_{18}N$ (Dennis 1977) concentration of radioactive isotopes in patient's tissue after treatment with beam of carbon ions might be estimated.

Another problem in cancer therapy with charged particle beam is the divergence of beam due to scattering reaction. This is especially important for small size tumors such as eye melanoma. If the beam divergence is too high, the lateral resolution of targeting the tumor becomes unacceptable, causing some damage to healthy tissue surrounding the tumor. The problem of widening the proton beam while passing through low-Z medium was studied before (Noshad 2005, Mertens 2007). In the present work the case is studied for carbon ion beam.

3. Results

Using a Monte Carlo method, the amount of beam divergence is obtained. It is assumed that a parallel beam of charged particle enters a water phantom. At first instant the beam was considered in cylindrical geometry. There was observed a smooth divergence leading to increase in the beam diameter, followed by a sharp spread of beam diameter in penetration depth corresponding to the Bragg peak region. The amounts of beam diameter increase are shown in table 2 for carbon ion beam.

Over the Bragg peak, carbon ion energy is reduced remarkably. On the other hand, due to restrictions in the computer code ALICE, it was not possible to compute the cross section for carbon ion energy more than 100 MeV. Thus in agreement with the physical facts, cross sections are obtained for E<100 MeV. Taking advantage of ALICE code abilities in providing various kinds of cross section data, all possible interaction products due to collision of carbon ion on major elements of soft tissue are elaborated. Among these nuclides, many are stable and some others are very short lived. Important nuclides with half-lives of the order of minutes or hour are obtained. Nuclear interactions leading to activation of patient are listed below.

$$^{12}C+^{12}C\rightarrow ^{6}Li+^{18}F$$

$$^{12}C+^{12}C\rightarrow ^{5}Li+^{19}F$$

$$^{12}C+^{12}C\rightarrow ^{4}Li+^{20}F$$

$$^{12}C+^{14}N\rightarrow ^{24}Na+(\alpha,d,p)$$

$$^{12}C+^{16}O\rightarrow ^{24}Na+(\alpha,d,p)$$

4. Conclusion

It is shown that among other radioisotopes produced in patient's body during carbon ion therapy, ^{24}Na is important due to its longer half-life. This radioisotope with the half-life of 15 hour, leads to patient being activated for many hours after undergoing radiation therapy with carbon ion. Thus it is inferred that after carbon ion therapy the patient must be quarantined. It is also shown that at the end of its range, carbon ion beam is spread laterally and less than 2mm is added to its radius, which might be important in irradiating small tumors in crucial organs of patient's body.

References

Abbas K, Kozempel J., Bonardi M.,et al. (2006). Cyclotron production of ^{64}Cu by deuteron irradiation of ^{64}Zn, Applied Radiation and Isotopes, 64, 1001-1005.

Chaudhri M. A., Cyclotrons and their applications. (2001). Production of secondary neutrons from patients during therapy with carbon ions, their dose contributions and potential risks. 16th International conference., Michigan, USA. 13-17 May, AIP Conference proceedings.

Dennis J. A.. (1977). Neutron Dosimetry for Biology and Medicine, ICRU Report 26 ICRU, Washington, DC._

Kettern K., & Shubin Yu N. & Steyn G. F.. (2004). Formation of short-lived positron emitters in reactions of protons of energies up to 200MeV, *Applied Radiation and Isotopes*, 609, 939-945.

Khoroshkov, V. S. & Minakova, E. I.. (1998). Proton beams in radiotherapy. *European Journal of Physics*, 19, 523-536.

Kiraly B., Tarkanyi F., Takacs S., et al. (2008). Excitation functions of alpha-induced nuclear reactions on natural erbium, *Nuclear Instruments and Methods in Physics Research B*, 266, 549-554.

Mertens J. C., Wilson J. W., Walker S. A., Tweed, J.. (2007). Coupling of multiple Coulomb scattering with energy loss and straggling in HZETRN, Advances in Space Research, 40, 1357-1367.

Noshad H., Givechi N. (2005). Proton therapy analysis using the Monte Carlo method. *Radiation Measurements*, 39, 521-524.

Parodi K, Bortfield T, Enghardt W, et al. (2008). PET Imaging for treatment verification of ion therapy: Implementation and experiments at GSI Darmstadt and MGH Boston, Nuclear Instruments and Methods in Physics Research A, 591, 282-286.

Pshenichnov I, Mishutin I, Greiner W. (2006). Distributions of positron-emitting nuclei in proton and carbon-ion therapy studied with GEANT4. *Physics in Medicin and Biology*, 51, 6099-6112.

Schardt D. (2007). Tumor therapy with high energy carbon ion beams. *Nuclear Physics A*, 787, 633c-641c.

Schardt D., Iwase H., Simon R. S.. (2006). Experimental investigation of secondary fast neutrons produced in Carbon ion radiotherapy. Proceedings of Science 038, FINDA April, 3-6, 2006, University of Cape Town, South Africa.

Table 1. Most important radioactive nuclides produced during carbon ion therapy

Interaction	C12+C12	C12+N14	C12+O16
Product	^{18}F	^{24}Na	^{24}Na
Half-life	110 min	15 hr	15 hr
Cross section	200 mb	50 mb	40 mb
Projectile energy	70-100 MeV	30-50 MeV	90-100 MeV

Table 2. Widening of carbon ion beam as function of penetration depth in tissue

Increment in radius	Penetration depth
0.4 mm	50 mm
0.7 mm	60 mm
1.1 mm	70 mm
1.6 mm	80 mm