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Original Article

Secondary Particles Produced by Hadron Therapy

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Abstract

Introduction
Use of hadron therapy as an advanced radiotherapy technique is increasing. In this method, secondary particles are produced through primary beam interactions with the beam-transport system and the patient's body. In this study, Monte Carlo simulations were employed to determine the dose of produced secondary particles, particularly neutrons during treatment.
Materials and Methods
In this study, secondary particles, produced by proton and ion beams, were simulated for a cancer treatment plan. In particular, we evaluated the distribution of secondary neutrons, produced by a 400 MeV/u carbon beam on an electronic crate, which was exposed to radiation field under radioactive conditions. The level of major secondary particles, particularly neutrons, irradiating the target, was evaluated, using FLUKA Monte Carlo code.
Results
The fluences and radiation doses were applied to determine the shielding efficiency of devices and the probability of radiation damage to nearby electronic systems. According to the results, by using maximum-energy carbon ions (400 MeV/u), electronic devices are exposed to a dose rate of 0.05 µSv/s and an integrated dose of about 34 mSv, each year.
Conclusion
The simulation results could provide significant information about radiation assessment; they could also be a major help for clinical facilities to meet shielding requirements. Moreover, such simulations are essential for determining the radiation level, which is responsible for radiation-induced damages.

Keywords: Hadron Therapy, Charged Particles, Simulation, Monte Carlo method

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1. Introduction

Hadron therapy is effectively used for the treatment of malignant tumors. In Italy, Centro Nazionale di Adroterapia Oncologica (CNAO) is regarded as the first nation-wide, hospital-based facility to treat deep-seated tumors, which are located between or adjacent to vital organs at risk. In this facility, the beam-delivery system distributes particle beams, produced by a synchrotron, on the target to control beam position, dimension and intensity by a monitoring system. Electronic devices in the beam-delivery system are mounted on a crate, which is placed in the treatment room, with exposure to secondary radiation during hadron therapy [1-3].

Neutrons rather than protons, photons and electrons are the most important components of secondary radiation field. Neutrons originate from primary proton beam (or carbon ion) interactions with the beam transport system, equipments and particularly patient's body. Overall, familiarity with radiation effects on devices, especially electronic devices in monitoring systems, is both essential and intriguing.

In the present study, Monte Carlo simulation was performed to determine the dose of secondary particles and secondary neutron fluence, arriving on the surface of the electronic crate. Furthermore, operational parameters related to radiation effects (i.e., damages and lifetime limitations of the device), neutron fluence, energy deposition in sensitive electronic materials and the absorbed dose by materials (gray or Gy) via kerma factors (by determining conversion factors) were calculated.

By measuring the neutron fluence, the absorbed dose was calculated and radiation effects could be macroscopically assessed, considering the effects of the threshold by Radiation Hardness Assurance [4].

2. Materials and Methods

Hadron therapy was performed by a synchrotron accelerator, delivering protons (60-250 MeV) and carbon ions (120-400 MeV/u). During a hadron therapy treatment the distributions of secondary neutrons, produced by carbon ion beams interaction with the patient tissue (as a source), were simulated as the main goal of this study. The electronic crate of monitoring system, placed in the treatment room as the target which was under exposure by secondary neutrons and a FLUKA Monte Carlo code, version 2008.3c were used in all steps of the simulation.

FLUKA Monte Carlo code is one of the few available codes for such calculations. This code can describe heavy ion collisions and includes the transport of fragments, along with hadronic cascades. It can also evaluate neutron contribution down to thermal energies, describe the secondary neutron spectrum, provide a general overview of simulation parameters and determine particle interactions with materials.

It should be mentioned that the total yield of secondary neutron radiation, produced by protons on patient's tissue is more intense in forward directions, while at angles larger than 90°, it becomes quasi-isotropic (Figure 1). Slight deviations from isotropy may be explained by neutron attenuation in thick, high-energy (0.0196-0.250 GeV) target materials.

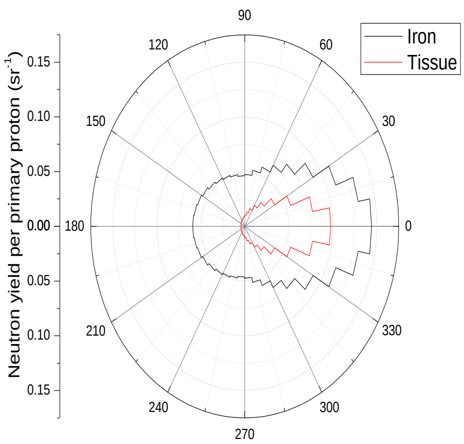
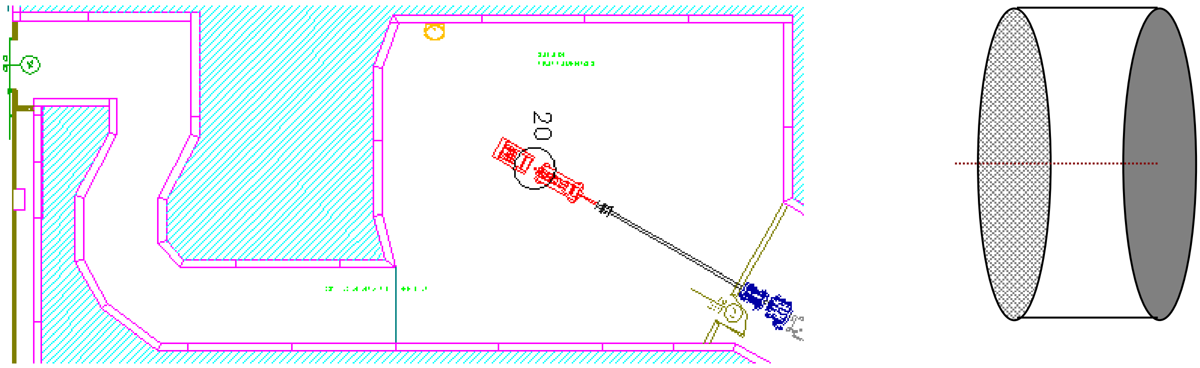


Figure 1. Distribution of secondary neutrons, produced by proton beam interactions with iron and tissue targets.

A general overview of the geometry model used to describe the treatment room in order to setup the simulation geometry, the shape and dimensions of the electronic crate and principal distances between source and target as well as the used materials, is given. [5]

Geometry of the treatment room: We assume a sphere volume of air as the hole space of treatment room where a radiation source is located at the center (V= 350m^3). For the exposure region which is distribution space of accelerated carbon ion (protons) beam we consider a cylindrical volume of air (V) as a more realistic model with 2m length of principal axes. Figure 2, shows the geometry parameters of simulation for treatment room and exposure volume models Figure 3, shows lay out of a treatment room indicating the position of beam line, source and target with principal dimensions and distances in order to use as input parameters for simulation of secondary neutron distribution.



(a) (b)

Figure 2. (a) Trattamento room (b) Geomety of beam line distribution

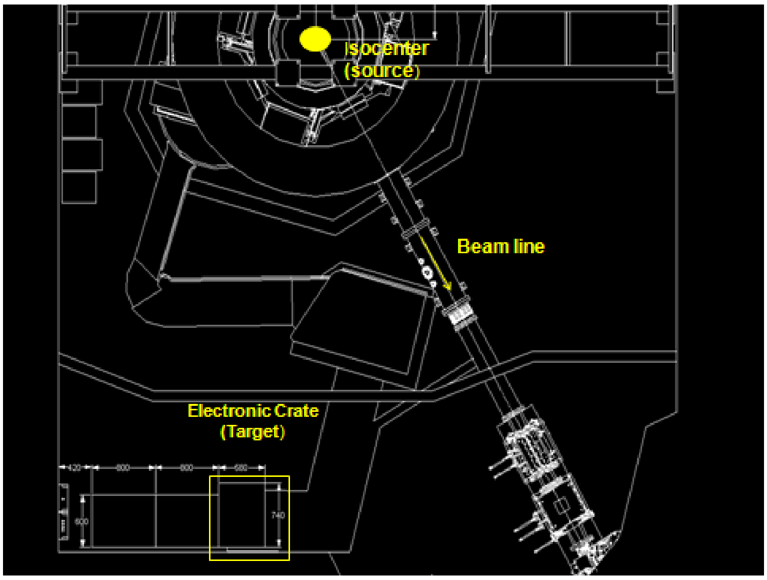


Figure 3. The treatment room layout where were located source and target.

Neutron source position: The neutron source has been located at the isocenter of the treatment room (Figure 3). The neutrons arriving on the crate are coming from the backscattered component of the radiation, produced by the interaction of the primary carbon ion beam with the patient tissue. Since in the backward direction we have essentially only the isotropic neutrons coming from the nucleus evaporation, then a neutron source uniform in the solid angle [0, 2π] has been assumed (we have considered as positive *z* axis the direction pointing from the isocenter toward the hadron beamline).

Geometry of elements: The most important ingredient to set up the geometry of the irradiated elements is to decide the shape and the volume of the sensitive elements. In the first step of this work the precise dimensions of the electronic rack have been set and they have been described in their exact positions respect to the isocenter, as shown in figure 3. The geometric bodies available in the FLUKA library have been used to characterize their geometric shapes.

Materials: The electronic rack has been considered as a parallelepiped with 5 cm thickness of Fe as material and an air-filled inner section. [5]

In order to qualify the distribution of radiation effects by secondary neutrons, produced by 400 MeV/nucleon carbon ion beams (particularly the distribution of secondary neutrons on patient tissue), energy spectrum, fluence and radiation dose rate should be simulated. In the present study, mainly, the electronic crate, which consisted of electrical components, data acquisition and computer systems in a backward direction, was evaluated in terms of the effects of secondary neutron radiation on patient's tissue.

The results obtained by the implementation of FLUKA simulation on the target tissue (depth of 30 cm) by the International Commission on Radiation Units and Measurements (ICRU), which was exposed to carbon ion beam at maximum operational energy, are presented in the current study.

To compare the obtained findings with the results reported in previous experimental studies [4], neutron fluences, impinging on the electronics, needed to be calculated. However, it should be mentioned that neutron fluences were not the only interesting quantities to be computed. Since targets in the treatment room may help with the calculation of ambient dose equivalent rate, it is useful to evaluate this rate, as well as the behavior at the same points under similar irradiation conditions.

Both effective dose and ambient dose equivalent conversion coefficients were implemented in FLUKA simulation and were enabled in the input file. Coefficients for converting the fluence to ambient dose equivalent were based on ICRP-74 values and the rates calculated by M. Pelliccioni [6]. These coefficients were implemented for protons, neutrons, charged pions, muons, photons and electrons; conversion coefficients for other particles were approximated by these coefficients.

3. Results

3.1. Air activation during treatment

Parts of radiation effects caused by the treatment were related to air activation in areas where accelerated particles were transported as beam lines (i.e., synchrotron hall, treatment room and experiment room). The results of relative evaluation of produced radionuclides during treatment are presented in Table 1.

During the experiments, use of a high-energy synchrotron produced a number of short-lived radionuclides by the proton beam (i.e., C^{11}, N^{13} and O^{15}); also, other radionucleads (e.g., Be^{7}, P^{32}, P^{33}, Cl^{38}, Cl^{39}, H^{3} and Ar^{41}) were produced. Table 2 shows the isotopes present in air as targets in the nuclear activation process.

Table 1. The mean value of carbon ions and protons produced during the treatment

	Isocentric treatment room (particle/s)	Isocentric experimentroom (particle/s)	Synchrotron hall (particle/s)
Activity produced by C^{12} (400 MeV/u)	3.64×10^{8}	4.78×10^{8}	5.51×10^{8}
Activity produced by Protons (250 MeV)	9.09×10^{9}	1.18×10^{10}	13.7610^{9}

3.2.The spectra of secondary neutrons and protons produced by air activation

Air activation is an important effect of radiation during a treatment operation in a hadron therapy center therefore in order to study of behavior of secondary particles (neutrons and protons) produced by primary carbon ions, since 400 MeV/u extracted from accelerator, had been performed a FLUKA simulation[7]. Figures 4 and 5 show the spectra of secondary neutrons and protons, produced by carbon ions exposed on the Cu target, respectively; this target was used for the evaluation of air activation in the treatment room.

Table 2. The percentage of major isotopes present in atmosphere under normal temperature and pressure (air density: 1.29 ×10-3 g/cm3)

Isotopes	Percentage of major isotopes in the atmosphere
N^{14}	78.08
O^{16}	20.95
Ar^{40}	0.93

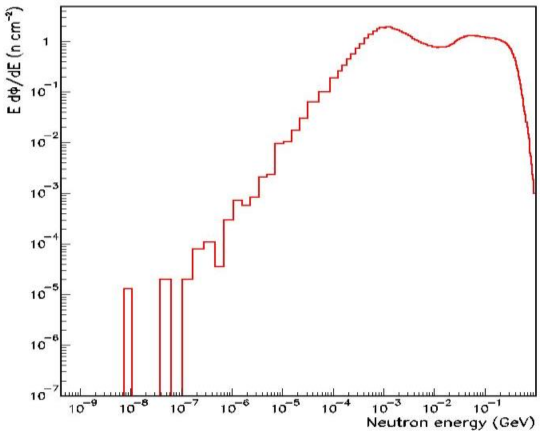


Figure 4. The spectrum of secondary neutrons, produced by 400 MeV/u carbon ions exposed on the Cu target with 5cm thickness as a source for air activation study in the treatment room (FLUKA simulation)

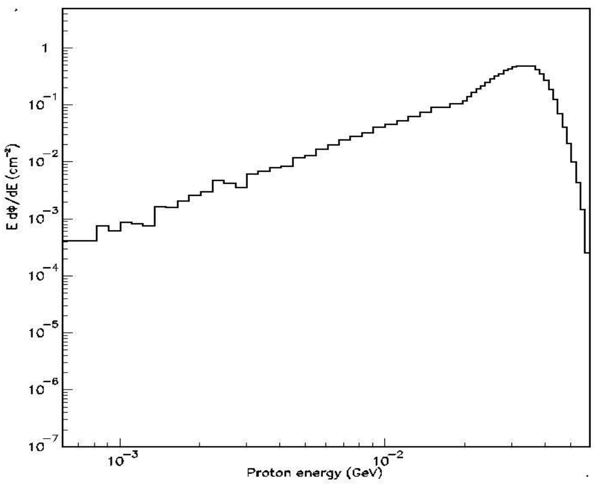


Figure 5. The spectrum of secondary protons, produced by 400 MeV/u carbon ions, exposed on the Cu target with 5cm thickness as a source for air activation study in the treatment room (FLUKA simulation)

In the next step, by considering the treatment room as the general space, secondary neutrons and protons were produced by the interactions between accelerated carbon ions and protons on the patient's tissue; the target was simulated as a phantom made of ICRU tissue (76.2% O, 11.1% C, 10.1 % H and 2.6% N), with a dimension of 30×30×15 cm^3. Figure 6 shows the spectrum of secondary neutrons, which were produced by 400 MeV/u carbon ions, exposed on the phantom of ICRU tissue. The fluence of secondary neutrons (number of neutrons across the target surface unity) calculated by E dΦ/dE, where Φ is indicative of the fluence of neutrons per ion [6].

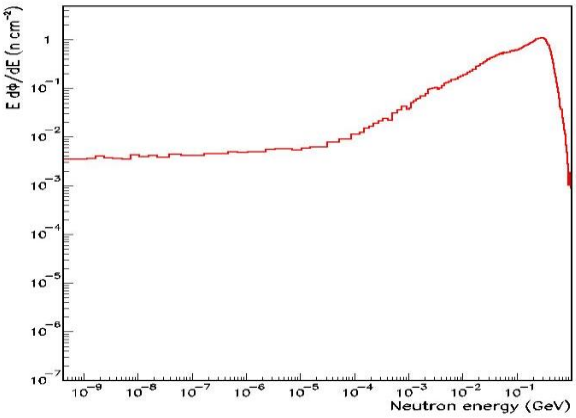


Figure 6. The spectrum of secondary neutrons, produced by 400 MeV/u carbon ions, exposed on the phantom made of ICRU tissue.

The number of neutrons (or protons) produced per primary carbon ion (or proton) was named neutron yield and indicated by n_{yield}, as the relative fluence calculated by integration of dΦ/dEdΩ, (Φ=fluence, E =energy of primary particles and Ω=solid angle) due to the simulation . The results are presented in Table 3.

The intensity of neutrons or protons irradiating the air was calculated by the following formula:

$$I\,(part/s) = n_{yield} \times \hat{c}\,(ions/s) \times f \qquad (1)$$

where ĉ is the mean value of primary ion or proton currents and f is the lost factor (f=1); n_{yield} values are presented in table 3. we can observe that the case of secondary neutrons from primary carbon ions is largely the most critical. For this secondary radiation the portion of the yield due to the backscattered component, n_{back}, has been evaluated:

$$n_{back} = 0.308\ n/ion \qquad (2)$$

To evaluate the effect of the radiation we have to characterize the neutron source intensity during the irradiation and then to do the integration of the results over a long operation time. The temporal length of one treatment is assumed in average 132 s. The number of neutrons per second during the irradiation is given by the higher intensity of the ^{12}C beam, I_{ions}, multiplied by the yield n_{back} of the backward neutrons:

$$I_{ions} \times n_{back} = 8\times10^8\ ions/s \times 0.308\ n/ion = 1.12\times10^8\ n/s \qquad (3)$$

We consider a standard condition of treatment; 4 treatments per hours, 60 extractions for each treatment and 8×10^8 ions have been delivered on tumor target, a mean cycle duration is 2.2 s, thus the effective exposure time is:

$$t_{irr} = 60\times2.2\ s = 132\ s \qquad (4)$$

Corresponding to current of ions in isocenter position at treatment room:

$$c_{iso} = 3.636\ 10^8\ ions/s \qquad (5)$$

As a result of this simulation, the yield value on secondary neutrons over 5MeV energy with a distribution angle between 0^o-90^o ,was 3.80 n/ion that presents only an error of 6% in comparison with an experimental result about 3.55 n/ion, including statistic and systematic errors.

Table 3. Number of secondary neutrons and protons produced by carbon ion and proton beams on the Cu target and ICRU tissue

Target	Primary Particles (Energy)	n/primary	p/primary
Cu	Carbon Ion (400 MeV/u)	9.23	0.85
ICRU tissue	Carbon Ion (400 MeV/u)	2.66	1.50
Cu	Protons (250 MeV)	0.75	0.06
ICRU tissue	Protons (250 MeV)	0.11	0.10

3.3.The spectrum of secondary neutrons

The spectrum of neutrons produced by a 400 MeV/u carbon ion beam in backward direction is presented in figure 7.

Figure 8 shows the simulated distribution of secondary neutrons, produced by high-energy carbon ions by considering the dimensions and geometry of the electronic crate as essential parameters.

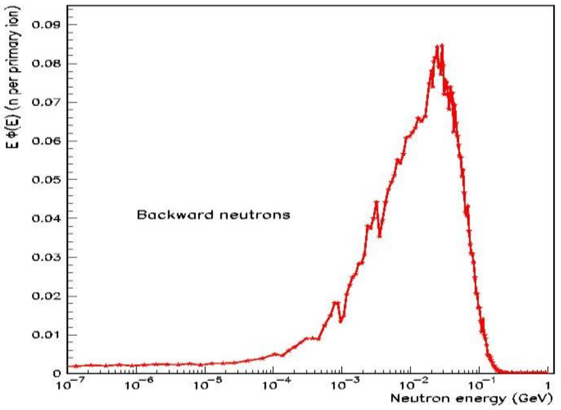


Figure 7. The spectrum of secondary neutrons, produced in the backward direction by 400 MeV/u carbon ions hitting a phantom made of ICRU tissue

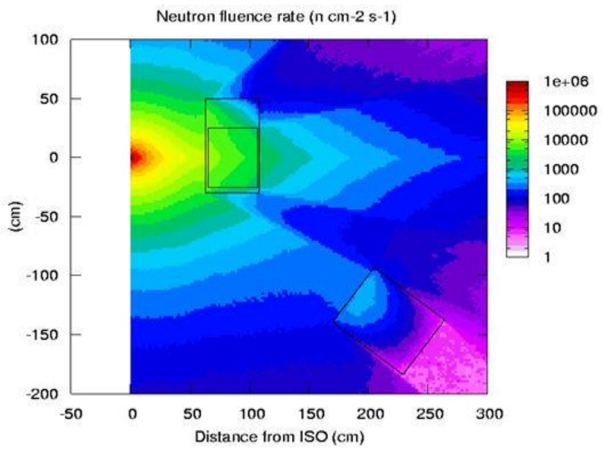


Figure 8. The fluence rate of secondary neutrons during treatment with a 400 MeV/c carbon ion beam

Finally, to evaluate the effect of radiation, the intensity of neutron source during irradiation was characterized, and the mean time of a typical treatment was considered to be 132 sec. This value is generally used for computing the life performance of a system for standard radiotherapy treatments, delivering 5×10^2 $(n\cdot cm^{-2})/s$ neutron fluences; the integrated value over one year is 3.4×10^8 n/cm^2 on the crate. Figure 9, shows the distribution of the dose rate of secondary neutrons. Therefore, each year, the crate is exposed to a dose rate of 0.05 µSv/s and an integrated dose of about 34 mSv [5].

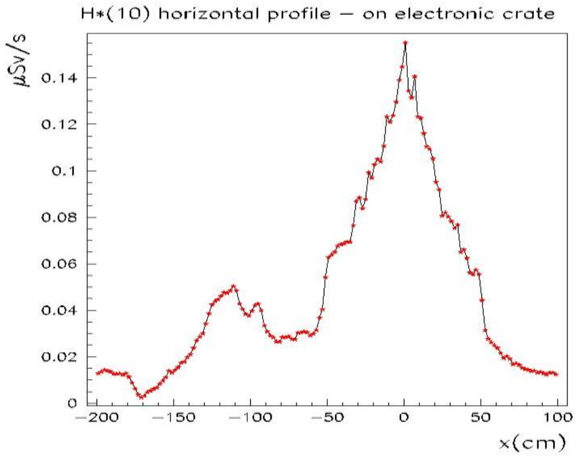


Figure 9. The dose rate of secondary neutrons, produced due to treatment with 400 MeV/u energy carbon ions, distributed on the electronic crate

4. Discussion

There is at present a lack of experimental data about the neutron yields from 400 MeV/u carbon ions on tissue. We used therefore the results of the Monte Carlo study performed at CNAO with the goal to offer a general reference about the yields of secondary particles needed for applications in hadron therapy. In this study the interactions of accelerated carbon ions and protons on a phantom made of ICRU tissue (76.2% O, 11.1% C, 10.1 % H, 2.6 % N) with dimensions 30 × 30 × 30 cm3 have been simulated. The maximum operation energy for the therapy has been considered both for proton and carbon ion beams. The secondary neutron and proton spectra have been then fully characterized, in polar angular bins having a step of 10° in the forward direction (0, 90°) and considering only a bin for the backward component of the radiation (90°, 180°)(Figure7).

5. Conclusion

Secondary neutron radiation on patient tissue had a significant impact in the backward direction**.** Neutron fluence rates were calculated in a mesh spatial structure, defined in the input file. The expected dose, delivered to the electronic system during treatment, could be simulated and measured, using the maximum energy of carbon ions.

Based on the experimental threshold for integrated fluence (4×10^{14} neutrons per year), it was concluded that the obtained simulation threshold was lower than the experimental value**.** The radiation environment was simulated to determine the probability of damage to electronic devices, estimate the lifetime of devices and determinate their adequate shielding, according to radiation protection procedures and safety standards.

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