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Electronic and nuclear interactions in tissues on Proton Radiotherapy

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1. Introduction

Radiotherapy (RT) for intracranial neoplasms, many of which are benign with a good long-term prognosis, or malignant with limited survival, is inherently associated with a risk of damaging the normal cerebral parenchyma and causing irreversible delayed neurotoxicity [1]. The latest effort to provide highly conformed RT, as well as to potentially decrease the chronic adverse effects of brain irradiation in several patients, is manifested by rapid support to PRT-encoded heavy ion radiotherapy, having as incident particles protons (H+), in general, or carbon ions (C_{12}^{6+}) or helium (He^{2+}). [1, 2]

Compared to conformal megavoltage radiotherapy (3DCRT-MV), by incident photons, PRT offers a single-dose deposition profile, known as Bragg peak, where before and after high ionization events in target volume (PTV), there is only limited energy absorption [3] in normal tissue and therefore induces reduced effects on non-target tissues, said organs at risk (OAR). Thus, the main advantage of PRT over the techniques of 3DCRT-M, the three-dimensional conformed RT as modulated radiotherapy (IMRT) and volumetric modulated arc therapy (VMAT), is the staggered dose gradient that provides a reduced symmetric profile at the entrance and output of the particle beam, reducing doses in the OARs, and higher dose in the PTV. [1]

Data from several tumor sites showed superior dosimetry of PRT than 3DCRT-MV modalities, which is also valid for brain neoplasms [1]. Dosimetry contributes significantly to the definition of a radiotherapeutic protocol; however, there are other factors involved such as: instrumental availability, operational cost, risk of radio-induced cancer, late and long-lasting deleterious effects, duration of treatment, differentiated radiobiological response, possibility of hypofractionation, quality of life after treatment, among others.[4]

The proton therapy for brain treatment is a technique in operation and expansion in the world, with installation of more than half a hundred centers [5]*;* but not yet deployed in Brazil. Thus, there is no systematic and accumulated experience in planning in PRT. In the country, in clinical practice, the uncertainties of the superiority of PRT benefits are disclosed compared to advanced techniques of 3DCRT-MV.

In turn, there is previous experience in the Nuclear Science and Techniques Program, in dosimetry and RT planning of PRT, VMAT and IMRT. It is cited the development of computerized planning voxalized human models, coupled with the MCNP code [6] as well as the code PROPLAN (Planning in Proton Therapy) for tumors in the eyeball coupled to the code GEANT [7]; in addition to computational tools for calculating the risk of radio-induced cancer [8]. Such computational tools coupled with stochastic methods, GEANT and MCNP6, which provide spatial dose distribution, have international precision and acceptability [9]. There is also extensive experience in experimental dosimetry with the construction of physical phantoms and use in the dose equation of internal synthetic organs measured by dosimeters of radiochromic films [10]. Systematizing the use of these already developed tools, adjusted to PRT therapy, for the purpose of therapeutic comparative analysis will be of great value for the development of the PRT area in Brazil.

The present revision work aims to present an analysis of the physical atomic and nuclear interaction events involved in proton radiotherapy, qualifying the electronic and nuclear reactions involved in the tissue.

2.Methodology

It is being proposed the description of the events that make up the absorbed dose in proton radiotherapy, including the nuclear and electronic interactions with the tissues of the human body in the processes of deposition of radiation with matter. The Janis software was used to select the possible nuclear reaction in the tissues. The software Q-value from BNL was used to set the nuclear reaction energy release and the threshold energy.

3. Results and Discussion

Protons interact directly with the electrons of the electronic clouds of the constituent elements of the tissue, hydrogen, carbon, oxygen, nitrogen, calcium, phosphorous, and others. Due to the electronic density of the tissue, the electrons are hit quickly, receiving part of the proton energy.

The dose is the measure of the amount of energy deposited in a small volume, by the secondary electrons and ion particles, from the proton interactions, or provided by the no charged secondary particles whose primary interactions occurred at distance.

Inelastic collisions. Protons lose energy by Coulomb interactions with electrons, shaping dose profiles and defining the range along the direction of the incident proton beam. Protons also undergo Coulomb scattering interactions with the atomic nuclei of tissue elements. These interactions shape the side dose profile. Protons also promote inelastic interactions with the tissue elemental nuclei, modifying the dose distribution profile in depth and laterally.

Protons lose their energy in electron collisions. The greatest energy losses are through Coulomb interactions with the electrons of the outer layer of the chemical elements of the tissue, generating an excitation and ionization on the matter. In turn, scatter losses are small and can be modeled by the "continuously slowing down approximation (CSDA)" model. The range of secondary ions of positive charge is less than 1mm and considered a local absorption. Protons have 2000 times greater mass than electrons and do not change direction, or their deflect are insignificant. The energy lost by inelastic collisions that lead to ionization and excitation can be evaluated by the Beth-Block equation. Thus, -dE/dx, said stopping power, governs the dose deposition tissue.

According to Beth-Block, the maximum kinetic energy of electrons is 4Tp(mec2)/(mpc2). For a 200 MeV proton, the maximum kinetic energy (Tmax) of the secondary electrons is 400 Kev with a range of 1.4 mm of water. This means that the most likely energy of secondary electrons is much lower than Tmax. According to Beth-Block the greater the kinetic energy of incident particle, defined by b on Beth-Block equation, the lower the energy loss in collisions with the electronic cloud.

Elastic collision. The elastic collisions that lead to deflection and change of motion direction have no significance, so high-energy protons move straight forward in the water. The greater the kinetic energy of the proton, the lower the lost energy; while, on the contrary, low proton energies lead to large energy losses, producing a chaotic path, said straggling.

Coulomb scattering. The elastic Coulomb interactions with nuclei of chemical elements provide the scatter of protons out its forward direction. The interaction provides small angle deflections, that can be approximated by Gaussian model, Moliere scatters, or Highland approximation.

Nuclear interaction.
About 20% of the incident protons can surfer inelastic interactions with the target nuclei, reducing the incident proton fluence with depth. There are various types of secondary charged particles, as p, He-3 t, d, alpha, recoil target nuclei that carries out 60% of the reaction energy, depositing it on the pathway of the incident proton;

and neutron particles as neutron and gamma particles with 40% of the energy, that deposit energy out of the proton path can produce activated radionuclides on its path in the tissue. The nuclide O-16 is the mainly element that suffers nuclear interaction of incident proton. It supposes that 1% of incident proton is lost per centimeter on nuclear reactions. Figure 1 represents the graph of the cross section by the energy of the reactions. Figure 1 represents the graph of the cross section by the energy of the reactions. Table 1 described the main nuclear reaction, possible to occur in the human body on the radiation proton therapy.

Figure 1: Cross section graph versus energy of reactions.[11]

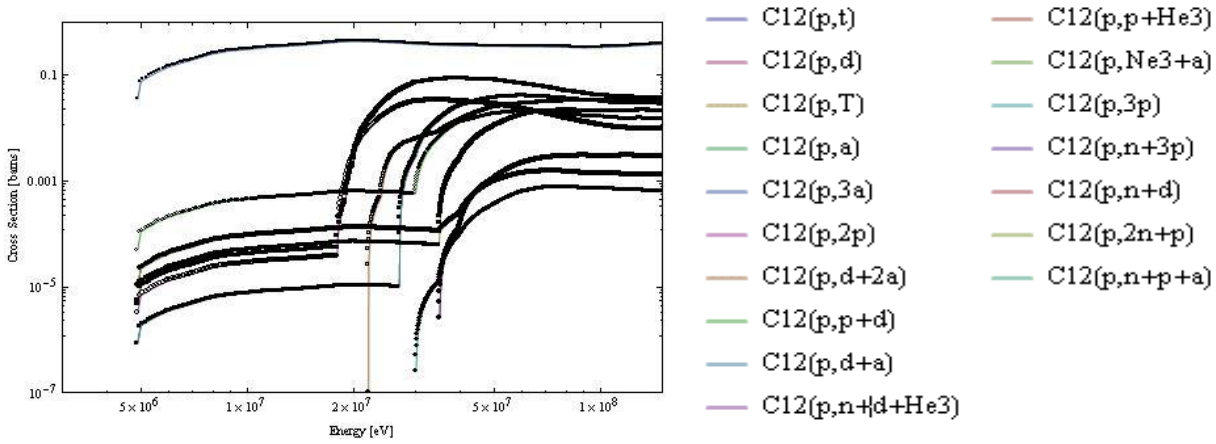

Table 1: Detailing of the main nuclear reactions induced by incident protons, characterized by the reaction Q, and the threshold energy.[12]

Ep 250MeV	Reaction (p,products) [Q-value, E threshold]
H-1	(p,p) [0,0]
C-12	(p, ^{3}He +d+ 2α) [-25627, 27779]; (p, ^{3}He + n +p +d + α) [-51698, 56039]; (p,n+p+α); (p,n+d); (p,2n+ p); (p,d); (p,α); (p,3α); (p,2p); (p, d+2α); (p ,p+d); (p,d+α); (p,3p); (p,n+3p); (p,t).
O-16	(p,n+p)[-15663, 16650];(p,n+d)[-26662, 28342];(p,^{3}He+α)[-32789, 34855]; (p,^{3}He+ n +d+α)[-53367, 56729];(p,^{3}H+ n +p+t) [-87501, 93013]; (p,^{3}He+n+2d+t) [-91534, 97300]; (p,2n+p); (p, n+p+α); (p,γ); (p,p); (p,d); (p,t); (p,α); (p,2p);(p,p+α);(p,d+2α);(p,p+d);(p,p+t); (p,d+α); (p,t+α); (p,n+d+α); (p,2n +p+α); (p, n +p+d); (p,2n+2p); (p,3p).
N-14	(p,n); (p, n+^{3}He); (p,d); (p,α); (p, p+α); (p, n+α); (p, n +p); (p,2α); (p,2p); (p, p+d); (p,p+t); (p, 2n + ^{3}He); (p, 3n+2p); (p,p+^{3}He); (p,d+^{3}He)
Ca-40	(p, n+p); (p, n+2p); (p,p); (p,d);(p,^{3}He); (p,p+α); (p, p+d); (p,^{3}He+ n+p); (p,^{3}He+d +p); (p,3p); (p,n+3p)
P-15	(p,d+2α); (p,3p)

4. Conclusions

The energy losses, scattering, nuclear interactions lead to the Bragg peak formation, and mold the dose distribution in the tissue. Thus, a pencil beam transforms at the end of the proton range in a large beam through

lateral and longitudinal scattering spreading. Straggling occurs at the distal end of the beam, near 1% of the final range.

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