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IONIZATION AND PHONON PRODUCTION BY ^{10}B IONS IN RADIOTHERAPY APPLICATIONS

Fatih EKINCI[1]

[1]Institute of Nuclear Sciences, Ankara University, Ankara, TÜRKİYE

ABSTRACT. The therapeutic use of heavy ions has received much attention due to their physical and radiobiological properties. Thanks to these features of heavy ion radiotherapy, radiation in tissues close to critical tissues can reduce LET while allowing an increase in LET in tumors. Selection of biomaterials closest to the tissue is critical to measure the accuracy of this LET transfer. The accuracy of LET and radiological features measured in phantoms created from biomaterials selected according to the characteristics of the target tissue is very important for human life. For this reason, the research of polymeric materials, which is the closest biomaterial to soft tissue and therefore phantom material, has increased recently. In this study, ionization to the polymeric biomaterials closest to the soft tissue in boron therapy application, and phonon release from all interactions were investigated and analyzed. This analysis was performed using MC-based TRIM simulation. In the analysis, the Bragg peak range closest to the soft tissue was 7.2% and PMMA was the phonon release from all interactions. It has been observed that the phonon production in phantoms results from ions on average 30% and recoils interactions 70%. The main novelty that this study will provide to the literature is to consider the phonon interactions as well as the ionization interactions. Thus, apart from proton and carbon, the most ideal polymeric biomaterial to be used instead of soft tissue was evaluated by calculating all interactions. Thus, it is aimed to determine the most ideal phantom material.

1. INTRODUCTION

Heavy ion therapy has been the focus of radiation oncology for over 60 years because of its superior physical and biological properties [1, 2]. In addition to the proton [4]

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fatih.ekinci@gsb.gov.tr-Corresponding author 0000-0002-1011-1105.

and carbon therapy centers that are widely used around the world, researchers have recently focused on the use of helium and oxygen ion beams in therapy [5, 6]. Before clinical applications of heavy ion therapy, accurate dose calculations and dosimetric verification procedures, including heavy ion beam delivery, are important. Therefore, most of the clinical knowledge in heavy ion therapy has been formed by radiotherapy planning and dose validations based on semi-analytical algorithms [7]. The selection and beam energies of each new heavy ion species mainly depend on the ionization interactions of the ions in question [8]. Thus, the ionization properties of heavy ion beams such as ^{1}H, ^{4}He, ^{6,7}Li, ^{8}Be, ^{10}B, ^{12}C, ^{14}N and ^{16}O on the target at therapeutic energy levels were investigated on the phantom with the help of different methods [9, 10].

It is accepted that the accuracy of the phantom close to clinical results is related to the fact that the building materials that make up the phantom are equivalent to the target tissue [11]. The International Atomic Energy Agency (IAEA) recommended water as the phantom building material for radiation measurements that are closest to the standard soft tissue, easily available and repeated [12]. In addition to these properties, the most important reason why water is a widely used biomaterial is that its bulk density is the closest material to soft tissue [13]. In addition to general properties, stopping powers, linear energy transfer (LET), Bragg curve properties and nuclear interaction results are important in the evaluation of biomaterials that make up phantoms radiologically [11, 14]. However, although less quantified and understood, recoil and phonon production are important in the selection of biomaterials in interactions [14, 15]. When all these properties are evaluated, one of the biomaterials close to soft tissue, such as water, is polymeric [15].

In this study, ionization, recoils, phonon and lateral scattering values of helium, lithium, beryllium and boron (^{10}B) ions formed by water phantom were calculated with the help of Monte Carlo (MC) Transport of Ions in Matter (TRIM) simulation program. In these calculations, the data obtained for each selected heavy ion were compared with each other. First of all, in these comparisons, it was tried to determine the ion that creates the most LET energy. Then the ion generating the lowest recoils and photon energy was determined. Finally, it is aimed to determine from which heavy ion the least lateral scattering value comes from.

2. Section

In the absence of an experimental ^{10}B beamline, MC-based simulations were used to generate reference values for our study. In this direction, it is important to investigate biological experiments with the help of simulation and to make experimental validation of the data obtained. One of these simulations, TRIM, is an MC-based system widely used in ion beam implantation and processing calculations [16].

TRIM can calculate radiological interaction on complex targets with layered structure. TRIM provides different options for calculating radiological interactions on a target based on the type of data outputs required. The full damage rank (F-C) mod can track every knockback atom until its energy drops below the displacement threshold energy (E_d) of any target atom. Thus, all collisions of the ion beam towards the target can be calculated and analysed. The fast damage calculation (K-P) mode can only follow the path of the ion beam, can be used when little attention is required to details of damage to the target or surface spraying. Damage calculated with this option is a rapid statistical method based on the Kinchin-Pease formalism "K-P" [17]. The K-P theory used by the TRIM system was first proposed by Kinchin and Pease, expanded by Lindhard, and later used by Norgett, Robinson and Torrens (NRT)] [18].

"Detailed Calculation with Full Damage Cascades" type was selected in the calculations from the display window of the TRIM program. The particle number of the heavy ion beam was entered as 10^5 particles with the "Total Number of Ions" tab. Calculation outputs from the "Output disk files" tab; Ion range, recoils, sputtered atoms and collision details output files were selected. In order to compare the selected heavy ions with each other, four different ion beam energies were determined as 80 MeV/u, 100 MeV/u, 120 MeV/u and 140 MeV/u. The phantom type was created from the "Compound Dictionary" tab as water and its geometry from the "Add New Layer" section. Of the polymeric materials used as biomaterials in this study; Phantoms formed from two polymeric biomaterials such as polymethylmetacrylate (PMMA) and polystyrene (PS), water and soft tissue (ST) materials were used. The phantoms created from these biomaterials were bombarded with a ^{10}B ion pencil beam with 105 particles at therapeutic energies (80, 100, 120 and 140 MeV/u) by forming a single-layer sheet phantom with a width of 15 cm and a length of 15 cm.

3. Results

The Bragg peak position formed by the ^{10}B heavy ion with 80-140 MeV/u energy obtained from this study in selected phantoms is shown in Figure 1. As the energy of the ^{10}B ion beam increases, the Bragg peak position is shifted in all phantoms, as expected. The longest Bragg peak range value of the ^{10}B ion beam was seen in the PMMA polymeric phantom. The next longest bracket peak range occurred in the water phantom. For each 20 MeV/u energy increase of the ^{10}B ion beam, the average Bragg peak range increases of 1.5 cm in the ST phantom, 1.4 cm in the PMMA phantom, 1.35 cm in the water phantom and 1.3 cm in the PS phantom, respectively. In terms of Bragg peak range, the closest phantom to soft tissue was PMMA with

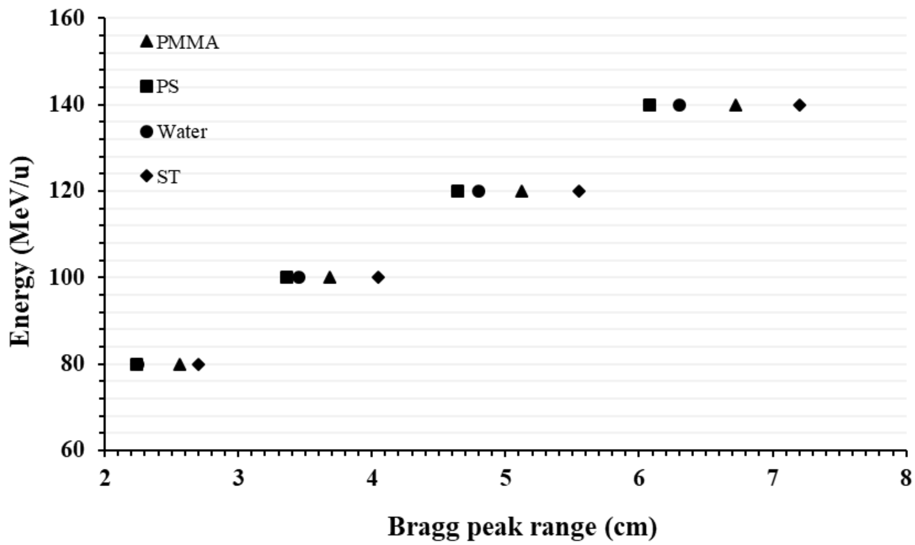

FIGURE 1. Bragg peak range (cm) created by the ^{10}B ion beam in four phantoms.

7.2% difference. In other phantoms, this difference is respectively; 14.4% in water and 16.5% in PS polymeric material.

Phonons are formed during and at the end of the interaction of ionization and recoils caused by the ^{10}B ion beam in plate phantoms. All phonon formations consisting of interactions received in the TRIM program are analyzed and given in Table 1. In order for the given phonon formations to be meaningful, they are presented by multiplying by 10^3. Looking at the presented data, it was seen that the biggest contribution to phonon production came from the recoils interactions. While PMMA was the closest biomaterial to ST in phonon contribution from ions, PS was the closest biomaterial to ST in phonon contribution from recoils interactions. It was observed that as the energy increased, the phonon contribution from the recoils interaction generally increased. In general, it was observed that the biomaterial that provides the closest phonon production to ST is PMMA.

In this study, Bragg peak range of 10B ion beam with therapeutic energy and phonon values consisting of all interactions were calculated in 4 different phantoms. In the selected phantom materials, it was tried to find the closest biomaterial to the soft tissue in 10B ion treatment. Thus, the interactions of the 10B ion beam in soft tissue, water and polymeric biomaterials were considered. The biological activity from these interactions may differ between the selected ion beam types [19]. These differences are not only limited to the type of ion, but each type of treatment can be customized depending on whether the target is hard or soft tissue [20]. At this point, it is considered to be an important issue to investigate selected soft tissue phantom biomaterials. Thus, ST water and two different polymeric biomaterials were selected for the phantom material and compared with ST. By using heavier ion beams apart from the 10B ion beam presented in this study, it provides the presence of an appropriate level of dose that ensures tumour control while sparing healthy tissues at risk [21]. It is noteworthy that ^{4}He, ^{6,7}Li, ^{8}Be, ^{10}B, ^{12}C, ^{14}N or ^{16}O beams are preferred over He beams, which increases the likelihood of treatment in clinical practice, as suggested in similar studies [22, 23]. It has been observed that as the atomic weight of the ions forming the beam increases, they exhibit advantageous physical properties [24-26]. This provides possible clinical advantages for radiation-resistant tumours [23]. In this study, the contribution of heavy ions recoil interaction [1, 15, 27] to total phonon production was investigated.

TABLE 1. Phonon values (eV/A×10^{3}) formed by ion and recoil interactions formed by ^{10}B ion beams in four phantoms and their percentage (%) contribution to this value.

Phantom	**80 MeV/u**				**100 MeV/u**				**120 MeV/u**				**140 MeV/u**			
	ion		recoil		ion		recoil		ion		recoil		ion		recoil	
	eV/A	%	eV/A	%	eV/A	%	eV/A	%	eV/A	%	eV/A	%	eV/A	%	eV/A	%
PMMA	**0.804**	**31**	**2.629**	**69**	**0.555**	**32**	**1.057**	**68**	**0.655**	**26**	**1.651**	**74**	**0.594**	**27**	**1.887**	**73**
PS	0.859	47	2.678	53	0.793	31	2.553	69	0.774	31	2.511	69	0.771	13	2.506	87
Water	0.801	26	3.133	74	1.038	31	3.333	69	1.022	26	3.567	74	0.987	34	3.483	64
ST	0.901	27	3.346	73	0.403	13	3.062	87	0.836	26	3.214	74	0.632	34	1.881	66

4. CONCLUSIONS

In this study, radiological interactions of ^{10}B ion beam in ST, water and polymeric biomaterial were investigated with the help of MC TRIM. From these interactions, ionization and the phonon state formed as a result of all interactions have been revealed. As a result of the obtained results and studies in the literature, biomaterials that are considered close to soft tissue were compared. It is recommended that these calculations be made for different heavy ions as well. Considering the importance of investigating biomaterials close to tissues in radiotherapy, it has been evaluated to be made in different biomaterial types.

Declaration of Competing Interests The authors declare no conflict of interest.

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