ORIGINAL ARTICLE

Monte Carlo Simulation of Radioactive Elements Production in Tissues by Spallation in Cancer Therapy

Mohammad Reza Rezaie Rayeni Nejad [1*], Saeedeh Khezripour [2*], Ali Nouraddini [3]

[1] *Department of Nuclear Engineering, Faculty of Modern Sciences and Technologies, Graduate University of Advanced Technology, Kerman, Iran*

[2] *Department of Molecular and Atomic Physics, Faculty of Modern Science and Technology, Graduate University of Advanced Technology, Kerman, Iran*

[3] *Department of Physics, Payame Noor University, Tehran, Iran*

*Corresponding Authors: Mohammad Reza Rezaie Rayeni Nejad, Saeedeh Khezripour

Email: mr.rezaie.r@gmail.com, Saeedeh1363@gmail.com

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Abstract

Purpose: High-energy heavy ions generated by accelerators utilized in industrial and medical uses. Ar, C, and He heavy ions have been used in the treatment of cancer. In this research, it was tried to calculate the radioactive elements production in healthy tissues around tumors by heavy ions spallation process in the direct usage of high-energy ions for the treatment of cancerous tumors.

Materials and Methods: The radioactive elements production in body tissues irradiated with heavy ions was calculated by Monte Carlo N Particle X-version (MCNPX) code based on the Monte Carlo method. The F8 tally card with FT8 command was utilized to derive the activation and spallation data in the range of Z1 to Z2 atomic numbers.

Results: A wide range of radioactive elements was created in healthful tissues in Ne, C, Ar, and He heavy ions therapy. Results show that ^{10}Be,^{14}C, ^{26}Al, ^{36}Cl, ^{39}Ar, ^{40}K, 39Ar, ^{32}Si, ^{22}Na, and ^{36}Cl radioactive materials were produced for high-energy heavy ions spallation in healthy soft tissue.

Conclusion: The results of this research show that due to using directly high-energy ions to treat internal tumors, healthy soft tissue is activated. Also, by irradiated Ne, C, Ar, and He ions, the radioactive elements are produced with high gains and long half-lives. Therefore, in the therapy of cancerous tumors with high-energy ions, due to the production of radioactive agents, healthy tissues are at high risk.

Keywords: Spallation; Activation; Heavy Ions; Neutron; Radioactive Elements; Soft Tissue.

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1. Introduction

Different approaches are used for the therapy of cancerous tumors, such as surgical operation, laser therapy, brachytherapy, nuclear radiation and massive ion radiation therapy, chemotherapy etc. [1-7]. Heavy ion accelerators have numerous uses in radiation therapy [8-16]. Recently, the possibility of utilizing energetic ions has been investigated in various laboratories that are quickened by special techniques in the therapeutics of cancerous tumors [17-22]. When substantial charged particles traverse human tissues, the quantity of Linear Energy Transfer (LET) is very elevated because of its high stopping power. High levels of LET increased tissue temperature along the path of high-energy ions [23]. Although ion energy is preserved in the Bragg peak in the environment, the amount of energy transferring along the direction to the Bragg peak location is also elevated because of the high energy of the particles. In addition, there is a possibility of increasing temperature and molecular degradation of body tissues in nuclear interactions by the tissue. In these interactions, the nucleus transforms into a composite nucleus by absorbing a charged particle, and the compound nucleus decays in variant modes such as the release of photons, neutrons, alpha, and more massive particles. The produced photons also affect other tissues by producing neutrons and they result in more radiation dangers in the body. The spallation process is one of the most significant methods of heavy ions interaction by the nuclei that can damage the tissues. In the spallation process, the nucleus evaporates by absorption of incoming particles and changes to the radioactive and non-radioactive materials whose mass number is smaller compared to the target mass number. The spallation process happens when the radiation energy reaching an element is greater compared to its threshold energy. Since the radiation energy is usually greater than the threshold energy, the spallation phenomenon actually happens.

In the spallation phenomenon for charged particles with elevated energy, as a result of energy transfer to the target nucleus, evaporation occurs and produces particles with a mass number lower than the target nucleus [24]. Recently, it can produce various heavy ions such as He, Ar, Ne, and C up to 3.5 TeV energy [25-29]. In direct application of heavy ions, high-energy ions were previously utilized to cure tumors in different organs, because of the Bragg peak of high-energy ions that transfer more energy to the tumor in comparison to healthful organs.

In this research, the activity of tissues examined by ions irradiation on many organs and the advantage of producing radioisotopes were determined utilizing the Monte Carlo N Particle X-version (MCNPX) code. The MCNPX code is a nuclear code established by the Monte Carlo method that is utilized for neutron, proton, and electron transport or coupled neutron/proton/electron transport [30-33]. This code is a software package program, which can be used for energy deposition and dosimetry calculation in most of the nuclear and radiation research [33-35]. Also, the quantity of spallation of these heavy ions and radioactive materials generated in the soft tissue is investigated due to the direct use of heavy ions such as Ne, C, Ar, and He in the treatment of internal tumors.

2. Materials and Methods

The spallation in the soft tissues and neutron production due to heavy ions spallation are investigated by MCNPX code. The input file of the MCNPX code is written in the first step which includes the geometry card, surface card, and data card. The geometry card in the MCNPX code is a sphere cell with a 2 cm radius that shows the soft tissue in this manuscript (Figure 1).

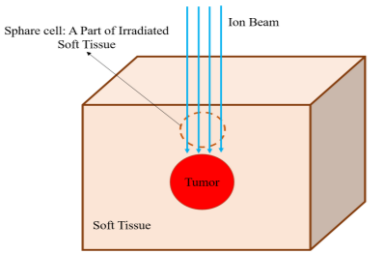

Figure 1. Schematic of the tissue to be simulated

The data card contains information about the percentage of elements used, the energy of the heavy ion sources, and the tallies required to extract the data. Tallies are used in MCNPX to obtain the number of particles, energy deposition, and other quantities of interest in a simulation. In fact, they provide a way to get information about the behavior of particles and radiation in a given system and can be used to analyze the results of a simulation.

The F8 tally card and the FT8 command were utilized to derive information about activity and spallation. The

FT8 command is indicated as FT8 Res Z1 Z2 that Res displays the gain of spallation. The activity is in the range of Z1 to Z2 atomic numbers. Also, particle flux can be extracted utilizing F1 tally. The output file of the MCNPX code involves lots of information that can be utilized to express the required data. The result data of the MCNPX code involve the number of simulated elements, the mean value, error the Variance of Variance (VOV), and Figure of Merit (FOM) to assess the statistical behavior. The FOM is proportional to the execution time and error. If the FOM value is constant at different simulation times, the program will run correctly. In this study, due to the need for interactive products, activity and spallation, the result of the F8 tally is different compared to the normal mode. The outputs of the FT8 tally include the atomic number and the mass number of the element produced and the increase in element production due to the spallation process. The gain of the spallation process is equal to the mass ratio of the produced element to the irradiated element. By extracting the produced elements data in the spallation process, the gain of the radioactive elements can be obtained with a table of radioisotopes. Energetic sources of Ne, C, Ar, and He heavy ions in soft tissue, which is healthful tissue, are investigated before treating internal tumors and calculating the amount of radioactive materials produced in them. The geometry investigated in this manuscript is a soft tissue sphere with a radius of 2 cm. The soft tissue information and the energetic ion source information used for this purpose are given in Tables 1 and 2, respectively.

3. Results and Discussion

The results of the spallation gain production by high-energy heavy ions in soft tissue are investigated in the following.

3.1. The Spallation Gains of Isotope Production in Soft Tissue without Tumors by High-Energy Heavy Ions

The spallation gain of isotope production is investigated in soft tissue without tumors by high-energy Ar, C, He, and C heavy ions. The results show in Figures 2-5 in terms of N and Z are Neutron and Atomic Numbers, respectively.

According to Figure 2, in the process of the spallation of the soft tissue by Ar ions with 21.964 TeV, the gain of isotope production is between atomic number z = 3 and z = 19. The production gains for z = 18 and z = 19 isotopes are higher than the others. High levels of z and N in this region indicate more radioisotopes with atomic numbers z = 18 and z = 19. The same behaviour was observed in the z = 6 to z = 9 atomic number range.

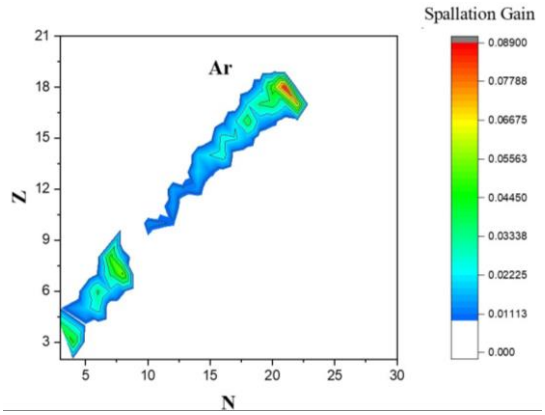

Figure 2. The spallation gains of isotope production in soft tissue before internal tumors by high-energy Ar ions

The result of Figure 3 shows that the atomic number range of isotopes produced by carbon spallation with energy 5.16 TeV is between z = 2 to z = 10 and most isotopes are produced in the range of z = 4 to z = 5.

Table 1. Materials density [35]

Material	Soft tissue	H	C	N	O	Na	p	S	Cl	K
Density (g/cm^3)	1.05	0.102	0.143	0.034	0.708	0.002	0.003	0.003	0.002	0.003

Table 2. Information on high ions energy [35]

Ion	E (MeV/u)	amu	E(MeV)	Target	Density (g/cm^3)
He	150	4	600	soft tissue	1.05
C	430	12	5160	soft tissue	1.05
Ne	230	20.17	4639	soft tissue	1.05
Ar	550	39.94	21967	soft tissue	1.05

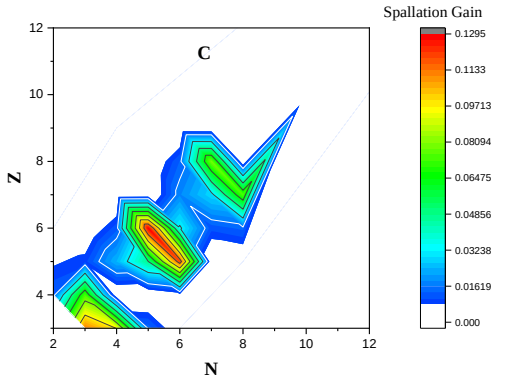

Figure 3. The spallation gains of isotope production in soft tissue without tumors by high-energy C ions

The results of Figure 4 show that the gain of isotope production is between z = 2 to z = 9 for Helium spallation in soft tissue with 600 MeV energy. Two important regions z = 7 to z = 9 and z = 6 to z = 7 show the highest gain of element production by the spallation process in soft tissues.

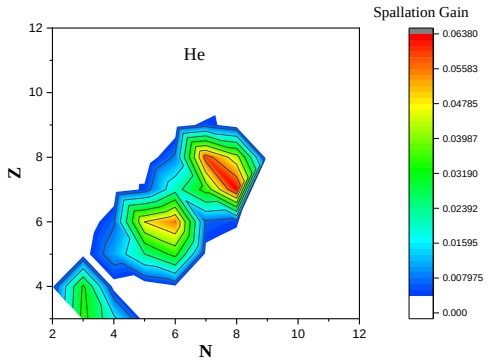

Figure 4. The spallation gains of isotope production in soft tissue before internal tumors by high-energy He ions

According to Figure 5, in the process of the spallation of the soft tissue by neon ions with 21.97 TeV energy, the gain of isotopes production between z = 6 to z = 7 and z = 9 to z = 10 is higher than other zones and the production of the maximum isotope is in the range z = 9 to z = 10. The results of Figures 2-5 show that neon and argon spallation have the highest isotope production gain in the soft tissue compared to other ions.

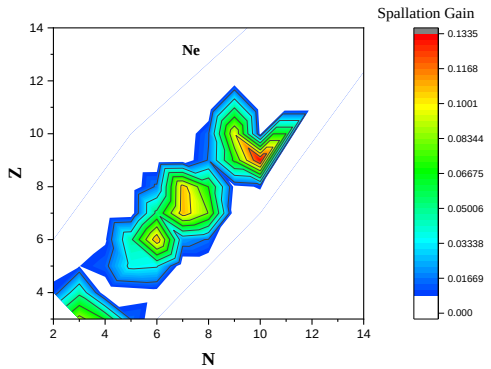

Figure 5. The spallation gains of isotope production in soft tissue without tumors by high-energy Ne ions

The radioactive elements produced in healthy soft tissue in ion therapy by Ne, C, Ar, and He with the spallation process were shown in Tables 3-6 which contain information about the radioactive elements produced in the soft tissue or ion nucleus with spallation process.

Tables 3 and 4 show that spallation in the soft tissue by Ne and C ions produces ^{10}Be and ^{14}C with a long half-life.

Table 3. The radioactive materials produced in healthy soft tissue without tumor by Ne Spallation

Element	Z	N	Decay mode	Half life
^{7}Be	4	3	ε	53.12d
^{10}Be	4	6	β^-	1.51E+6y
^{11}C	6	5	ε+β+	20.39m
^{14}C	6	8	β^-	5730y
^{13}N	7	6	$\varepsilon^+\beta^+$	9.965m
^{18}F	9	9	$\varepsilon^+\beta^+$	109.77m

Table 4. The radioactive materials produced in healthy soft tissue without tumor by C Spallation

Element	Z	N	Decay mode	Half life
^{7}Be	4	3	ε	53.12 d
^{10}Be	4	6	β-	1.51E+6 y
^{11}C	6	5	ε+β+	20.39 m
^{14}C	6	8	β-	5730 y
^{13}N	7	6	ε+β+	9.965 m
^{18}F	9	9	ε+b+	109.77 m
^{24}Ne	10	14	b-	3.38 m
^{30}P	15	15	ε+b+	2.498 m
^{34m}Cl	17	17	ε+β+, IT	32.00 m
^{37}Ar	18	19	ε	35.04 d
^{38}K	19	19	ε+b+	7.636 m

Table 5 shows that spallation in the soft tissue by Ar ions produces ^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl, ^{39}Ar, ^{40}K, ^{39}Ar, and ^{32}Si with a long half-life.

Table 6 shows that spallation in the soft tissue by He ions produces ^{10}Be, ^{14}C, ^{22}Na, ^{36}Cl with a long half-life.

Table 5. The radioactive materials produced in healthy soft tissue without tumor by Ar Spallation

Element	N	Z	Decay mode	Half life	Element	N	Z	Decay mode	Half life
^{7}Be	4	3	e	53.12 d	^{30}P	15	15	e+β+	2.498 m
^{10}Be	4	6	β-	1.51E+6 y	^{32}P	15	17	β-	14.262 d
^{11}C	6	5	e+β+	20.39 m	^{33}P	15	18	β-	25.34 d
^{14}C	6	8	β-	5730 y	^{35}S	16	19	β-	87.32 d
^{13}N	7	6	e+β+	9.965 m	^{37}S	16	21	β-	5.05 m
^{18}F	9	9	e+β+	109.77 m	^{38}S	16	22	β-	170.3 m
^{24}Ne	10	14	β-	3.38 m	^{34m}Cl	17	17	e+β+, IT	32.00 m
^{22}Na	11	11	e+β+	2.6019 y	^{36}Cl	17	19	β-, e+β+	3.01E+5 y
^{24}Na	11	13	β-	14.9590 h	^{38}Cl	17	21	β-	37.24 m
^{27}Mg	12	15	β-	9.458 m	^{39}Cl	17	22	β-	55.6 m
^{28}Mg	12	16	β-	20.91 h	^{40}Cl	17	23	β-	1.35 m
^{26}Al	13	13	e+β+	7.17E+5 y	^{37}Ar	18	19	e	35.04 d
^{28}Al	13	15	β-	2.2414 m	^{39}Ar	18	21	β-	269 y
^{29}Al	13	16	β-	6.56 m	^{38}K	19	19	e+β+	7.636 m
^{31}Si	14	17	β-	157.3 m	^{40}K	19	21	β-, e+β+	1.277E+9 y
^{32}Si	14	18	β-	150 y					

All radioisotopes produced by spallation with a long half-life remain the long-term radiation hazards to the body. If these radioisotopes enter the blood circulation system, they are excreted from the body or deposited in the stem cells of the bone marrow led to genetic mutations and changing the stem cells.

Table 6. The radioactive materials produced in healthy soft tissue without tumor by He Spallation

Element	Z	N	Decay mode	Half life
^{7}Be	4	3	ε	53.12 d
^{10}Be	4	6	β–	1.51E+6 y
^{11}C	6	5	ε+β+	20.39 m
^{14}C	6	8	β–	5730 y
^{13}N	7	6	ε+β+	9.965 m
^{18}F	9	9	ε+β+	109.77 m
^{22}Na	11	11	ε+β+	2.6019 y
^{31}Si	14	17	β–	157.3 m
^{30}P	15	15	ε+β+	2.498 m
^{32}P	15	17	β^-	14.262 d
^{36}Cl	17	19	$\beta^-\varepsilon+\beta^+$	3.01E+5 y
^{38}K	19	19	$\varepsilon+\beta^+$	7.636 m

4. Conclusion

Heavy ions are used to treat internal tumors. By using high-energy ions directly to treat internal tumors, healthy soft tissue is considered the most common tissue at risk. The results show that when Ne, C, Ar and He ions are used, the radioactive elements are produced with high gains. Neon and argon spallation have the highest isotope production gain in the soft tissue compared to other ions. Therefore, due to hazards of the secondary particle production in soft tissue, it is better that used the C and He ions for cancer treatment than others. Results of Tables 3-6 show that ^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl, ^{39}Ar, ^{40}K, ^{39}Ar, ^{32}Si, ^{22}Na, and ^{36}Cl radioactive elements were produced with long half-lives for high-energy heavy ion spallation in healthy soft tissue. These radioactive elements can enter the blood circulation system and can damage healthy body tissues. Therefore, in the treatment of cancerous tumors with high-energy ions, due to the production of radioactive agents, healthy tissues are at high risk.

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