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RESEARCH

Dose Analysis of Gadolinium Neutron Capture Therapy (GdNCT) on Cancer Using SHIELD-HIT12A

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ABSTRACT This research aimed to determine the dose of radiation received in cancer therapy for each decay of Gadolinium atomic nuclei with isotope 157 (^{157}Gd) in Gadolinium Neutron Capture Therapy using the SHIELD-HIT12A program. Knowing the amount of dose given to cancer tissue should aid in minimizing the damage that could occur in the healthy tissue around the cancer tissue, effectively killing only the cancer cells. The simulation employed in this research used the SHIELD-HIT12A program by providing input on beam.dat, mat.dat, detect.dat, and geo.dat files. The output data from the program comprised the value of recoil energy lost (energy absorbed into the target materials) for each of the ^{157}Gd atomic nuclei, which was then processed by the dose determination equation to determine the dose given by the ^{157}Gd nucleus to soft tissue. Based on the results, the amount of the dose given by each atomic nucleus ^{157}Gd to soft tissue was 5.44×10^{-11} Gy/decay.

1. INTRODUCTION

Cancer is a type of disease caused by abnormally expanding tissue cells, usually due to two main factors, namely external factors and internal factors. Cancer can be caused by external factors such as unhealthy lifestyle choices, including smoking, physical inactivity, and the consumption of carcinogenic foods, or viral or bacterial infections. Internal causes include genetic factors that result in mutations, hormones, or a weak immune system (American Cancer Society 2015). Based on data from the World Health Organization (WHO), in 2014, most cancer cases comprised lung cancer, breast cancer, and colorectal cancer. However, the highest number of cancer-related deaths stemmed from lung cancer, stomach cancer, and liver cancer. In women, breast cancer is the most prevalent form of cancer, while in men, prostate cancer is most common.

Various types of cancer treatment methods continue to evolve, from surgical methods to chemotherapy, and even to the exploitation of radiation from nuclear reactions, referred to as radiotherapy. In surgical methods, cancer tissue is removed during a surgical procedure. In chemotherapy, treatment encompasses giving drugs to kill cancer cells. In radiotherapy, patients who have cancer are injected with radioisotopes that will be irradiated by neutron rays. The resulting reaction will produce energy and various types of rays and particles that will be used to kill cancer cells (American Cancer Society 2015).

In radiotherapy, neutrons will be irradiated on cancer so as to minimize damage to other parts of the body (Capala et al. 2003). Neutron capture therapy (NCT) is a type of radiotherapy that utilizes neutrons as reagents. In the NCT methods, the neutrons will be sent to the tissue of cancer cells, which have previously been injected with stable nuclides. The nuclide will absorb the emitted neutrons so that the stable nuclide will turn into an unstable nuclide which will then emit energy and various particles that will kill the cancer cells (Enger et al. 2013).

Examples of radioisotopes used for NCT-based treatments include B-10 (Boron) and Gd-157 (Gadolinium) because they have a large cross-sectional number, making them more effective at capturing the thermal neutron (Hosmane et al. 2012). Several types of NCT-based radiotherapy currently being developed are boron neutron capture therapy (BNCT), a method used to kill cancer cells by utilizing neutron activation in stable 10B, and gadolinium neutron capture therapy (GdNCT) nuclei, which uses the same method as BNCT but relies on the activation of neutrons at stable atomic nucleus ^{157}Gd (Cember and Johnson 2009; Uusijärvi et al. 2006).

In a study conducted by Rosidah et al. (2017), the element used in the treatment of skin cancer was a Boron element with Boron-10 isotope that has a cross-section of 3840 Barns. The neutrons used in this case were thermal neutrons, as they are more effective for reacting or absorbtion by nuclei compared with epithermal neutrons (Carron 2007). In this study, the authors focused on the use of GdNCT in cancer treatment. The potential of cross-sectional on Gadolinium ^{157}Gd compared with Boron ^{10}B is greater. For σ ^{157}Gd is 255000 Barns and for σ ^{10}B only 3835 Barns (Sauerwein 2012). Gadolinium included in this type of rare earth metal, in the periodic table is located in the lanthanide group, is a solid metal at room temperature and is a liquid at 1313°C. Physically, Gadolinium is characterized as a silver, ferromagnetic metal, and is usually found in monazite minerals (Goorley 2002).

TABLE 1. Abundance of gadolinium isotopes and the amount of respective cross sections.

Stable isotope	Abundance (%)	Cross section (Barns)
152	0.20	700
154	2.18	60
155	14.80	61000
156	20.47	2
157	15.65	255000
158	24.80	2.41
160	21.86	1

The radiation dose shows how much damage occurs to a material when got irradiated by radiation. In radiation protection, the dose is the amount of radiation energy or the amount of energy contained in the radiation field (Alatas et al. 2014). While the measurement of how much radiation is caused and about a material called radiation dosimetry. The abundance of gadolinium isotopes in nature and amount of cross sections for ^{152}Gd, ^{154}Gd, ^{155}Gd, ^{156}Gd, ^{157}Gd, ^{158}Gd and ^{160}Gd according to Enger et al. (2013) are presented in Table 1.

In GdNCT, thermal neutrons will react with the Gadolinium ^{157}Gd nucleus to produce a particular reaction (Kulabdullaev et al. 2016) Figure 1. Electron auger, gamma rays, and the resulting energy will be used to kill cancer cells. Therefore, a simulation program is required that can be simulated the process. Various simulation programs are used for the modeling or determination of various radiation absorbent doses such as MCNP, MCNP5, MCNP6, GEANT4, or SHIELD-HIT12A. In this research, SHIELD-HIT12A is used as a running program because the research using this program is still rare. The SHIELD-HIT program is a program that can be used to simulate ion transport in a material. Ions are simulated even to heavy ions that can't be simulated on the MCNP program. The main part of SHIELD-HIT12A consists of four parts beam.dat, mat.dat, geo.dat, and detect.dat (Bassler et al. 2017).

2. MATERIALS AND METHODS

This research is a simulation to find out how much of the dose produced by each Gadolinium ^{157}Gd nuclei is absorbed in the tissue containing cancer cells. The research was conducted at the Accelerator Science and Technology Center of the National Nuclear Energy Agency of Indonesia (BATAN), Yogyakarta. The flowchart of the research is presented in Figure 2.

This research is limited to simulations of the doses of Gadolinium ^{157}Gd absorbed in tissues that contain cancer cells in general. As such, the type of cancer and cancer location is not detailed. The geometry of the cancer is made cylindrical with a radius is 10 cm and a cylinder height is 30 cm (standard geometry of SHIELD-HIT12A).

In the SHIELD-HIT12A program, the input data are written in a Notepad file which will be run via a command prompt. Basically, the SHIELD-HIT12A program used the Monte Carlo method on its process. Data in SHIELD-HIT12A for Gadolinium nuclei is different in the beam.dat file only, because for geometry and material target in this research is made same that is a cylinder with material from soft tissue. So the three files used in this research (namely geo.dat, mat.dat, and detect.dat) all have the same input data. The beam.dat file is the sole exception because Gadolinium has 7 stable isotopes which in this research is used as sample data to know dose value at each atom nucleus from the isotopes.

After the geometry form is described at the geo.dat section, then data on gadolinium ^{157}Gd and target material are specified at the beam.dat, mat.dat, and detect.dat parts. In this case, the target material used is soft tissue with the database already stored in the program SHIELD-HIT12A. After all, inputs are completed, the SHIELD-HIT12A program is running by the command prompt or the shieldhit.exe file can be used directly to obtain the recoil energy value generated on each decay of ^{157}Gd atomic nuclei. The next step is to determine the value resulting dose and that is absorbed by the target material due to the atomic nucleus of ^{157}Gd based on the absorption dose equation. Equation 1 is the general equation of dose absorption.

$$D = \frac{\Delta E}{\Delta m} \quad (1)$$

where D is the value of dose absorption, ΔE is the value of energy (Joule), and Δm is the mass of the target (kg). In the

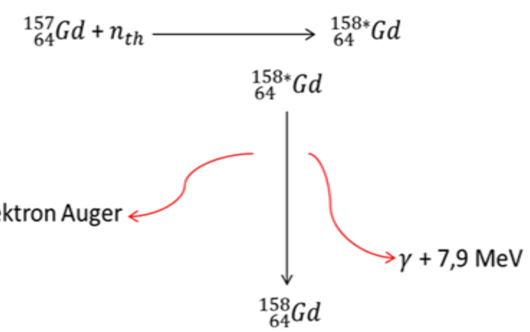

FIGURE 1. Neutron thermal and Gd-157 reaction.

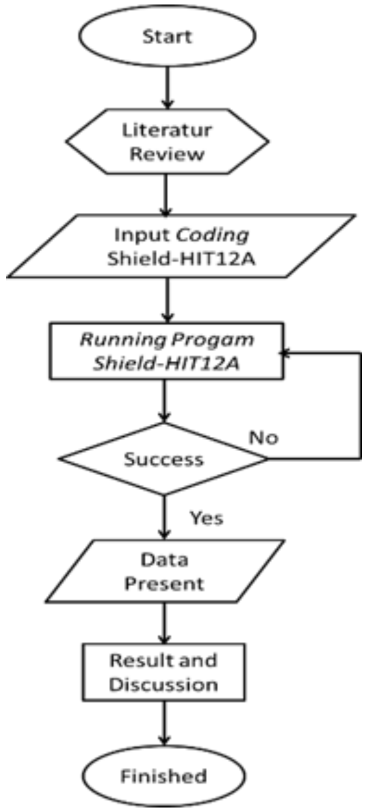

FIGURE 2. Flowchart of the research.

SHIELD-HIT12A program, the energy show on MeV units not on Joule units (Equation 2).

$$\dot{D} = \frac{\left(\frac{E_{\text{prog}}}{m_{\text{target}}} \times 1.609 \times 10^{-13}\right)}{\text{decay}} \qquad (2)$$

where $\dot{D}$ is the value of absorption dose per decay for each nucleus, E_{prog} is the energy from simulation and m_{target} is the mass of the target.

3. RESULTS AND DISCUSSION

This section describes the results and analysis of the simulation using SHIELD-HIT12A. The determination of Gadolinium dose as the ingredient for cancer therapy (GdNCT). The input code regarding the target material and the particles used as the beam particles is determined first in the SHIELD-HIT12A program. Furthermore, the energy value radiated by the Gadolinium nucleus absorbed by the target material is stored, then processed using by absorption dose equation to determine the value of the radiation dose given by each nucleus that decay to the target material.

The energy produced is energy when the Gadolinium atomic nucleus reacts with the thermal neutrons that occur in the target material. The energy will be absorbed by the target material for the next calculated the value of the adsorbent dose. The SHIELD-HIT12A program can be used to determine the total energy value result from the reaction. The result value is the amount of energy produced by the reaction of an atomic nucleus as a particle with a thermal neutron occurring in the target material with the unit MeV per decay. That means the energy produced is the energy for each atomic nucleus that reacts in MeV/decay unit. After running the SHIELD-HIT12A program, the output of the form of energy absorbed by the soft tissue as a result of the decay of the nucleus ^{157}Gd atom due to neutron activity will be obtained. In the SHIELD-HIT12A program, the output is only the total energy absorbed in the tissue containing the cancer cells. The energy γ, Auger electron energy are not shown or available. Table 2 is the absorbed energy for Gadolinium stable isotope based on SHIELD-HIT12A.

The energy absorbed in the tissue is 0.33984 MeV. This energy is the energy produced by a nucleus of a ^{157}Gd atom that absorbed by the target material, so the energy is still in MeV/decay unit. The energy converted into Joule units to obtain a value of absorbent dose because Gy is equivalent to Joule/kg. So the energy obtained:

$$E_{\text{d}} = 0.33984\,\text{MeV/decay} \times 1.602 \times 10^{-13}\,\text{Joule/MeV}$$
$$E_{\text{d}} = 5.44 \times 10^{-14}\,\text{Joule/decay}$$

where E_d is the energy per decay for each nucleus of ^{157}Gd. Then, we can determine the dose absorption each nucleus from Equation 2, so the result will be shown in Table 3.

After the energy for each nucleus ^{157}Gd is obtained, dose amount can be obtained as follows:

$$\dot{D} = 5.4443 \times 10^{-11}\,\text{Gy/decay}$$

where $\dot{D}$ is the resulting dose for a single nucleus of ^{157}Gd absorbed by the target material (Gy/decay).

TABLE 2. The energy of gadolinium isotopes.

Isotope (Gd)	Energy	
	(MeV/decay)	(Joule/decay)
152	0.23438	3.75×10^{-14}
154	0.75879	1.22×10^{-13}
155	0.10547	1.69×10^{-14}
156	0.32027	5.13×10^{-14}
157	0.33984	5.44×10^{-14}
158	0.31281	5.01×10^{-14}
160	0.38574	6.18×10^{-14}

TABLE 3. The doses of Gadolinium isotopes.

Isotope (Gd)	Dose (Gy/decay)
152	3.7546×10^{-11}
154	1.2155×10^{-10}
155	1.6896×10^{-11}
156	5.1307×10^{-11}
157	5.4443×10^{-11}
158	5.0112×10^{-11}
160	6.1795×10^{-11}

4. CONCLUSIONS

Based on research of the dose ^{157}Gd analysis of GdNCT for cancer therapy that has been done, it can be concluded that the result of the dose value is the resulting dose for each nucleus of Gadolinium, and that the result of dose value using the SHIELD-HIT12A program was 5.4443×10^{-11} Gy/decay for isotope ^{157}Gd.

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