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RESEARCH

Dosimetry of In Vivo Experiment for Lung Cancer Based on Boron Neutron Capture Therapy on Radial Piercing Beam Port Kartini Nuclear Reactor by MCNPX Simulation Method

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ABSTRACT Cancer is one of the leading causes of death globally, with lung cancer being among the most prevalent. Boron Neutron Capture Therapy (BNCT) is a cancer therapy method that uses the interaction between thermal neutrons and boron-10 which produces a decaying boron-11 particle and emits alpha, lithium 7 and gamma particles. A study was carried out to model an in vivo experiment of rat organisms that have lung cancer. Dimensions of a rat's body were used in Konijnenberg research. Modeling lung cancer type, non-small cell lung cancer, was used in Monte Carlo N Particle-X. Lung cancer was modeled with a spherical geometry consisting of 3 dimensions: PTV, GTV, and CTV. In this case, the neutron source was from the radial piercing beam port of Kartini Reactor, Yogyakarta. The variation of boron concentration was 20, 25, 30, 35, 40, and 40 µg/g cancer. The output of the MCNP calculation was neutron scattering dose, gamma-ray dose and neutron flux from the reactor. A neutron flux was used to calculate the alpha proton and gamma-ray dose from the interaction of tissue material and thermal neutrons. The total dose was calculated from a four-dose component in BNCT. The results showed that the dose rate will increase when the boron concentration is higher, whereas irradiating time will decrease.

1. INTRODUCTION

Cancer is the second leading cause of death globally (WHO 2017). According to WHO in 2015, cancer caused 8.8 million deaths (22%) from an estimated 40 million deaths (WHO 2017). In 2012, there were approximately 247 million people in Indonesia, and cancer caused 1.5 million deaths (WHO 2014). There are several common cancer cases: lung, heart, stomach, breast and colorectal. The lung tumors are one the most common causes of death for cancer in the world. (Farías et al. 2014).

Cancer is an abnormal cell that grows uncontrollably (Hejmadi 2010). This uncontrolled spread requires therapy to inhibit or eliminate cancer cells. A few types of cancer treatment there are chemotherapy, radiotherapy, and surgery (Benjamin 2014). Each method has its own risks, the method of surgery allows the emergence of advanced cancer (National Cancer Institute 2007). High dose radiation can help beneficial for cancer treatment, but the patient can get an increased risk of developing cancer again (American Association for Cancer Research 2012).

The one alternative method is boron neutron capture therapy (BNCT). BNCT irradiation is based on the nuclear and fission reactions that occur with B^{10} when unradioactive natural boron is radiated with low energy (0.025 eV) (Barth et al. 2012). The reaction produces ${}_2He^4$ particle and ${}_3Li^7$ with high low linear energy transfer (LET) (> 175 keV.µm^{-1}) and has short radiation range 4.5 until 10 µm, so the radiation interaction is limited to the cell (Burn et al. 2006). Formulae interaction of production LET alpha particles (^{4}He) and the recoiling of lithium-7 (^{7}Li) nuclei is shown in Figure 1.

This research used Kartini Reactor as a neutron source. Kartini Reactor was developed at BATAN in Yogyakarta, Indonesia. The Reactor has optimal thermal power at 100 kW with the other facilities for BNCT research within vivo and in vitro experiment. The vivo experiment is a test that uses organisms such animals, assuming that all tissue along with the body's constituent cells and enzymes present in the animal body have similarities to humans (Sauerwein 2012).

Mice have similar DNA organization and 98% gene expression with humans. Mice also have similarities to humans in the reproductive system, nervous system and have similar diseases (cancer, diabetes, and even anxiety). Protti et al. (2009) has studied the calculation of the distribution of doses in mice lung irradiated with thermal ducts at the

$$\left[{}^{10}_{5}B\right] + \left[{}^{1}_{0}n\right] \longrightarrow \left[{}^{11}_{5}B\right]^{*} \begin{cases} \rightarrow \left[{}^{4}_{2}He\right] + \left[{}^{7}_{3}Li\right] + 2.79\ MeV\ (6.1\%) \\ \rightarrow \left[{}^{4}_{2}He\right] + \left[{}^{7}_{3}Li\right]^{*} + 2.31\ MeV\ (93.9\%) \\ \qquad\qquad \rightarrow \left[{}^{7}_{3}Li\right] + \gamma\ (0.48\ MeV) \end{cases}$$

FIGURE 1. Interaction in BCT (Barth 2005).

TRIGA Reactor in Pavia. Calculations are displayed with MCNP. A mouse model was designed with MCNP geometry and is positioned in a box with a wall of lithium carbonate. The minimum time required to transmit 40 Gyw doses the tumor is at least 10 min.

2. MATERIALS AND METHODS

This study used Kartini Reactor as a neutron source and utilized a radial translucent beam port as a neutron beam distributor. Radial translucent beam port is a beam port that directly penetrates the reactor so that this beam port is bypassed by neutrons with the highest flux value compared to other channels.

The collimator used in this study is a collimator that has been designed by Ilma Muslih in 2013 as shown in Figure 2. The specification of this collimator consists of, a collimator wall with Ni material of 1.5 cm thick and 2 cm aperture. The moderator with material Al 1350 (99.5%) as thick as 15 cm. Gamma shield with Pb material 1 cm thick and Boron aluminum (Boral) as thick as 1.5 cm.

There are a few procedures to make a dose treatment in a vivo experiment. The first is design in vivo simulation BNCT with MCNP. The simulation consists of making the body's geometry, lungs and cancer residing in the lungs. Body size and lung of rats refers to Konijnenberg et al. (2004). The body of the mouse is designed with the form of a beam, while the lung of the mouse is designed with a simple sphere shape approach. There are three main volumes in radiotherapy planning. The first is position and extent of gross tumor is example what can be seen, palpated or imaged, this is known as the gross tumor volume (GTV), plus margin for sub-clinical disease spread which therefore cannot be fully imaged, clinical target volume (CTV) and the third volume, the planning target volume (PTV), allows for uncertainties in planning or treatment delivery. The difference between the three volumes is the mass, fraction, and volume. The mass portion of the tumor. GTV has a larger fraction mass of a tumor than PTV and CTV. The mass fraction used in the study refers to ICRU 23. The next method is the variation of boron concentration on a lung tumor. There are five boron concentrations: 20, 25, 30, 35, 'and 40 μg/g tumor.

The dose treatment calculation in BNCT consists of four components according to the interactions that occur in the body. The component is composed of a boron dose, gamma dose, proton dose, and a scattering neutron dose. The doses were calculated by MCNP and manual calculation. The output of MCNP was the neutron scattering dose, gamma-ray dose and the neutron flux from the reactor. The neutron dose and gamma-ray dose are used to calculate the other dose manually. Multiplication between the four component doses, with each weight factor, will produce the total dose rate (Equation 1).

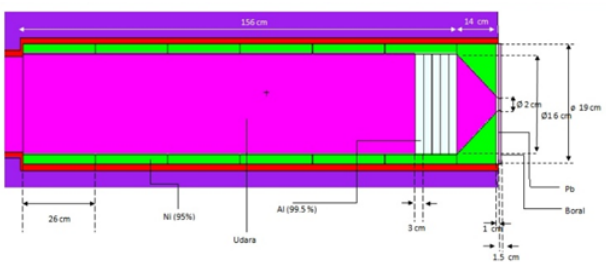

FIGURE 2. The design of collimator for radial piercing beam port of Kartini Reactor.

$$\dot{D}_T = w_B \dot{D}_B + w_P \dot{D}_P + w_\gamma \dot{D}_\gamma + w_f \dot{D}_f \quad (1)$$

The weight factor in each component refers to Bortolussi's research in 2004. Each component was different at the organ such as a tumor, skin, lung and healthy tissue.

The irradiation time is the time interval required when the dose received by cancer is sufficient (Equation 2). The minimum dose limit that can kill cancer cells is 50 Gy.

$$\text{Irradiation time} = \frac{\text{Minimal doses damaging cancer tissue}}{\text{Total dose rate}} \quad (2)$$

3. RESULTS AND DISCUSSION

This research used Kartini Reactor with radial piercing beam port as a neutron source designed by Ilma Muslih. The output of that value is the flux epithermal neutron, the ratio of fast neutron dose rate and flux neutron epithermal, the ratio of gamma dose rate and flux neutron epithermal, the ratio of thermal and epithermal flux, and the ratio between neutron current and flux neutron.

Figure 3 shows the model of dosimetry of in vivo experiment on lung cancer. Rats were used as the organism to be modeled. The body of rats is modeled with a beam geometry that has dimensions 25.8 cm long, 7.8 cm wide and 3.4 cm high. The dimensions refer to Konijnenberg's research for modeling rat's organs. In Figure 3, the body of rat shown as number 2. Lung, organ, and tumor were modeled with a spherical geometry. In Figure 3, there are four circles with a different radius of volume. The first spherical is lung geometry has a 1.75 cm radius of volume. The second is PTV with 1.5 cm radius, the fractions mass of that tissue is almost same with the lung organ. The third volume is CTV with 1 cm radius. The fractions mass of CTV tissue is almost the same as the tumor because there is still tumor infiltration from the tumor region. The fourth is GTV with 0.5 cm radius consisting of cancerous tissue.

The dose treatment calculation consists of a treatment calculation in BNCT consisting of four components according to the interaction that occurs in the body. The components are boron dose, gamma dose, proton dose and scattering neutron dose. The values of these components are shown in Table 1.

The gamma, boron, and proton doses were calculated manually. The flux of thermal neutron, a dose of neutron and dose of gamma result from MCNPX output. The gamma dose is the result of interactions between hydrogen and thermal neutron. Meanwhile, the proton dose is the result of interactions between nitrogen and thermal neutron.

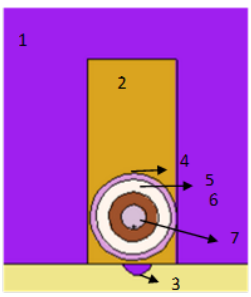

FIGURE 3. Simulation of dose treatment planning for lung tumor on rats: 1) irradiation room; 2) rat body; 3) aperture for source; 4) rat's lung; 5) PTV; 6) CTV; 7) GTV.

TABLE 1. Dose rate component for dosimetry of BNCT.

Concentration of boron (μg/g)	Neutron dose (10^{-6} Gy/s)	Gamma dose (10^{-6} Gy/s)	Boron dose (10^{-6} Gy/s)	Proton dose (10^{-6} Gy/s)
20	4356.18	7.87	1.882	7.468
25	4356.18	9.83	1.882	7.465
30	4356.18	11.8	1.881	7.462
35	4356.16	13.8	1.880	7.458
40	4356.10	15.7	1.879	7.455

Multiplication of four component doses with each weight factor component gave the result of total absorbed dose rate. Variations in boron concentration influenced the total absorbed dose rate. Figure 4 shows the correlation between absorbed dose rate and different boron concentrations.

The dose rate absorbed influenced irradiation time to destroy cancer cells. The irradiation time is obtained by ensuring the total dose received can kill cancer cells. The dose value that is needed to kill cancer cells is 50 Gy.

Figure 5 shows the correlation between boron concentration and irradiation time. Irradiation time destroys cancer cell range in 9 min. Irradiation time for cancer cells will decrease if boron concentration increases. Contrary to dose rate, what is absorbed will increase if boron concentration increases.

4. CONCLUSIONS

Based on the results of the dosimetry research of the in vivo experiment for lung cancer based on Boron Neutron Capture Therapy on the radial piercing beam port of Kartini Reactor, it can be concluded that boron concentration influenced the rate of absorption and irradiation time. The dose rate will increase when boron concentration increases. Contrarily, the irradiation time will decrease when boron concentration increases. The irradiation time's range to destroy the cancer cell is 9–10 min.

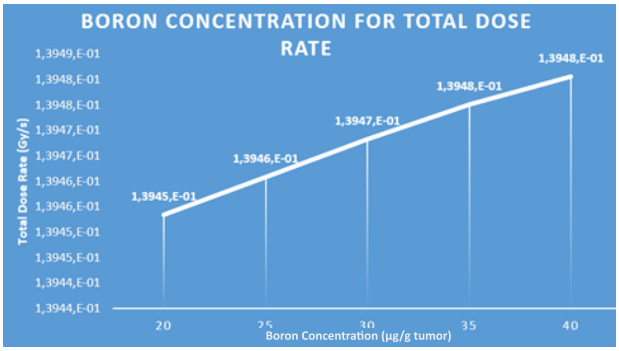

FIGURE 4. Correlation between boron concentration and total absorbed dose rate.

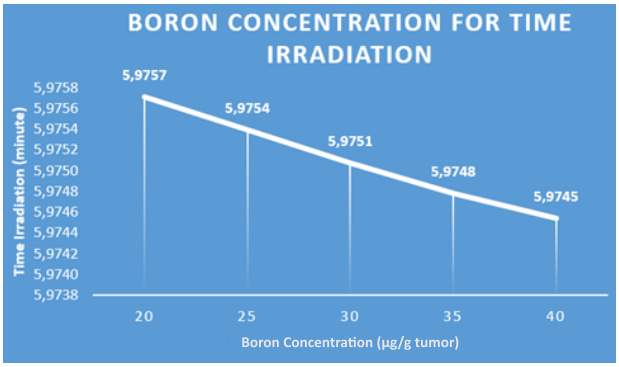

FIGURE 5. Correlation between boron concentration and irradiation time.

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