Radiation Dose Analysis in the Cervix Area by Cobalt-60 Irradiation Using the Monte Carlo Method

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Abstract. The scattering of radiation rays from Co-60 affects the absorbed dose received by cancer cells and healthy organs. Herein, we tried to investigate the distribution of absorbed dose with skin-to-source distance (SSD) variations inside the cervix area due to irradiation of Co-60 from different locations. As the SSD increased, the absorption dose rate decreased. However, the skin received a lower dose as the SSD is closer to the phantom due to the effect of the linear attenuation coefficient. Furthermore, we also tried to adopt two different treatment scenarios, resulting in an excess absorbed dose of 1.066 Gy in the first scenario and 0.663 Gy in the other one to the cancer cell. The total dose from each scenario to the minor tissue such as skin, blood, and hip bones was obtained with no significant difference observed. The result indicates that the treatment scenario would affect the absorbed dose produced during the treatment process.

Keywords: Cervical Cancer · MCNPX · Radiotherapy · Treatment Scenario

1 Introduction

Cancer is the second leading cause of death after cardiovascular disease. According to the International Agency for Research on Cancer (IARC), 8.2 million people died from cancer-related causes in 2012, and there were 14.1 million new cases, 64.9% of it classified as death from cancer. Cervical cancer is the second most common malignant tumor in developing countries [1]. Yogyakarta is an endemic area of cervical cancer, reaching 4.86 out of 1000 people. From the reports, the incidence of cervical cancer is increasing every year in several regions in Indonesia [2, 3].

Various cancer treatments have continued to develop, one of which is radiotherapy methods. Effective cancer treatment can help the patient's cure rate. Surgery is not always the best option to treat cervical cancer due to the location of the disease and the way it spreads. In order to kill cancer cells, radiotherapy, which uses high-energy particles or waves like X-rays, gamma rays, and electrons, is the treatment of choice for cervical cancer [7]. It uses ionizing radiation to kill as many cells as possible and create minimum damage to normal cells. The ability of high-energy radiation to ionize

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atoms and store their energy in the tissues of the cells it enters makes it a useful tool in radiotherapy. This radiation energy can destroy or harm cancer cells. The shape of the cervix is given in Fig. 1. When living tissue is exposed to ionizing radiation, its constituent atoms are immediately ionized and excited. Molecules containing these atoms tend to decay, creating what are known as free radicals which are unstable and react with other nearby molecules to spread chemical damage [12]. One crucial cellular component is deoxyribonucleic acid (DNA). DNA is also a part of cells that are susceptible to radiation damage. Radiation damage can result in the loss (or alteration of) some genes, so the loss of certain functions can be essential for survival. However, cells have evolved to withstand such damage. They have a powerful arsenal of advanced repair enzymes that continuously monitor DNA integrity, detecting and repairing the damage [8, 12].

Caesium-137 and Cobalt-60 are the most common radioactive sources used in radiotherapy. Both are emitting beta minus and gamma radiation as it decays into a more stable nuclide. Co-60 emits two main peaks of gamma radiation and has a high probability of gamma emission; thus, it can be an effective source to kill cancer cells. Additionally, Co-60 has a relatively long half-life of about 5.27 years, which is cost-effective for the use in medical industry.

Since high-energy radiation might be harmful to a living creature, it is necessary to do a simulation before executing a radiation treatment. The Monte Carlo method can be used to simulate the particle interaction within the material via random walk and the probability of interaction with atoms. Subsequently, the ionization which is occurred in the process can be approximated by calculating the total energy deposition inside the material. Several researchers have performed simulations using the Monte Carlo method to investigate the interaction of ionizing radiation for cancer cell treatment [5]. Besides, the total radiation dose should be examined not only to the cancer cells but also the dose received by healthy organs.

Previous research from Dortua H and Evi Setiawati has shown the effect of irradiation field shape on the absorbed dose in which they found that the dose value between square and rectangular fields is only slightly different, with the value of 0.04 up to 1.30 Gy [10]. They also showed the effect of the depth of irradiation on the absorbed dose [11]. However, the effects of radiation in a living cell can be controlled by adjusting the total

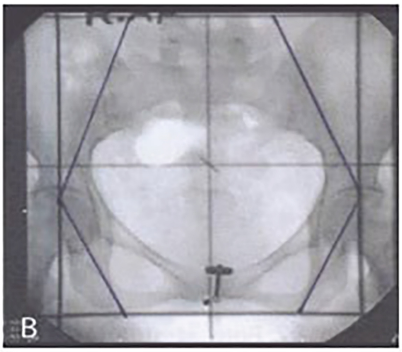


Fig. 1. Cervix Area [9]

dose received. The adjustment can be done by varying the distance from the source to the target, exposure time, and the exposure condition. The treatment plan is also indispensable in radiotherapy. The aim of a treatment plan is to give effective treatment to a patient, by maximizing the dose received in cancer cells and minimizing the side effects of radiotherapy, such as the damage to healthy tissues and organs which are located near the cancer cells.

In this study, we performed a simulation of radiotherapy by assessing the absorbed dose rate in the cervix area due to the Co-60 irradiation using the Monte Carlo N Particle X (MCNPX) program. The cervix area is represented by a phantom consisting of cancer cells, skin, blood, lower pelvic bone, and upper pelvic bones. Furthermore, the cancer cell in the cervix is divided into nine parts. The aim is to have the distribution of the radiation dose in cancer cells. The phantom is usually used as a substitute for the human body, to test the accuracy of the radiation dose received by the patients, thus the harmful effects can be avoided. The magnitude of the absorbed dose rate was determined by the amount of particle flux and energy absorbed in the cell that comes at each event. Several variations of SSD were used in this study, mainly to ensure that the target radiation beam's intensity and distribution were appropriate. We also tried to simulate the phantom using Co-60 sources located at two positions, above and below the phantom to investigate the distribution of radiation beam spread due to the addition of SSD values. Furthermore, we also evaluate the difference in deposition energy of each source location used.

2 Methodology

Radiotherapy is a method of cancer treatment that uses high-energy electromagnetic radiation or particle to kill the cancer cells with a specific amount of dose [7]. In this study, we source used activity of 8000 Ci which is assumed to have a high purity of Co-60. The two peaks of gamma emission from Co-60 are higher energy than Cs-137. Although it has a shorter lifetime, Co-60 gives the advantage to the specific activity over Cs-137. Co-60 decays into a stable nuclide of Nickel (Ni-60) which the decay scheme is shown in Fig. 2.

External beam treatment or teletherapy aims to treat the cancer cell by exposing it to high-energy radiation where the source is located outside the body of the patient.

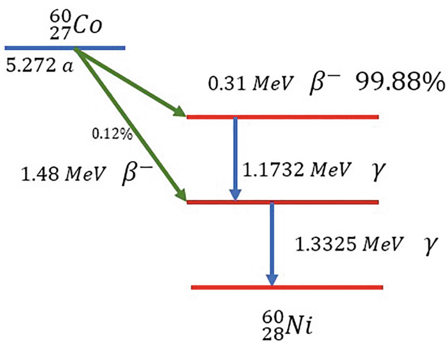


Fig. 2. The decay scheme of Co-60

Basically, when gamma radiation interacts with material, some of its kinetic energy will be transferred and causes the electrons to be ionized. For nearly 1 meV energy, most of the photons will undergo the Compton scattering effect instead of photoelectric. The ionization of atoms can cause damage to DNA via direct and indirect reactions, resulting in the collapse of living cells. Hence, the treatment may also affect other tissues inside the body since they were being exposed all along.

As illustrated in Fig. 3, the simulation attempted to give the radiation beam as precise as possible to the cancer cells. The SSD is then modified from 40, 60, 80, 100, and 120 cm. Furthermore, the location of the source is positioned above and below the target.

To calculate the amount of dose received in treatment, we could simulate the interaction of radiation to the target by using the Monte Carlo N-Particle X (MCNPX) program based on the Monte Carlo method. It also allows us to calculate the energy deposition in a specific cell such as a cancer cell, healthy organs, or tissues near the cancer, by implementing the tally number F6. By having the absorbed dose rate information, we could design a scenario for treatment by adjusting the time of exposure along with the SSD used in the treatment. The absorbed dose received in a specific cell is described by the formula as follows:

$$D = \frac{d\varepsilon}{dm} \tag{1}$$

where dε is energy and dm is mass [8]. The absorbed dose rate $\dot{D}$ is basically the absorbed dose in a cell per unit of time.

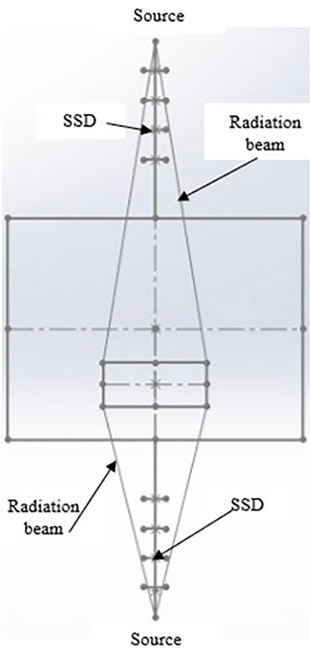
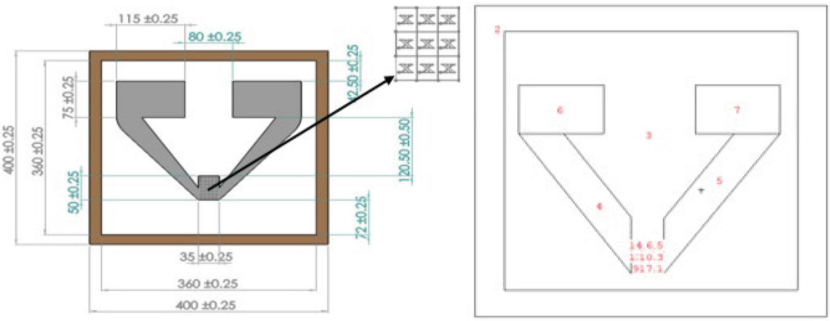


Fig. 3. The schematic diagram of the simulation with a variation of SSD and location.



(a) (b)

Fig. 4. (a) Design of phantom used in simulation (b) Cell view for MCNPX simulation

Figure 4 shows the design of the phantom which represents the cervix area and is divided into several parts. Cell number 2 and 3 are the skin and blood parts which has a density of 1.11 and 1.06 gr/cm^3, respectively. Cells number 4 to 7 represent the bones consisting of upper pelvic bones and lower pelvic bones. Each has a density of 1.85 gr/cm^3. The main part is the cancer cell, which is divided into 9 cells represented by numbers 9 to 17 and each has a density of 1.1 gr/cm^3.

3 Results and Discussions

The rate of the absorbed dose received by cancer cells was calculated from the energy deposition inside the particular cell. Figure 5 shows the photon and electron absorption dose rate curve from the source position above and below the phantom with 80 cm SSD. It is shown that electrons and photons from Co-60 which were exposed to the cancer cells are evenly distributed. A slight fluctuation may appear due to a stochastic particle interaction with air and other tissues. From Fig. 5(a), the absorbed dose rate of the photon as the source was located above the phantom varies from 0.00111 to 0.00117 Gy/s. However, as the source was positioned at the bottom, the absorbed dose rate increased more than 3 times to around 0.00360–0.00364 Gy/s.

As the irradiation was done from the bottom, the location of cervical cancer was closer to the source for the same SSD. Since the photon can undergo scattering, the air between the source and the phantom, and the healthy tissues such as skin, blood, and bones can give effect to the transmission of photon. The closer the source is to the phantom, the lower photon being absorbed and scattered due to the interaction of photons.

Figure 5(b) shows the absorbed dose rate for electrons inside the cancer cells. The electron absorbed dose rate was not very distinct compared to the photon. Interestingly, since the electron capability to penetrate the material is weaker than the photon, yet the dose received in the cells is still large. These electrons might not be originated from the source since some of the electrons will be deflected away or their energy has been reduced significantly due to the interaction with air and other tissues. However, there is a probability of photon interactions might produce secondary electrons due to

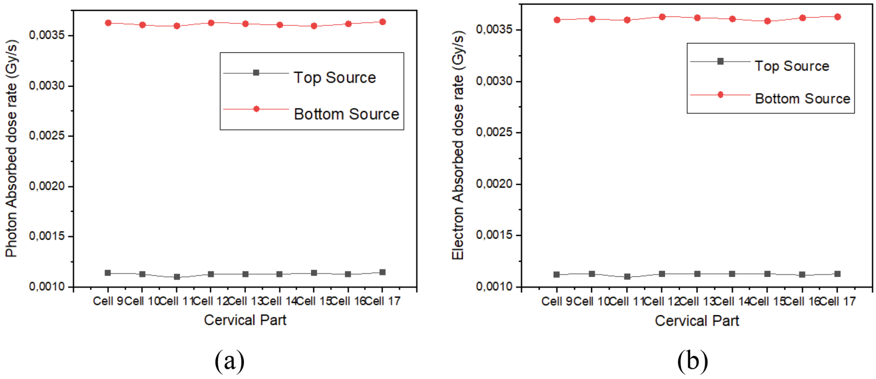


Fig. 5. Absorbed dose rate in cancer cells (a) photons, (b) electrons.

the orbital electron ionization and the Auger effect which the energy is sufficient to penetrate into the cancer cells [5]. Besides, the tertiary electrons can also be generated by the delta ray, which is a secondary electron that has enough energy to ionize other atoms. Similar results to the photon dose indicate that the secondary electron is the major cause. Therefore, the secondary electrons are proportional to the photon intensity. These effects can also damage the DNA of the rapidly growing cancer cells, which will eventually kill them.

Previously, Safitri et al. (2021) simulated the photon irradiation due to Co-60 using the Monte Carlo N-particle method with the ORNL MIRD phantom model and used a similar SSD (80 cm), which they obtained the absorbed dose rate of about 0.00907 Gy/s. It is not significantly different from the results of our simulation. Since the phantom model used in their simulation is much more complex, we could verify that our simplified version of the cervix area phantom is quite accurate.

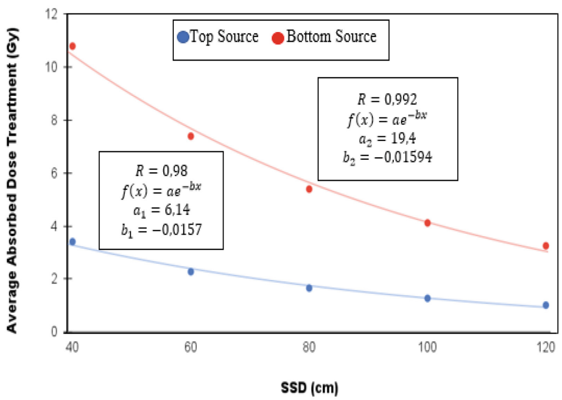


Fig. 6. Average photon absorbed dose in cervix area for 15 min treatment using ^{60}Co source with different source locations and variation in SSD

Figure 6 shows the relationship between the average absorbed dose of photon radiation and the SSD used in the simulation. An exponential decay model is used and fits well with the data. This indicates that the photon absorbed dose is affected mostly due to the attenuation effect [5, 7]. The fitting results show that the attenuation coefficient (b1 and b2) is not significantly different when the source is located above and below the phantom. Hence, the photon coming from the top has a similar experience with the bottom one, since it will pass through the same materials. However, the initial absorbed dose from the bottom source is 3.15 times higher than the top source. It shows that the location of the source plays a major role due to the difference in the incident kinetic energy of the particle.

However, the irradiation of Co-60 to the cervix area can also damage the healthy tissues as it will be exposed whether it is located in the central region, the penumbra, or the umbra according to the beam profile. Figure 7 shows the photon dose received by the healthy tissues for different locations of sources. Interestingly, the position of the source gives a similar profile to the photon-absorbed dose in the healthy tissues due to the irradiation of Co-60. The upper pelvic bone received the lowest dose, contrary to the lower pelvic bone which received the highest dose. We also obtained that most of the healthy tissues received a lower dose as the SSD is increased, except for the skin and the upper pelvic bones.

Subsequently, we tried to simulate two treatment scenarios which were fractioned into 30 parts with the variation of SSD. In accordance with the guidelines set forth by the Indonesian Ministry of Health, the minimum required dose to eliminate the cancer cell is about 45 Gy–50 Gy [3]. The treatment time for a fraction used in the scenario was about 15 min. From these two parameters, we designed two treatment scenarios and compared them to each other to find the optimum absorbed dose obtained by the cancer cells and minimize the dose received by the healthy tissues. In the first scenario, the SSD values consisting of 80, 100, and 120 cm were used, while in the second scenario, we added an additional SSD of 60 cm.

Figure 8 shows the accumulation of dose received by the cancer cells and the healthy tissues from two treatment scenarios. If we take the minimum 45 Gy radiation dose for

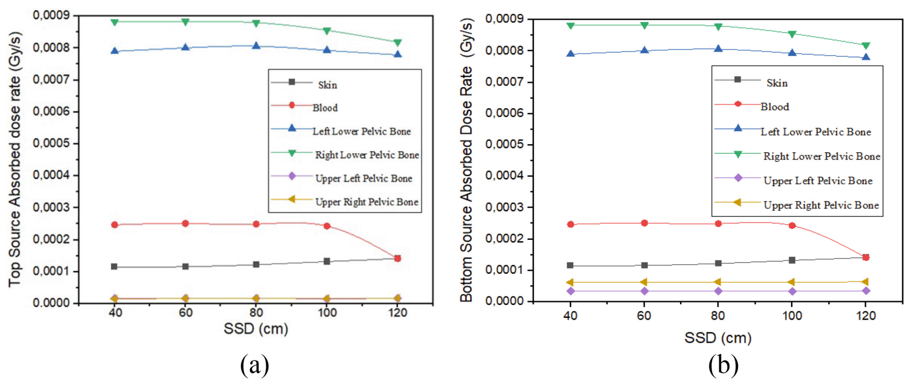
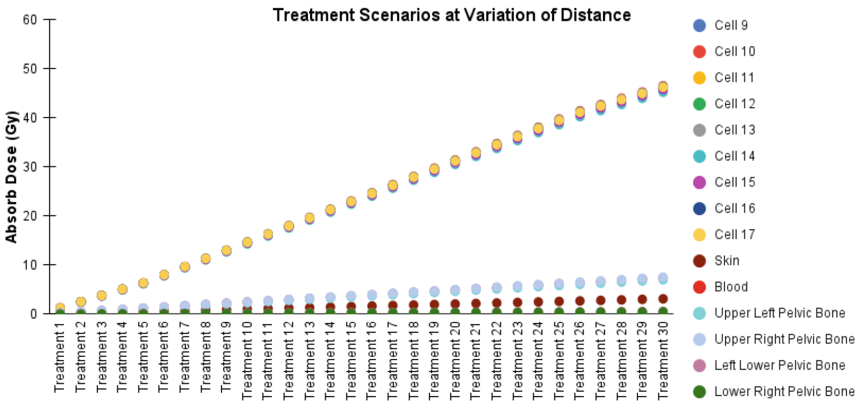
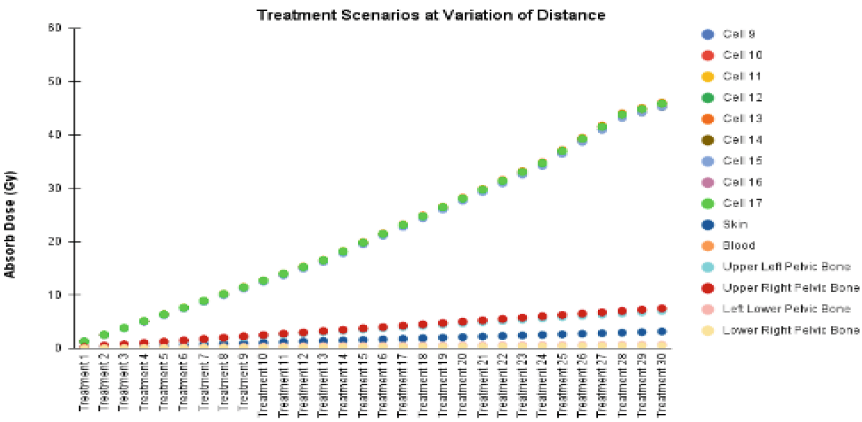


Fig. 7. Photon dose rate received by healthy tissues with different source locations (a) Top, (b) bottom.



(a)



(b)

Fig. 8. Accumulation of absorbed dose in cancer cells and healthy tissues with different treatment scenario (a) with 3 variations of SSD (b) with 4 variations of SSD

the cancer treatment, the excess dose received by the cancer cells in the first scenario is 1.0666 Gy, while in the second scenario is 0.6633 Gy. Nonetheless, the excess dose is still within the allowed range in the treatment of cervix cancer, in which the maximum is 50 Gy.

The total dose obtained for the healthy tissues from both treatment scenarios are listed in Table 1. As shown, the first scenario resulting a higher total dose in blood and both the pelvic bones, while the second scenario has a higher total dose in the skin and both the hip bones. However, both scenarios still have the potential to damage healthy organs. The biological dosimetry assessment of these tissues should be conducted to minimize the risk of side effects.

By looking at the distribution of radiation dose, we could design the treatment scenario based on the condition of the patient. For example, if there is an abnormality exists on the skin or hip bones of the patient, it is recommended to use the first scenario instead

Table 1. Accumulation of cancer cells and healthy tissues for scenario (a) 1 on 2 variations of SSD (b) 2 on 3 variations.

Tissues	**Total Dose**	
	1st scenario	**2nd scenario**
Skin	3.138 Gy	3.161 Gy
Blood	7.431 Gy	7.4064 Gy
Left lower pelvic bone	7.014 Gy	6.984 Gy
Right lower pelvic bone	7.554 Gy	7.4945 Gy
Right upper pelvic bone	0.5781 Gy	0.69295 Gy
Left upper pelvic bone	0.4722 Gy	0.4738 Gy

of the second one, to avoid further potential damage caused by radiation. For further research, it is possible to make a design to optimize the radiation dose based on variations in SSD and source position to get the optimum dose value.

4 Conclusion

The simulation of the radiation dose received by the cancer cells and healthy tissues in the cervix area due to the irradiation of the Co-60 source was done by using MCNPX. The cervix area is represented by the phantom and the source is positioned above and below the phantom. The radiation dose in the cancer cells is almost evenly distributed. The electron absorbed dose can still be observed due to the secondary electron interaction within the material and the level is nearly identical to the photon dose. The obtained absorbed dose rate is close to the reference.

As we evaluate the average absorbed treatment dose in relation to SSD, the exponential decay model fits well with the data. The fitting results of SSD variation in cancer cells to absorbed dose give nearly similar results for the value of b1 and b2, but the incident particle condition a_2 is much higher than a_1. The radiation dose is also received by the healthy tissues, which the lower pelvic bones experienced the highest value of absorbed dose rate. From the two treatment scenarios which were introduced using the variation of SSD, the excess radiation dose for the second scenario is lower. Furthermore, the first scenario is suitable to avoid damage to the lower pelvic bones and blood.

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