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Determination of absorbed dose of Palladium-103 radiation sources in prostate brachytherapy using the Monte Carlo method

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Abstract: Prostate cancer is one type of cancer that can be treated with the Brachytherapy Technique. Brachytherapy is a cancer therapy method by implanting radioactive nuclei through electromagnetic radiation from radioactive material placed near the tumor or cancer. The optimal number of implants of Palladium-103 radioactive source needs to be known to ensure the safety level before performing the therapy. The stages carried out in the research include modeling radiation sources and inhomogeneous phantoms around cancer, running the program, and processing the running data. The value of radiation absorbed dose based on the interaction of photons on organs can be obtained using the tally code *f8 in the MCNPX user code input. Based on the research results, the absorbed dose value received by each organ was successfully obtained. In addition, the variation of the implanted Palladium-103 radiation source had a significant effect on the increase of absorbed dose received by each organ. Sources were varied as 10, 11, 12, 13, 14, 15, and 16 sources, respectively. The greater the number of radiation sources implanted, the greater the absorbed dose value received by each organ.

Keywords: cancer treatment, absorbed dose, prostate brachytherapy, palladium-103, MCNPX.

1. Introduction

Cancer is a type of tumor that experiences abnormal growth in dividing to make new cells. Cancer cells have a very high rate of division but cancer cells have a low level of cell maturity. The level of cell maturity is the ability of the cell to carry out the complete and perfect functions of the living organelles in the cell. Prostate cancer is a type of cancer that can be treated with brachytherapy techniques (Song, 2021). Brachytherapy is a cancer therapy by implanting a radioactive nucleus through electromagnetic radiation from radioactive material placed near a tumor or cancer. The prostate brachytherapy technique can only be done in the early stages of cancer. The determination of safe doses for certain organs in brachytherapy is very important to note (Gaikwad, 2019; Effendi, 2019; Tekin, 2020; Akman, 2020; More, 2021). So far, the method used for determining the dose assumes that all radiation sources are located locally and ignores the relative effect of photons on the absorbed dose in the tumor. The possibility of placing a detector or so-called radiation apparatus and a radioactive substance on the body simultaneously is very unlikely because the body will receive a lot of radiation from the detector and radioactive substance, so a simulation is needed that can calculate the absorbed dose as accurately as possible (Effendi, 2022). Generally, the Monte Carlo method is used to define the dose distribution function, dose variation, and dose calculation of brachytherapy sources (Novak, 2019; Farmer, 2020; Tugrul, 2019; Paluotto, 2019). The prostate cancer brachytherapy technique currently uses 60% radioisotope Iodine-125 and 40% uses radioisotope Palladium-103 and only a few hospitals in Indonesia provide this type of treatment. The radioisotope Palladium-103 has a half-life of 16.9 days. According to the Pignol experiment (2005), the results of using Palladium-103 are relatively safe compared to using Iodine-125. The radioactive core is made in the form of tiny needles that are implanted in the body which are often known as seeds.

Closely related organs or Organs at Risk (OAR), namely the urinary bladder and rectum. The OAR will take into account the absorbed dose of radiation because the position of the bladder organ (urinary bladder) is attached to the top of the prostate and the rectum is next to the prostate. The absorbed dose results from the urinary bladder and rectum will be used as a comparison to the absorbed dose values in the prostate organ. Research on prostate brachytherapy has previously been carried out by Rianaris (2011) on determining the absorbed dose using a point-shaped Iodine-125 radiation source by varying the number of seeds. Another study was also conducted by Setiawan et al (2015) regarding the measurement of the absorbed dose of radioactive Palladium-103 single seed in prostate cancer brachytherapy with a radius of 2 cm by varying a certain distance measured around the implanted seed. The optimal absorbed dose value is 145 gray for Iodine-125 radiation sources and 125 gray for Palladium-103 radiation sources.

The brachytherapy simulation in this study used the Monte Carlo method with the MCNPX software to determine the effect of the absorbed dose on the prostate, urinary bladder, and rectum. MCNPX is one of the applications that can calculate the dose. MCNPX requires input in the form of ORNL-MIRD geometry (Oak Ridge National Laboratory – Medical Internal Radiation Dose), the definition of radioactive sources, the number of seeds implanted, and tally selection. After knowing the absorbed dose from the prostate, bladder, and rectum, a relationship between the number of seeds implanted and the absorbed dose was obtained in the form of a graph. The graph results can show the optimal number of seeds to be implanted in prostate brachytherapy. The value of the absorbed radiation dose produced and the number of implants used in this study can be used as a reference material as an initial estimate in conducting a treatment planning system (TPS).

2. Experimental methods

Determination of the absorbed dose using a Palladium-103 radiation source in prostate brachytherapy is carried out to find out how many absorbed doses are absorbed in the

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prostate and other organs. The absorption dose was determined by adding the number of implants which were varied, namely 10, 11, 12, 13, 14, 15, and 16 implants. The research steps are as follows.

1. Tools preparation,
2. Palladium-103 source modeling,
3. Modelling phantom inhomogeneous prostate, bladder, and rectum,
4. The addition of the number of sources of Palladium-103 in the prostate gland using transformation data on the implant,
5. Running programs using NPS with as much as 200,000,000 particles,
6. Unit conversion of energy absorbed by organs per transformation in units Gray.

2.1. Tools Preparation

The tools and materials used during the research were Personal Computer (PC) Windows OS (4 GB Ram, AMD A9-9420 Radeon R5 Processor), MCNPX Visual Editor software, notepad++, origin, Microsoft Office Excel, geometry source Palladium-103, basic components organ, and organ density obtained from an inhomogeneous reference phantom body of an adult male.

2.2. Simulation Creation

Simulating prostate, bladder, and rectum organs according to the data in an inhomogeneous phantom. The density, mass, and position of these organs are adjusted to the actual organs. The procedure for making the simulation includes three stages, namely, creating the geometry of the organ and seed, defining the radiation source and the position of the radiation source, and selecting the tally.

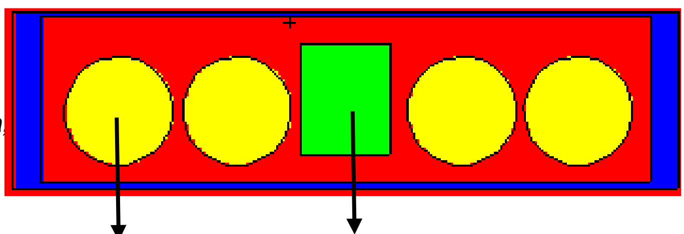
2.3. Calculation of Absorbed Dose

At the calculation stage, what is counted is how many absorbed doses are absorbed by the prostate, bladder, and rectum organs in the running time of 200,000,000 particles. The output from MCNPX is still in MeV units and then converted to Gray which is the SI of the absorbed dose.

3. Results and Discussion

3.1. The geometry of Palladium-103 Radiation Source

Palladium-103 is a radioactive source used in prostate cancer brachytherapy where one seed implant contains four radioactive sources. Palladium-103 is spherical with a density of 1.046 g/cm3. Each of the radioactive balls is 0.5 mm in diameter. The four balls are divided into two separated by X-ray markers. The X-ray marker is silver with a diameter of 0.5mm and a length of 1.25mm. The four Palladium-103 radioactive sources and X-ray markers are wrapped in 0.05 mm titanium with a diameter of 0.8 mm and a length of 4.5 mm (Sowards, 2007). The results of modeling the geometry of the sources are shown in Figure 1 below.



Palladium-103 X-ray marker

Figure 1. Geometry of Palladium-103 Radiation Source

The yellow color and the geometry in the image above are the active areas of the radiation source, the green color is the X-ray marker and the blue color is the source wrapping which is made of titanium. The radioactive source used is in the form of a cylindrical rod whose radiation spreads from the entire surface of the rod with discrete energies 0.20074 MeV, 0.10216 MeV, 0.22717 MeV, 0.23312 MeV, 0.39755 MeV, 0.06251 MeV, 0.29495 MeV, 0.35746 MeV, 0.497054 MeV. The use of this energy is adjusted to the energy spectrum of Palladium-1033 which emits gamma rays. Furthermore, Figure 2 shows the pattern of planting seeds in prostate cancer brachytherapy based on the Morton configuration reference. Where A is the prostate organ, B is prostate cancer, and numbers 1, 2, 3, …, n are radiation sources. The radiation source is placed inside the catheter or wire in a position with a distance of 5-10 mm between the radiation sources. The center of the image is not implanted with a radiation source due to a urinary tract which must be avoided so that the source is properly implanted in tissues that require radiation treatment. The placement or pattern of this Morton configuration corresponds to the pattern used in the BC Cancer Agency. This pattern is used as a starting point pattern for each planning modality (Morton, 2015).

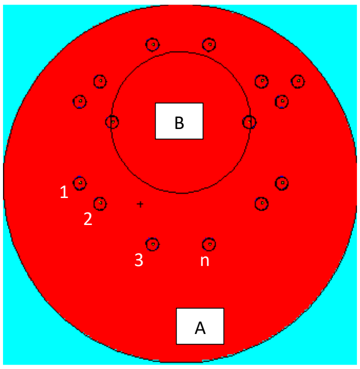
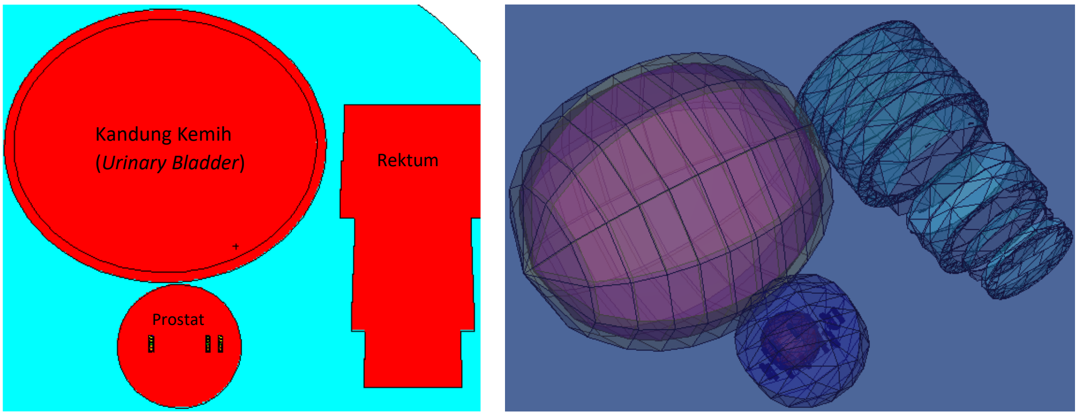


Figure 2. Source Position in x-y Coordinates

3.2. Inhomogeneous Phantom Geometry

The geometric model of the prostate, bladder (Urinary Bladder), and rectum cancer refers to the ORNL phantom geometry with a mathematical analysis of dose by the MIRD committee. The geometry model can be displayed using running Vised in both 2D and 3D. Bladder and rectum are organs at risk because these two organs are located adjacent to organs affected by cancer cells as part of the therapy plan. The construction of the bladder organ which consists of the bladder wall and bladder contents is modeled with an elliptical geometry in 3D. The position of the bladder contents is inside the bladder wall with a volume of 38.46 cc for the bladder wall and 96.15 cc for the bladder contents. The prostate organ is modeled as a ball with a volume of 72.5cc while the rectum organ is modeled by combining 15 cylinders to form a spiral with a volume of 19.23cc. Cancer cells are modeled as small balls with a radius of 1 cm and are located in the prostate organ. The modeling of these organs can be seen with 2D and 3D visualization as shown in Figure 3.



(a) (b)

Figure 3. Prostate cancer area modeling (a) modeling in two dimensions (b) modeling in three dimensions

The prostate gland in this study was modeled in the form of a ball with a radius of 2.2 cm. The prostate gland is at position 0.5 0.25 -0.05 and is modeled using the S surface card. The S surface card is a surface card in the MCNPX user code that is used to model organs in the shape of a solid ball with a center point x y z. To check the suitability of the simulation results refers to organ volume (Lazarine, 2006).

The bladder organ which consists of the bladder wall and bladder contents is modeled using the SQ surface card which is used to model the organ in the form of an ellipsoid. An ellipsoid is a closed quadratic surface which is the three-dimensional analog of an ellipse. The rectum organ is modeled using a C/Z surface card which shows that the surface is a cylinder parallel to the Z axis with the input center point being on the x and y axes. Meanwhile, for cutting cylinders, the surface type PZ is used. The PZ surface type is a surface type that indicates the line intersecting the z-axis. The density of each material or organ in this study refers to Lazarine's thesis, where each soft tissue has a density of 1.04 g/cc (Lazarine, 2006).

3.3. The absorbed dose of radiation to the prostate gland and surrounding organs

The main objective in making this simulation is to calculate the absorbed dose and analyze the results obtained. In determining the results of calculating the absorbed dose of radiation in brachytherapy for prostate cancer and surrounding organs using MCNPX, input is required in the form of tally data input. The tally used in the study is the *F8 tally which gives results after the running process is carried out, namely the distribution of deposition energy per transformation (MeV/Trans) for each organ when the radiation source is implanted (Rianaris, 2011). The radiation source in this study was Palladium-103. Palladium-103 will decay until its activity is exhausted. Therefore, the total number of transformations that will occur in seeds that exceed the half-life of the radionuclide must be calculated.

After the total transformation number is calculated, the next step is to multiply the total transformation number by the energy absorbed per transformation (MeV/Trans). To determine the absorbed dose of radiation per organ mass, the MeV unit must be converted to Gray units.

$$1\frac{MeV}{g} = 10^6 \, x \, 1{,}602 \, x \, 10^{-19} \frac{J}{10^{-3} Kg} \quad (1)$$

The output results in the form of deposition energy or energy absorbed per organ transformation can be seen in Table 1 below.

Table 1. MCNPX simulation running results

No.	Number of Implants	Energy (MeV/Trans)			
		Prostate (10^{-3})	Bladder wall (10^{-4})	Bladder Content (10^{-3})	Rectum (10^{-4})
1	10	6.57	7.13	2.64	6.40
2	11	6.63	7.15	2.64	6.20
3	12	6.59	7.16	2.64	6.08
4	13	6.41	7.13	2.64	6.30
5	14	6.60	7.12	2.63	6.50
6	15	6.02	7.09	2.62	6.69
7	16	6.54	7.06	2.61	6.83

Then, Table 2 shows the absorbed dose in the prostate, the bladder wall, bladder contents, and the rectum.

Table 2. Gray Radiation Absorption Dose for Each Organ in Gray Units

No.	Number of Implants	Absorbed Dose (Gy)			
		Prostate	Bladder wall	Bladder Content	Rectum
1	10	12.54	2.06	3.82	4.65
2	11	13.89	2.84	4.20	4.95
3	12	15.05	3.10	4.59	5.27
4	13	15.95	3.35	4.96	5.92
5	14	17.68	3.61	5.33	6.58
6	15	18.67	3.84	5.68	7.25
7	16	19.92	4.07	6.05	7.89

It can be seen that the absorbed dose in the prostate is greater than the bladder wall, bladder contents, and the rectum. The difference in the value of the absorbed dose in each organ is because the placement of a radioactive source in the prostate will cause a much greater distribution of energy in the prostate to be absorbed by the prostate organ. Calculation of the absorbed dose to the prostate, bladder wall, bladder contents, and rectum in this study was carried out to compare the absorbed dose value which is useful to provide information that the organs around the organs affected by cancer are relatively safer against the side effects of brachytherapy (Rianaris, 2011). An overview of the pattern of changes in absorbed dose caused by the number of implants is shown in Figure 4 below.

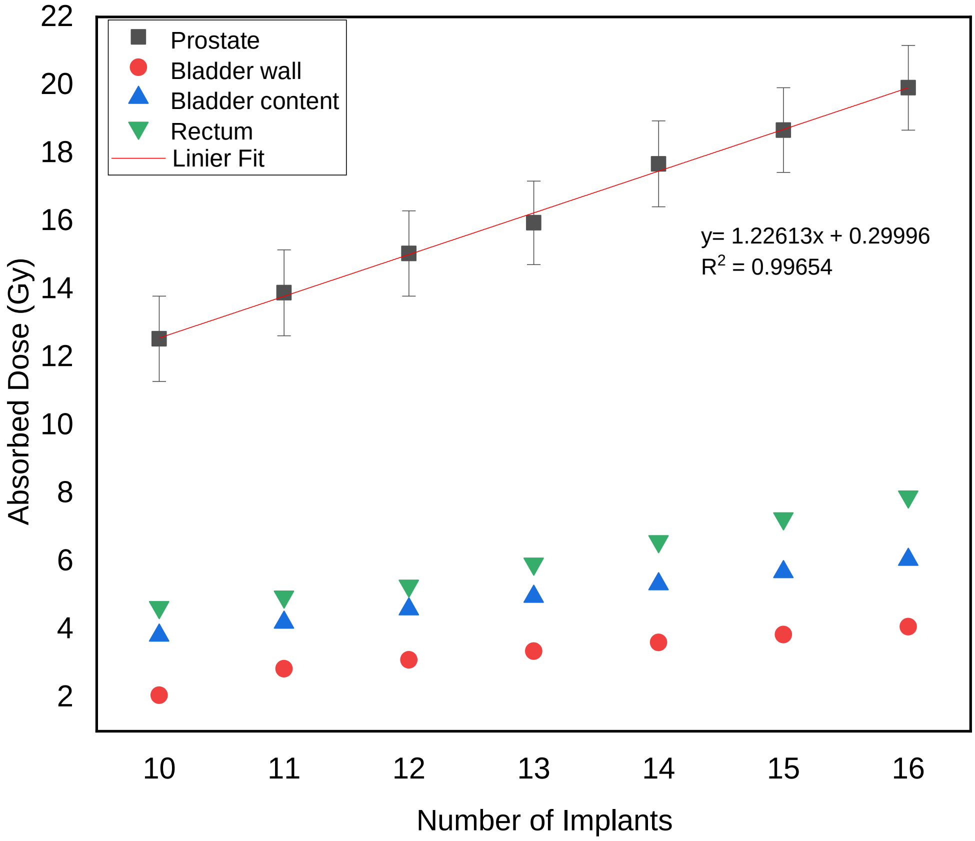


Figure 4. The relationship between absorbed dose and the number of implants in each organ

Figure 4 shows that the greater the number of implants used in the simulation, the greater the absorbed dose. It can be interpreted that the number of implants affects the photon decay every second. In this figure, the graph is a graph with a linear trendline model that has a line equation:

$$y = 1.22613x + 0.29996 \tag{2}$$

The equation above describes the absorbed dose value function and the number of implants used in the target treatment with y as the absorbed radiation dose variable whose value depends on the x variable which indicates the number of implants. The R2 value is used to determine the percentage change in the dependent variable (Y) caused by the independent variable (X) (Sujarweni, 2015), based on the trendline in Figure 4.9 the R2 value is 0.99654 or equal to 99.654% which indicates that the number of implants affects the absorbed dose of 99.654%. While the remaining 0.346% is influenced by other factors such as the distance between implants.

The total radioactive activity is affected by the variation in the number of implants used, the variation in the number of implants in the research was carried out to vary the total activity used in the simulation. The more implants used, the greater the total activity value and the greater the absorbed dose value for each organ that is calculated. From the research results, the absorbed dose value produced and the number of implants used can be used as reference material as an initial estimate in carrying out a treatment planning system.

4. Conclusion

Based on the results of a brachytherapy simulation on the prostate using a Palladium-103 radiation source with the monte carlo method, it is obtaining the following conclusions. The Geometry modeling of Palladium-103 radionuclide and the human body around cancer-affected organs has been successfully modeled and simulated radiation of Palladium-103 radionuclide on organs. Then, the absorbed dose of radiation to the organs has a much greater value compared to the surrounding organs and is relatively safer because the organs that are near the prostate organ get an absorbed dose value of less than 75% of the dose received. Further, the greater the number of implanted radiation sources, the greater the total activity value, and the absorbed dose received by the organs will also be greater. Additionally, the optimal number of implants in this study is 101 implants which have an absorbed dose of 124.14 gray. Therapy is carried out in 19-20 fractions with 0.06 Gy per fraction in one day.

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References

Akman. F., Ogul, H., Kaçal, M. R., Polat, H., Dilsiz, K. and Turhan. M. F. (2020), “Impact of lead(II) iodide on radiation shielding properties of polyester composites,” Appl. Phys. A Mater. Sci. Process., vol. 126, no. 4, pp. 1–9.

Effendi, M., Fatimah, R. U., Sholeh, A., and Fatchurohmah, W., (2019), “Design of the aluminum compensating filter to improve the image quality in the lateral projection of lumbosacral vertebrae,” AIP Conf. Proc., vol. 2094, no. April.

Effendi, M., Anindhita, T., Fatchurohmah, W., and Sholeh, A., (2022), “The effects of the operating voltage and source image distance of X-ray device on the absorption dosage and the improvement of the image for abdomen object,” AIP Conf. Proc., vol. 2391, no. March.

Farmer, J., and Roy, S., (2020), “A quasi-Monte Carlo solver for thermal radiation in participating media: A QMC solver for thermal radiation in participating media,” J. Quant. Spectrosc. Radiat. Transf., vol. 242, p. 106753.

Gaikwad, D.K., et al. (2019), “Physical, structural, optical investigation and shielding features of tungsten bismuth tellurite based glasses,” J. Non. Cryst. Solids, vol. 503–504, no. July, pp. 158–168.

Lazarine, D. A. (2006). Medical Physics Calculations With MCNPTM: A Primer. Texas: Texas A&M University.

More, C. V., Alsayed, Z., Badawi, M.S., Thabet, A. A., and Pawar, P. P. (2021), Polymeric composite materials for radiation shielding: a review, vol. 19, no. 3. Springer International Publishing.

Morton. (2015). Prostate high-doe-rate brachytherapy, transrectal ultrasound-based planning. 5-40.

Novák, J., Georgiev, I., Hanika, J., and Jarosz, W., (2018), "Monte Carlo methods for volumetric light transport simulation," Comput. Graph. Forum, vol. 37, no. 2, pp. 551–576.

Palluotto, L., Dumont, N., Rodrigues, P.. Gicquel, O., and Vicquelin, R., (2019), "Assessment of randomized Quasi-Monte Carlo method efficiency in radiative heat transfer simulations," J. Quant. Spectrosc. Radiat. Transf., vol. 236, p. 106570, 2019.

Rianaris, A. (2011). Simulasi Penentuan Dosis Serapan Pada Brachytherapy Prostat Menggunakan Software MCNP5. Surakarta: Universitas Negeri Surakarta.

Setiawan, P., Suharyana, & Riyatun. (2015). Simulasi Pengukuran Dosis Serap Pada Brachytherapy Prostat Berjari-Jari 2 CM Menggunakan Software MCNP5 Dengan Model Seed Implant ISOAID ADVANTAGETM IAPD-103A. Jurnal Fisika, 82-85.

Song, C.W., et al. (2021), "Biological Principles of Stereotactic Body Radiation Therapy (SBRT) and Stereotactic Radiation Surgery (SRS): Indirect Cell Death," Int. J. Radiat. Oncol. Biol. Phys., vol. 110, no. 1, pp. 21–34.

Sowards, K. (2007). Monte Carlo Dosimetric Characterization of the IsoAid ADVANTAGE 103Pd Brachytherapy Source. J.Appl.CLin.Med phys, 18-25.

Sujarweni, V. W. (2015). Metodologi Penelitian Bisnis Dan Ekonomi. Yogyakarta: Pustaka Baru Press.

Tekin, H.O., et al., (2020), "Sodium dodecatungs to phosphate hydrate-filled polymer composites for nuclear radiation shielding," Mater. Chem. Phys., vol. 256, no. July, p. 123667.

Tuğrul, T., and Eroğul, O., (2019), "Determination of initial electron parameters by means of Monte Carlo simulations for the Siemens Artiste Linac 6 MV photon beam," Reports Pract. Oncol. Radiother., vol. 24, no. 4, pp. 331–337.