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Original Article

The Effect of Scattering from Leg Region on Organ Doses in Prostate Brachytherapy for ^{103}Pd, ^{125}I and ^{131}Cs Seeds

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Abstract

Introduction
Dose calculation of tumor and surrounding tissues is essential during prostate brachytherapy. Three radioisotopes, namely, ^{125}I, ^{103}Pd, and ^{131}Cs, are extensively used in this method. In this study, we aimed to calculate the received doses by the prostate and critical organs using the aforementioned radioactive seeds and to investigate the effect of scattering contribution for the legs on dose calculations.

Materials and Methods
The doses to organs of interest were calculated using MCNPX code and ORNL (Oak Ridge National Laboratory) phantom.

Results
Doses to the prostate as a source of radiation for ^{125}I, ^{103}Pd, and ^{131}Cs were approximately 108.9, 97.7, and 81.5 Gy, respectively. Bladder, sigmoid colon, and testes received higher doses than other organs due to proximity to the prostate. Differences between the doses when tallying with the legs intact and with the legs voided were significant for testes, sigmoid colon contents, and sigmoid colon wall because of their proximity to the prostate. There was also a good consistency between our results and the data published by Montefiore Medical Center and Albert Einstein College of Medicine for the prostate.

Conclusion
Scattering from leg region had a significant effect on doses to testes, sigmoid colon contents, and sigmoid colon wall in the pelvic region, and prostate and the other organs were unaffected. Brachytherapy treatment plans using ^{131}Cs seeds allow for better sparing of critical tissues, with a comparable number of, or fewer, seeds required, compared to ^{125}I seeds.

Keywords: Brachytherapy, Monte Carlo, Prostate, Scattering, Phantom

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1. Introduction

Brachytherapy is an effective method for elimination of cancer cells and preventing cancer recurrence in comparison to other modes of treatment, namely, surgery and external beam therapy [1]. Besides, prolonging the lives of patients and bringing them back to normal life are the long-term benefits of this therapeutic method. Although there are considerable advantages for this treatment, a series of issues such as side effects and protection of adjacent organs against radiation must be considered.

In brachytherapy, the radioactive seeds are placed near or in contact with a target volume (tumor) so that a very high radiation dose can be delivered locally with rapid dose fall-off in the surrounding healthy tissues [2,3]. Brachytherapy is often used to treat diseases such as prostate, head and neck cancers.

Radium has been used in intracavitary prostate brachytherapy for years [4]; however, with the advent of the nuclear reactor, numerous artificial radioisotopes have become available, which offer important advantages such as appropriate gamma-ray energy and half-life, source flexibility, and source size under some circumstances [2]. Currently, isotopes such as ^{125}I, ^{103}Pd, and ^{131}Cs are applied in prostate brachytherapy. These seeds with different half-lives offer the advantages of low energy with rapid dose fall-off to minimize doses to the surrounding tissues [5].

Several studies were performed on prostate brachytherapy. Wuu et al. offered dosimetric and volumetric criteria to select a source type (^{125}I or ^{103}Pd) and activity in the presence of irregular seed placement in permanent prostate implants [6]. Beyer et al. evaluated dose distribution with various commercially available ^{125}I sources during prostate brachytherapy. It was observed that peripheral dose at or near the prescription dose was 145 Gy [7]. In 2003, delivered doses through ^{125}I and ^{103}Pd were calculated for prostate and other organs using MCNP4C while patients were undergoing prostate brachytherapy. The doses were in the range above 100 Gy for both nuclides [1]. Peschel et al. evaluated the clinical outcomes and compared complication rates for patients with prostate cancer treated with ^{125}I and ^{103}Pd. It was observed that the clinical outcome for patients treated with either radionuclide was similar with respect to biochemical disease-free survival [8]. Herstein et al. compared ^{125}I and ^{103}Pd for low-risk prostate cancer. They noted that patients treated with ^{103}Pd recovered from their radiation-related symptoms sooner than ^{125}I because palladium has shorter half-life [9]. In 2006, dose calculation was conducted for prostate brachytherapy using ^{125}I radioactive seeds, and the effect of scattering from legs on dose values was studied [10]. Yang et al. systematically analyzed and compared the dosimetric parameters of ^{125}I, ^{103}Pd, and ^{131}Cs for prostate brachytherapy. It was revealed that ^{131}Cs allows for better dose homogeneity [11]. Moreover, Kehwar mentioned the advantages of ^{131}Cs radioactive seeds in prostate permanent implants [12]. In 2010, the changes in radiation exposure due to prostate displacement in permanent prostate brachytherapy were calculated using MCNP4C and MCNPX. The obtained results exhibited a negligible change in radiation exposure around patient due to prostate displacement after bladder filling [13]. In 2011, isodose curves of the prostate were determined for the treatment of brachytherapy using MCNPX for 79 ^{125}I seeds using MAX voxel phantom [14].

In the mid-1960's, Fisher and Snyder developed a mathematical phantom representing an adult human at Oak Ridge National Laboratory (ORNL) with 22 internal organs and more than 100 sub-regions [15-17]. The disadvantage of this phantom was that the volumes, shapes, and positions of the internal organs were determined by the scaling factors and was not realistic for a particular organ. Another drawback was that the distribution of active bone marrow was not accurately described [16]. In 1987, Cristy and Eckerman developed a series of phantoms representing adult men and children of different ages. These phantoms followed the format of Snyder and Cristy [17,18]. Eckerman revised the head region to include a neck, esophagus, and extra thoracic airways [18].

Dose calculation in prostate brachytherapy using MCNP4C and evaluation of the effects of scattering from legs for just ^{125}I radioactive seeds have already been performed [10]. In this study, ^{125}I seeds with different activity from the study by Lazarine [10] and two other common radioactive seeds were considered and the simulation was conducted using MCNPX. Besides, a comparison was made between the obtained results and data published by previous studies [10] carried out at Montefiore Medical Center and Albert Einstein College of Medicine [5].

2. Materials and Methods

2.1. MCNP Code

Direct measurement of dose distribution in patients is clinically impossible during brachytherapy; thus, Monte Carlo simulation is applied as an alternative method for dosimetry calculations. Moreover, it is a useful tool in calculating the quantities of interest in complex geometries. In this study, doses to the internal organs were determined using MCNPX code.

During the simulation, the photon transport was considered (*mode p*). Because of the low energies involved in this study, electrons were not transported [1, 18]. The deposited energy in organs of interest was calculated using tally *F8. The number of histories was considered to be 5e7. Six codes were created to simulate the brachytherapy. Radioactive seeds were defined as point sources and distributed at various positions inside the volume of the prostate gland. The seeds were placed peripherally so that they can be external to the prostatic urethra. Specifications of radioactive seeds used in the simulation are represented in Table 1. Two-dimensional seed implants on prostate are shown in Figures 1 and 2. In these figures, different retractions of the needle placements are shown. These retractions are the depths from the prostate surface where the seeds are implanted. The numbers in the Figure depict the number of seeds in each needle. This arrangement was chosen so that the entire prostate can be irradiated and the dose outside the surface of the gland is restricted.

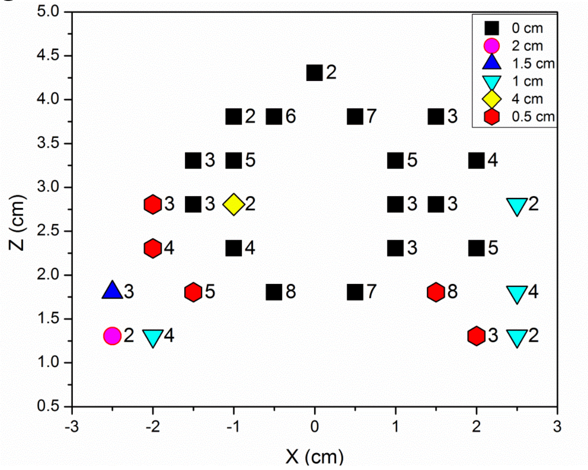

Figure 1. Seed placement in prostate cross-section for ^{103}Pd seeds

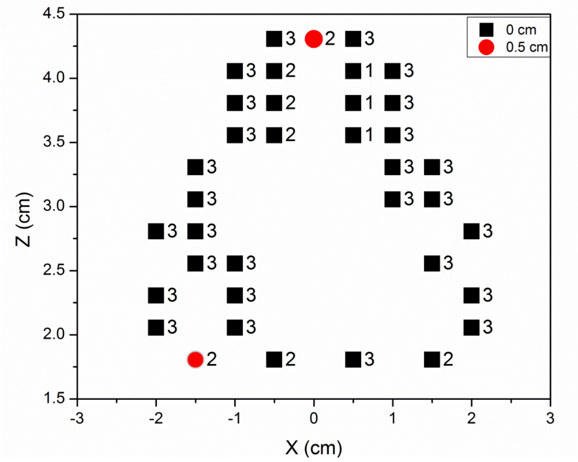

Figure 2. Seed placement in prostate cross section for either ^{125}I or ^{131}Cs seeds

Table1. Isotope characteristics

Isotope	Half-life (Days)	Energy (keV)	Number of seeds in simulation [1]	Activity per seed (mCi)
^{103}Pd	17.0	21	115	0.7
^{125}I	59.4	35.49	98	0.2
^{131}Cs	9.7	29	98	0.7

2.2. ORNL Phantom

The ORNL phantom was used as the geometric basis for simulation. The prostate was not originally included in the phantom; thus, it was added to phantom through the analytical process. The prostate was regarded as a soft tissue and considered as a sphere of radius 2.2 cm under the bladder and centered at (0, -6.0025, 2.505) [19]. This size of the prostate was considered to prevent overlapping with the bladder. Different organs at risk (i.e., small intestine, descending colon contents and wall, sigmoid colon contents and wall, testes, urinary, and prostate) were considered [1, 20,21]. A lateral cross-section of the modified phantom (including prostate) is presented in Figure 3.

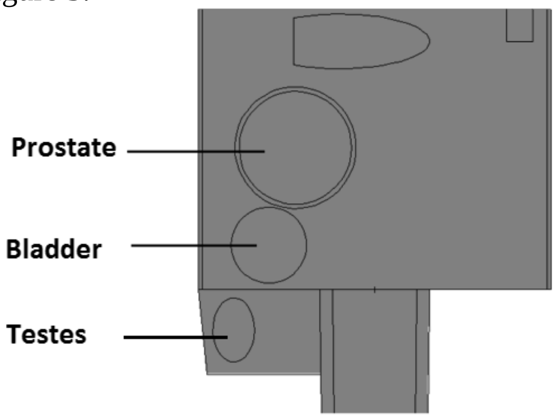

Figure 3. Lateral view of the pelvic region and the relative position of prostate with respect to the bladder and testes

To investigate the effect of scattering on the dose received by the target organs, doses in both cases (with and without scattering) were calculated. The material numbers and densities of legs, leg skin, and leg bones were replaced with zero to remove any possibilities of scattering from the legs of phantom. A schematic phantom can include legs, leg skin and leg bones as shown in Figure 4 (obtained by MCNP visual).

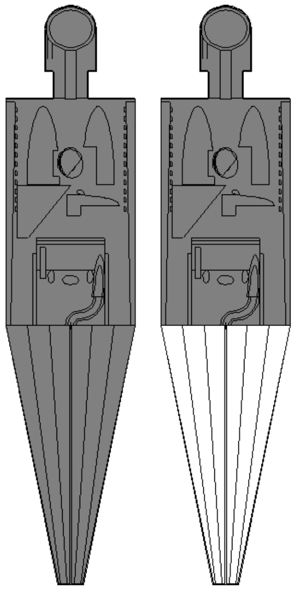

Figure 4. Schematic of modified ORNL Mird phantom with and without leg region

2.3. Dose Calculation

To calculate the absorbed dose, the total transformations of the brachytherapy seeds over the mean lifetime should be estimated. The relationship between lifetime (τ) and the decay constant (λ) is represented as

$$\tau = \frac{1}{\lambda} \tag{1}$$

The number of total transformations is:

$$U_s = \frac{A_0}{\lambda} \tag{2}$$

where A_0 is initial activity.

Finally, the total dose to the organs was determined by multiplying the tallies obtained by simulation in terms of MeV/trans by the total number of transformations and dividing by the mass of each organ.

3. Results

The relative errors were obtained from output files of MCNPX runs. It was always less than 5% for each input file, one including the legs and one without the leg region. The tallies passed all the ten statistical tests. The mean and figure of merit (FOM) were relatively constant, the relative error and variance of variance (VOV) were monotonically decreasing, and the slope had a perfect value of 10. As a result, the

simulation was properly performed using MCNPX.
The total dose to the organs was determined using absorbed energy. The obtained results are exhibited in Tables 2, 3, and 4 for both cases including legs and without leg region. From these tables it can be noted that prostate received doses of approximately 108.9, 97.7 and 81.5 Gy from ^{125}I, ^{103}Pd, and ^{131}Cs seeds, respectively. Percent difference between the doses when tallying with the legs intact and with the legs voided was calculated for each radioisotope and represented in Table 5. Finally, the values for ^{125}I seeds were compared with those of ref [10] and demonstrated in Table 6.

Table 2. The obtained results for ^{125}I seeds

Organ	Volume (cm^3)	Including scattering			without scattering		
		Absorbed energy per transformation (MeV/trans)	Absorbed dose per transformation (Gy/trans)	Total dose (Gy)	Absorbed energy per transformation (MeV/trans)	Absorbed dose per transformation (Gy/trans)	Total dose (Gy)
Small intestine	1060	5.21E-5	7.76E-18	0.0417	5.19E-5	7.53E-18	0.00405
Descending colon wall	89.9	1.54E-5	2.63E-17	0.141	1.52E-5	2.60E-17	0.139
Descending colon contents	102	1.76E-5	2.65E-17	0.142	1.74E-5	2.62E-17	0.140
Sigmoid colon wall	70.4	2.46E-4	5.37E-16	2.88	2.31E-4	5.04E-16	2.71
Sigmoid colon contents	35.6	1.21E-4	5.22E-16	2.80	1.13E-4	4.88E-16	2.62
Testes	37.6	2.20E-4	9.00E-16	4.83	1.92E-4	7.87E-16	4.22
Urinary bladder wall	45.7	5.25E-4	1.76E-15	9.45	5.22E-4	1.75E-15	9.40
Urinary bladder contents	203	2.04E-3	1.54E-15	8.27	2.03E-3	1.53E-15	8.21
Prostate	44.58	5.86E-3	2.02E-14	108.5	5.83E-3	2.01E-14	107.9

Table 3. The obtained results for ^{103}Pd seeds

Organ	Volume (cm^3)	Including scattering			without scattering		
		Absorbed energy per transformation (MeV/trans)	Absorbed dose per transformation (Gy/trans)	Total dose (Gy)	Absorbed energy per transformation (MeV/trans)	Absorbed dose per transformation (Gy/trans)	Total dose (Gy)
Small intestine	1060	1.05E-7	1.52E-20	9.58E-5	1.05E-7	1.52E-20	9.58E-5
Descending colon wall	89.9	2.51E-7	4.30E-19	2.71E-3	2.51E-7	4.30E-19	2.71E-3
Descending colon contents	102	2.65E-7	4.00E-19	2.52E-3	2.65E-7	4.00E-19	2.52E-3
Sigmoid colon wall	70.4	5.70E-4	1.25E-15	7.88	5.67E-4	1.24E-15	7.81
Sigmoid colon contents	35.6	1.85E-4	8.00E-16	5.04	1.83E-4	7.9E-16	4.98
Testes	37.6	3.98E-5	1.63E-16	1.03	3.51E-5	1.44E-16	0.91
Urinary bladder wall	45.7	2.06E-4	6.9E-16	4.35	2.05E-4	6.9E-16	4.35
Urinary bladder contents	203	5.83E-4	4.42E-16	2.78	5.82E-4	4.41E-16	2.78
Prostate	44.58	4.48E-3	1.55E-14	97.7	4.47E-3	1.54E-14	97.00

Table 4. The obtained results for ^{131}Cs seeds

Organ	Volume (cm^3)	Including scattering			without scattering		
		Absorbed energy per transformation (MeV/trans)	Absorbed dose per transformation (Gy/trans)	Total dose (Gy)	Absorbed energy per transformation (MeV/trans)	Absorbed dose per transformation (Gy/trans)	Total dose (Gy)
Small intestine	1060	1.06E-5	1.50E-18	4.65E-3	1.06E-5	1.50E-18	4.65E-3
Descending colon wall	89.9	5.57E-6	9.54E-18	2.96E-2	5.48E-6	9.39E-18	2.91E-2
Descending colon contents	102	6.47E-6	9.77E-18	3.03E-2	6.47E-6	9.77E-18	3.03E-2
Sigmoid colon wall	70.4	1.67E-4	3.65E-16	1.13	1.61E-4	3.52E-16	1.09
Sigmoid colon contents	35.6	7.97E-5	3.45E-16	1.07	7.59E-5	3.28E-16	1.02
Testes	37.6	1.77E-4	7.25E-16	2.25	1.62E-4	6.63E-16	2.05
Urinary bladder wall	45.7	5.19E-4	1.75E-15	5.43	5.18E-4	1.74E-15	5.39
Urinary bladder contents	203	1.82E-3	1.39E-15	4.31	18.1E-3	1.37E-15	4.25
Prostate	44.58	7.61E-3	2.63E-14	81.5	7.60E-3	2.62E-14	81.2

Table 5. Percent difference between the dose when tallying with the legs intact and with the legs voided

Organ	Source		
	^{103}Pd	^{125}I	^{131}Cs
Small intestine	0	2.88	0
Descending colon wall	0	1.42	1.69
Descending colon contents	0	1.41	0
Sigmoid colon wall	0.89	6.05	3.54
Sigmoid colon contents	1.19	6.43	4.67
Testes	11.65	12.63	8.89
Urinary bladder wall	0	0.53	0.74
Urinary bladder contents	0	0.73	1.41
Prostate	0.72	0.55	0.37

Table 6. Comparison of percent difference doses obtained in this study and the values calculated in ref [10] for ^{125}I seeds

Organ	This study	Ref [10]
Small intestine	2.88	1.49
Descending colon wall	1.42	1.42
Descending colon contents	1.41	1.61
Sigmoid colon wall	6.05	7.64
Sigmoid colon contents	6.43	7.09
Testes	12.63	7.62
Urinary bladder wall	0.53	1.53
Urinary bladder contents	0.73	1.42
Prostate	0.55	0.51

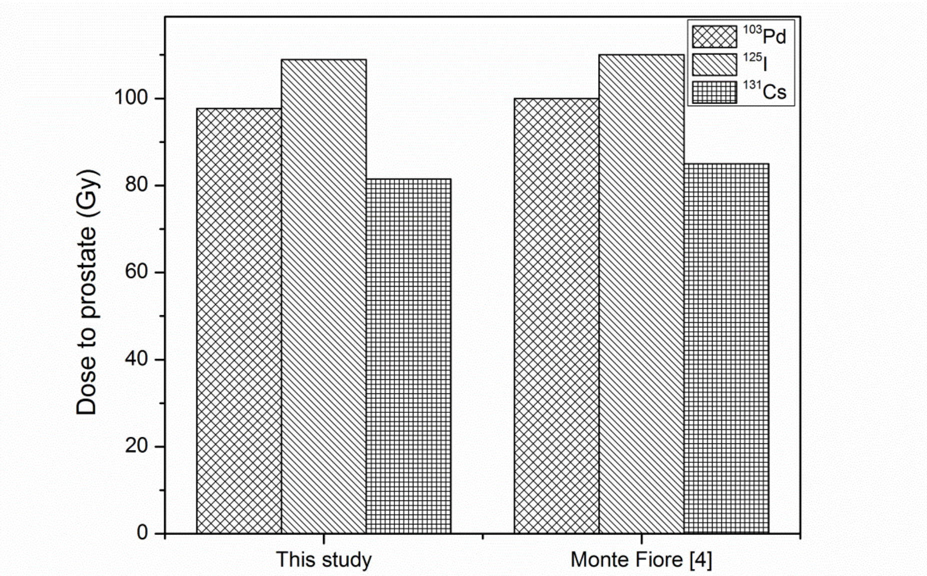

Figure 5. Comparison between the obtained results and the data published by Montefiore Medical Center and Albert Einstein College of Medicine for the prostate [5]

As shown in Figure 5, a comparison was made between the obtained results and the data published by Montefiore Medical Center and Albert Einstein College of Medicine for the prostate [5].

4. Discussion

Some researchers calculated the dose delivered to the prostate and critical organs during brachytherapy and showed that the urinary, sigmoid colon, and testes received the highest dose [1, 10]. The effect of scattering from legs on dose calculations was also studied for ^{125}I. It was shown that this scattering contribution could alter the dose calculations for the sigmoid colon wall, sigmoid colon contents, and testes. The small intestine, prostate, and urinary were unaffected by the leg scatter [10]. The results of this study are in agreement with the results obtained by Usgaonker and Lazarine. Generally, for each condition, the organs nearest to the prostate received the highest doses. Tables 2 to 4 also verify that the bladder, sigmoid colon, and testes received significantly high doses from radioactive sources in the prostate, which was expected due to their proximity to the prostate.

Besides, the difference between the dose when tallying with the legs intact and with the legs voided is significant for the testes and sigmoid colon contents and wall because they are close to the leg region. This difference was not significant between the bladder wall and contents and prostate as particles do not scatter in the legs and return to these areas. The difference for the small intestine and other organs far from the legs is also negligible because the scattered particles do not have enough energy to return to these regions. Moreover, results of the current study showed that the absorbed doses to the prostate were approximately what patients would receive from practical prostate brachytherapy procedures from ^{125}I, ^{103}Pd, and ^{131}Cs radioactive seeds. The results of this study are in line with the data published by Montefiore Medical Center and Albert Einstein College of Medicine [5]. Also as expected, the prostate doses from ^{125}I and ^{103}Pd seeds were relatively the same since the ^{103}Pd case had more seeds with lower photon energies compared to the ^{125}I case, which had lower number of seeds with higher photon energies. Since the energy of the ^{125}I seeds was higher than that of ^{131}Cs, a slightly higher dose to the prostate gland was obtained.

From dosimetric point of view, brachytherapy treatment plans using ^{131}Cs seeds allow for better sparing of critical tissues with a comparable number of, or fewer, seeds required, compared to ^{125}I seeds. However, clinical history with ^{131}Cs seed implants is limited [5, 22]. Regardless of the isotope chosen for implantation, a careful investigation on the dose values within the prostate and surrounding organs is necessary for establishing appropriate standards of care.

5. Conclusion

Our results indicate that the scattering contribution can alter the obtained dose in significant excess of the margin of error for the testes and sigmoid colon contents and wall. The exact received doses by patients were not represented in this study because of geometric factors and distances between the organs. In this paper, a phantom of 18 years old male was employed. Even though the differences in size and position of prostate and other organs for different ages are minimal, it can be a source of error. Thus, for different ages and sizes, position of the prostate and phantom should be considered. Besides, height, fat content, and varying bone masses can affect the obtained results.

Moreover, in the current study, the prostate was added as a sphere with a diameter of 4.4 cm, which is not accurate for different ages and may vary from patient to patient. Therefore, it should be modified for various problems.

The use of MCNPX in dose calculations enabled us to successfully complete this study, which would have been extremely complicated with conventional mathematics due to the complex geometries and issues such as attenuation and build-up.

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