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Using MCNP5 to evaluate radiation doses in prostate brachytherapy with cesium-131

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Abstract. Prostate brachytherapy with the radioactive nucleus cesium-131 was studied using the Monte Carlo code MCNP5. The sources of radiation were in the form of encapsulated grains called the seeds. The radiation dose rates from the radioactive sources were evaluated using the F4 tally. Both photons and electrons were transported from the prostate to other places in the body. The body depiction is a modified version of the ORNL phantom. Several values of the seeds' activities and their numbers were considered. The doses were evaluated for the prostate and other places nearby, assuming the seeds to be the point sources. The effects of changing the seeds' form of distribution inside the prostate and taking into account their geometrical construction are investigated. The period taken for delivering the prescribed dose was predicted. The results are found to be in good agreement with other estimations.

Keywords. Radiation; cesium-131; radiation therapy; doses; MCNP5; brachytherapy; prostate.

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1. Introduction

Brachytherapy is a type of radiotherapy, or radiation therapy, which, as the name implies, utilises radiation in medicine for remedial purposes. It is used basically to treat cancer by irradiating the tumour with a suitable dose of radiation to kill the cancerous cells. Depending on the place where the radioactive source is set, radiotherapy is mainly divided into two types: external radiotherapy and internal one. In the first type, the source of radiation is outside the body. In the second type, which is also known as brachytherapy, the source of radiation is inside the body. According to the location of the tumour, different radionuclides can be used in brachytherapy. For the one under study here, prostate cancer, the radionuclide considered for the study, cesium-131, is one of the preferred sources [1]. Other radionuclides that can also be used are iodine-125 and palladium-103 [2,3].

During the 1970s iodine-125 started to be used as seed implantation by open surgery [4]. Later on, open surgeries were replaced by different approaches [5]. In the 1980s, by positioning the patients in a lithotomy posture, an incision under the navel was used to do the implantation [6,7]. Transrectal ultrasonography was then performed successfully [8]. In the beginning, it had problems related to the accurate placement of the seeds. By improving the techniques, iodine-125 and palladium-103 had become the famously used radionuclides in the early 1990s [9], and brachytherapy with low dose rates was adopted for treating early-stage prostate cancer by several institutes, e.g. the American Society for Radiation Oncology and the American Brachytherapy Society. A most recent radionuclide, cesium-131, is also used now in prostate cancer brachytherapy [1]. Due to its shorter half-life, cesium-131 has the advantage of delivering the prescribed dose in smaller periods than iodine-125 and palladium-103 and may help in lowering the duration of exposing the urinary tract to infection [10].

For the brachytherapy operation to be successful, the radiation has to be concentrated on the cancerous cells, leaving the other healthy cells intact. This entails caution for the way the brachytherapy is applied with regard to each factor included in the operation [11], e.g. the number of seeds adopted, the activity per seed, the form of spreading the seeds around the tumour, the energy of the photons and the rate of giving the dose. Practically, this is very tedious and needs plenty of time and work to perform tests on patients to examine the above-mentioned factors. An essential way of doing these studies and tests is by performing simulation processes. Of course, the simulation work cannot be a substitute for the real practical work, but it helps very much by providing initial

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results that can suggest some ideas for developing and progressing the practical work, by saving a large amount of time, effort and budget.

In this article, a broad range of simulation data is set up for the prostate brachytherapy using the radionuclide cesium-131. Different values for the seeds' numbers and radioactivities are used in accordance with the actual ones that are used in practical therapy. Unlike several studies where the tumour is taken to consist of water [12–14], the tumour is taken here to be composed of soft tissues. In comparison to other techniques [11,12], this study uses methods and approaches implemented through Monte Carlo codes of MCNP5 [15]. Moreover, similar studies [12,16] deal with prostate brachytherapy mainly from a medical point of view, regarding the success rates, patients' status before and after the operation, side effects, different treatment options like monotherapy or boost therapy, etc., and the focus in the low-dose-rate prostate brachytherapy is on the radionuclides I-125 and Pd-103. But, this article deals with prostate brachytherapy from a physics point of view, and with applying the radionuclide Cs-131.

The presented article offers a simulation scheme that gathers between simplicity and capability of giving precise dose estimations for the prostate and several organs near the prostate, by providing several values for the important factors that are involved in the brachytherapy operation. It also helps in checking whether any harm happens to the surrounding healthy tissues and organs. Additionally, the expected period the brachytherapy operation will last until the prescribed dose is almost delivered was estimated.

2. The MCNP code

The Monte Carlo N-Particle software is a general-purpose code that can be used for transporting and tracking different types of particles like photons, electrons, neutrons or couplings between them, over a wide range of continuous energy. It can be applied in multiple areas, such as radiation shielding, radiation dosimetry, nuclear safety, medical physics, etc. It is very versatile and has many useful tallies that enable the calculation of several physical quantities. Some tallies can be used to estimate particle currents, fluences, pulse heights or energy depositions, in addition to radiography tallies and point detectors [15]. For calculating the organs' internal dose rates, two tallies can be used; the F4 tally and the F8 tally. The latter gives the energy deposition per transformation, and so it requires some further calculations that have to be made after getting the results from the codes. That is, to get the total deposited energy, the total number of transformations has to be calculated. This requires calculating the total activities in Bq units instead of the given Ci ones. Furthermore, the energy has to be changed from MeV to Joules to get the absorbed dose in the gray units, and this requires calculating the masses of several organs of interest as only their densities and volumes are provided in the codes. In the end, the results, which are the lifetime doses, have to be divided by the lifetime of the radionuclide to get the dose rates. On the other hand, the F4 tally, which evaluates the average fluence of particles through some volume, gives almost direct results. That is, by accompanying the F4 tally with the dose energy and function cards [17], the outcomes from the codes are dose rates per unit activity in units of rem/h·Ci, which can very easily be changed to Gy/h. Here in this study, we employ tally F4. In the mode card, we select both photons and electrons to be tracked. Additionally, the importance of photons and electrons in all organs has been set to one to track their fluxes in various organs. The basic idea of tally F4 in estimating the particles flux in some region is that if there is a particle of a given energy that makes some track length through a certain region, then the contribution of this track length to the flux is estimated, and then the sum of the contributions is calculated by integrating the energy and angular distribution over the entire energy range and the entire volume of the region of interest [18].

3. The ORNL phantom

The Oak Ridge National Laboratory (ORNL) human body phantom is the first embodied phantom representing an epicene adult for internal dosimetry [19,20]. A phantom of the human body means a theoretical specification of different portions of the human body. This specification is given by mathematical equations that account for the shape of each portion. Not only the shapes and sizes of the body portions are specified, but also their composition and the distances between them are specified. Since it is not a stand-alone unit and has to be integrated with some other software to be in action, the phantom has to be constructed in a way that enables the integration process. For example, to be integrated with the MCNP software, the ORNL phantom's theoretical specification has to be consistent with the structure of the Monte Carlo code. It happens by using geometrical forms that are known for the MCNP code, and moreover, the portions of the body are to be made up of the intersections and unions of these known forms.

To explain how the geometrical construction is made in the ORNL phantom, let us take an example of how a portion of the body is constructed. If we consider the stomach, for example, we see that it is constructed by using two ellipsoids having a common centre. The inner ellipsoid has approximate dimensions of 3.4 cm, 2.4 cm and 7.4 cm, while the outer ellipsoid has dimensions of 4 cm, 3 cm and 8 cm. The contents of the stomach are defined as the space inside the inner ellipsoid, which means that it has a volume of about 250 cm^3. The wall of the stomach is defined as the gap between the inner and outer ellipsoids, which means that it has a volume of about 152 cm^3, since the outer ellipsoid has a volume of nearly 402 cm^3. Other portions in the body can be defined in a similar way. After defining all portions, their materials are also defined by including their chemical structures and their densities. For example, the material of the stomach is taken as soft tissues with a density of 1.04 g/cm^3.

4. Geometry of the study and specification of the radiation source

As mentioned above, the phantom represents an epicene adult. It means it is a general one that can be used for either a man or a woman. For this study, the phantom is used to describe a man, and therefore things related to women, like the uterus, ovaries and breasts are suspended in the codes. In figure 1, the ORNL phantom is shown. In this figure, one can see that the basic portions of the human body are specified. However, some tiny portions might be unspecified, like for example the prostate, which is our main organ of study in this article. Therefore, a specification for the prostate has been included by the author. The prostate is taken as an ellipsoid of size 40 cm^3 [21], which is actually bigger than the normal size of the prostate, which is about 25 cm^3 [21,22], to account for the fact that the studied prostate is an unhealthy one with a tumour. In accordance with the human anatomy, the position of the prostate is just down to the urinary bladder, with its centre slightly to the front [11,23] (see figure 2). To show the prostate inclusion clearly, a side view of the phantom is given in figure 3, which is made using the MCNP5 graphics.

As mentioned already, the radiation sources are in the form of seeds, which contain radioactive nuclei covered with titanium. These seeds have almost the form and size of long thin grains of rice. They can be implanted inside the prostate in two different styles: single ones or a chain. In this article, they will be taken as single ones spread uniformly around the centre of the prostate which has the tumour. Three different sets of seeds will be considered: 60 seeds, 90 seeds and 120 seeds. The seeds will be taken as point sources, and the photons coming out from them will be assumed to have the same energy, taken as 30 keV, which is the mean energy of photons from cesium-131 [12,24].

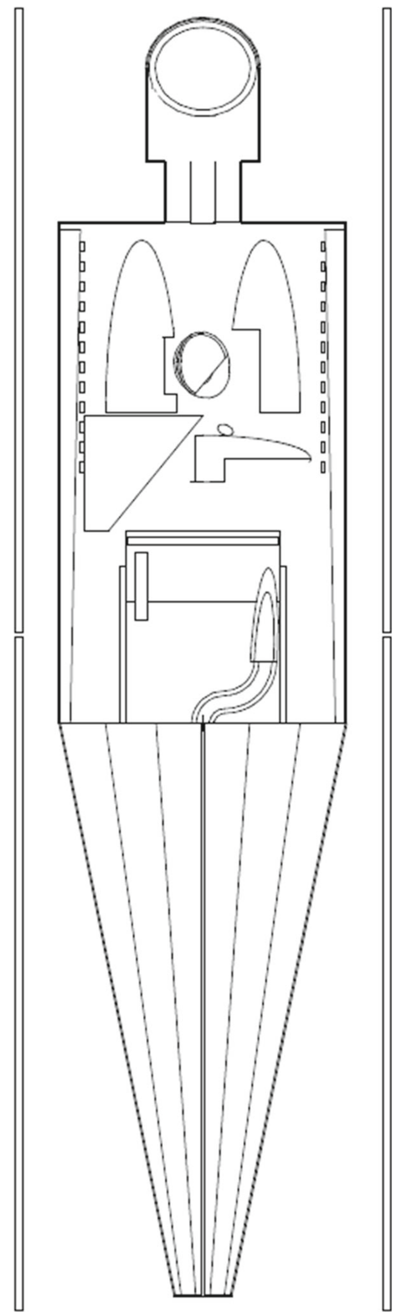

Figure 1. The human body description as given by the ORNL phantom. The drawing is from MCNP5 graphics [15].

5. Physics and tally specifications

In the simulation process, the interactions of both photons and electrons with the different body portions are taken into account. However, using the radioactive nucleus cesium-131, with an average photon energy of 30 keV, the contribution of electrons is not expected to be significant. It has been confirmed by tracking and calculating the electron and photon fluxes separately in the organs of interest. It is found that the electron fluxes are negligible compared to the photon ones. The ratio

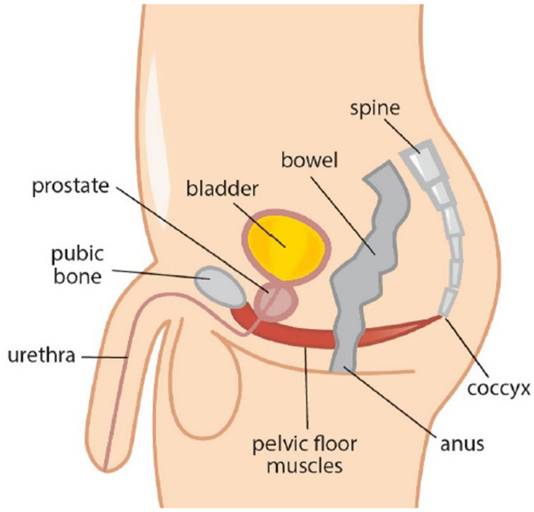

Figure 2. A side view of the pelvic region of the human body (taken from ref. [23]).

of the electron flux to the photon flux is in the order of 10^{-3}. Therefore, in the constructed codes, the transfer of photons and electrons from the source organ to the other portions of the body is taken into account, but the tallied amounts are only the photon's average fluxes. In other words, all kinds of interactions of the photons and electrons are taken into account through the body, but when it comes to flux estimation, only photon fluxes in different organs of interest are calculated by the tally F4. It helps overcoming the technical problem that the F4 tally does not allow the calculation of photon and electron fluxes at the same time, but only one at a time. The calculated photon fluxes are then changed to dose rates using the International Commission on Radiological Protection ICRP-21 conversion factors that are provided by the MCNP5 manual [15].

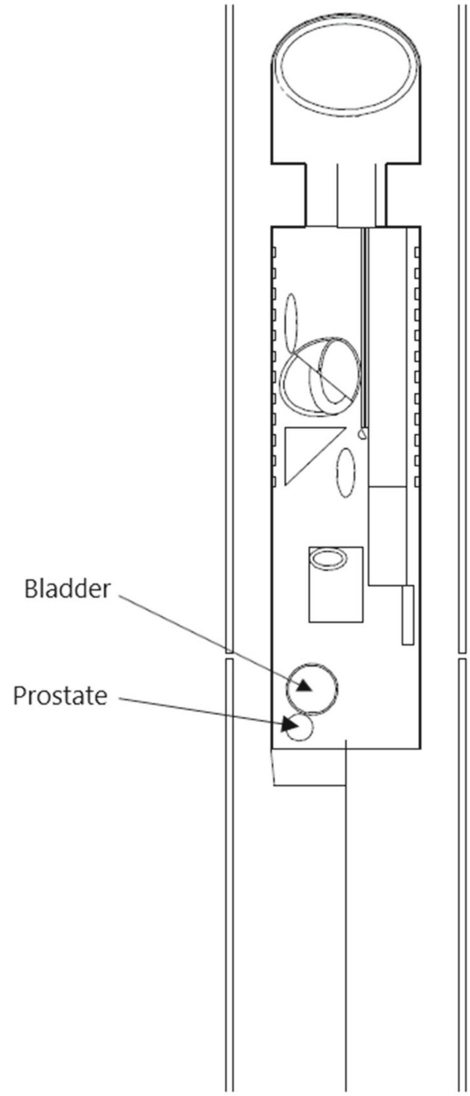

Figure 3. A side view of the human body description as given by the ORNL phantom by including the prostate. The drawing is from MCNP5 graphics [15].

6. Results and discussion

To easily spread the seeds inside the prostate in a uniform way, a seed block is constructed. This block is composed of five seeds, one in the centre and the other four surrounding it. Each of these four seeds is away from the central one by 4 mm. The dimensions of the block and the number of seeds in it are selected to fit the prostate size and at the same time to easily accommodate the required number of seeds as multiples of the seed block, keeping equal distances between the seed blocks with no overlapping. For example, if we are to put 60 seeds, 12 blocks will be used. To satisfy the uniformity of the spread, the distances between successive blocks are 4 mm, and they are put in equal numbers along the three main directions, with the same numbers on both sides of the prostate's centre.

Three activities are applied to cover the practical values that are known to be used in prostate brachytherapy. Activities between 2.5 and 3.5 mCi are practically used with cesium-131 [25], and so we choose to take the values 2.5 mCi, 3.0 mCi and 3.5 mCi. The obtained dose rates of the prostate and some of the nearby organs are given in tables 1–3. They are expressed in the units mGy/h, and each table includes three values of the seed number, 60, 90 and 120, at one of the activities. The relative errors in the dose rates are shown in the last column of the tables. These are the average for the three seed values because they are close to each other. For example, the radiation dose rates for the transverse colon wall have errors of 0.0766, 0.0786 and 0.0826, for the seed numbers 60, 90 and 120, respectively, with an average of 0.0793, which is the one shown in the tables. The

Table 1. Radiation dose rates using cesium-131 when the seed activity is 2.5 mCi.

Number of seeds→ Part of the body↓	60 seeds Dose rate (mGy/h)	90 seeds Dose rate (mGy/h)	120 seeds Dose rate (mGy/h)	Error (%)
Prostate	758.175	1101.310	1400.070	0.02
Left testis	30.858	46.964	63.813	0.27
Right testis	30.932	46.982	64.197	0.27
Urinary bladder wall	16.347	24.930	33.984	0.15
Urinary bladder contents	14.153	21.529	29.207	0.16
Small intestine	0.025	0.037	0.050	1.95
Ascending colon wall	0.039	0.059	0.077	3.41
Ascending colon contents	0.041	0.060	0.078	4.13
Transverse colon wall	0.004	0.005	0.007	7.93
Transverse colon contents	0.004	0.006	0.007	9.47
Descending colon wall	0.128	0.197	0.258	1.69
Descending colon contents	0.121	0.186	0.248	2.02
Sigmoid colon wall	5.245	7.982	10.810	0.31
Sigmoid colon contents	4.950	7.511	10.157	0.44

Table 2. Radiation dose rates using cesium-131 when the seed activity is 3.0 mCi.

Number of seeds→ Part of the body↓	60 seeds Dose rate (mGy/h)	90 seeds Dose rate (mGy/h)	120 seeds Dose rate (mGy/h)	Error (%)
Prostate	909.810	1321.572	1680.08	0.02
Left testis	37.030	56.357	76.576	0.27
Right testis	37.118	56.378	77.036	0.27
Urinary bladder wall	19.616	29.916	40.781	0.15
Urinary bladder contents	16.984	25.835	35.048	0.16
Small intestine	0.030	0.044	0.060	1.95
Ascending colon wall	0.047	0.071	0.092	3.41
Ascending colon contents	0.049	0.072	0.094	4.13
Transverse colon wall	0.005	0.006	0.008	7.93
Transverse colon contents	0.005	0.007	0.008	9.47
Descending colon wall	0.154	0.236	0.310	1.69
Descending colon contents	0.145	0.223	0.298	2.02
Sigmoid colon wall	6.294	9.578	12.972	0.31
Sigmoid colon contents	5.940	9.013	12.188	0.44

relative errors are calculated as the standard deviation of the mean divided by the mean [26].

In addition to the prostate, the dose rates are evaluated for the urinary bladder (wall and contents), the two testes, the sigmoid colon (wall and contents), the descending colon (wall and contents), the ascending colon (wall and contents), the small intestine and the transverse colon (wall and contents). The dose rates were also evaluated for more organs, but their relative errors were very high, and so they are not included in the tables. The high relative errors may have been caused by the long separation of those organs from the prostate. Other organs, like the liver, had relative errors that were not so high but their dose rates were very small because of the small photon fluxes through them, and so they are also not included in the tables.

Table 3. Radiation dose rates using cesium-131 when the seed activity is 3.5 mCi.

Number of seeds→ Part of the body↓	60 seeds Dose rate (mGy/h)	90 seeds Dose rate (mGy/h)	120 seeds Dose rate (mGy/h)	Error (%)
Prostate	1061.445	1541.834	1960.098	0.02
Left testis	43.201	65.750	89.338	0.27
Right testis	43.305	65.775	89.876	0.27
Urinary bladder wall	22.886	34.902	47.578	0.15
Urinary bladder contents	19.814	30.141	40.890	0.16
Small intestine	0.035	0.052	0.070	1.95
Ascending colon wall	0.055	0.083	0.108	3.41
Ascending colon contents	0.057	0.084	0.109	4.13
Transverse colon wall	0.006	0.007	0.010	7.93
Transverse colon contents	0.006	0.008	0.010	9.47
Descending colon wall	0.179	0.276	0.361	1.69
Descending colon contents	0.169	0.260	0.347	2.02
Sigmoid colon wall	7.343	11.175	15.134	0.31
Sigmoid colon contents	6.930	10.515	14.220	0.44

As can be seen from tables 1–3, the dose rates of the organs in the pelvic region are much smaller than that of the prostate. If we take for example table 1, with the 60 seeds case, we see that the prostate has a dose rate of about 758.18 mGy/h, while the nearest organs to the prostate, namely the urinary bladder and the testis, have dose rates of about 30.5 mGy/h and 30.9 mGy/h, respectively. The dose rate of the urinary bladder here is the sum of that of its wall and its contents, and the dose rate for the testis is the average of the left and right testes. This means that the dose rate for either the urinary bladder or the testis is only about 4% of that of the prostate. The corresponding percentages for the cases of 90 and 120 seeds in table 1 are about 4.25 and 4.5%, respectively. This indicates that, in the process of having prostate brachytherapy with cesium-131, the operation is safe with regard to the organs surrounding the prostate [27].

The way the seeds are spread in the prostate is expected to have some small effect on the calculated radiation doses. To quantify this, we consider a different way of spreading the seeds and see how the results change. For the new distribution form, the seeds are spread along the three main directions around the centre of the prostate with interspaces of 1 mm. Considering the 60 seeds case; 20 seeds are put along each direction: ten on each side. Labelling this new form of distribution as form (2) and the previously studied one as form (1) table 4 shows the calculated dose rates of the prostate and the surrounding organs for the two distributions. The seed activity is the same as in table 1; 2.5 mCi. As can be seen from table 4, the dose rates for the two distributions do not have significant differences. The maximum change is for the prostate and it is only about 1%. By considering other forms of distributions, e.g. squares around the prostate centre, similar conclusions are drawn.

Now we examine what happens if the geometrical construction of the seeds is taken into account. The seed's real form is that of a very small cylinder of 0.45 cm length with a circular cross-section of 0.08 cm diameter [28]. These dimensions are for the outside capsule, while the actual source (radionuclides) is on the surface of an inner rod of size about 60% of the capsule's size. Since it is already established that different ways of spreading the seeds in the prostate do not have a significant effect on the calculated dose rates, for simplicity, we arrange the seeds next to each other in the form of squares around the prostate centre. Considering again the case of 60 seeds with 2.5 mCi seed activity, the resulting radiation dose rates are shown in table 5 in the column named Case (2) which refers to the case when the seeds' geometrical construction is taken into account. This is compared to the previous calculations where the seeds were considered as point sources; the first case, Case (1). As one can see from table 5, taking into account the geometrical construction of the seeds does not alter the results much. The maximum difference is just about 4%, which is for the descending colon wall. These results show that approximating the seeds by point sources is a good approximation.

Tables 1–3 explain the expected behaviour of increasing the dose rates by increasing the activity of the seeds

Table 4. Radiation dose rates using 60 seeds of cesium-131 when the seed activity is 2.5 mCi. The results are shown for two different forms of spreading the seeds, named form (1) and form (2), as explained in the text.

Distribution of the seeds→ Part of the body↓	Form (1) Dose rate (mGy/h)	Form (2) Dose rate (mGy/h)
Prostate	758.175	767.325
Left testis	30.858	30.657
Right testis	30.932	30.753
Urinary bladder wall	16.347	16.254
Urinary bladder contents	14.153	14.087
Small intestine	0.025	0.024
Ascending colon wall	0.039	0.039
Ascending colon contents	0.041	0.040
Transverse colon wall	0.004	0.004
Transverse colon contents	0.004	0.004
Descending colon wall	0.128	0.130
Descending colon contents	0.121	0.121
Sigmoid colon wall	5.245	5.221
Sigmoid colon contents	4.950	4.907

Table 5. Radiation dose rates using 60 seeds of cesium-131 when the seed activity is 2.5 mCi. The results are shown for the case of considering the seeds as point sources (Case (1)) and when taking into account the geometrical construction of the seeds (Case (2)).

Depiction of the seeds→ Part of the body↓	Case (1) Dose rate (mGy/h)	Case (2) Dose rate (mGy/h)
Prostate	758.175	763.635
Left testis	30.858	29.627
Right testis	30.932	29.789
Urinary bladder wall	16.347	15.831
Urinary bladder contents	14.153	13.726
Small intestine	0.025	0.024
Ascending colon wall	0.039	0.039
Ascending colon contents	0.041	0.039
Transverse colon wall	0.004	0.003
Transverse colon contents	0.004	0.003
Descending colon wall	0.128	0.123
Descending colon contents	0.121	0.122
Sigmoid colon wall	5.245	5.310
Sigmoid colon contents	4.950	4.979

or their number. These tables can be used to predict the time the brachytherapy operation will last until the prescribed dose is almost delivered. To show this, let us consider, for example, table 1 and let us take the first case of having 60 seeds. According to ref. [25], the prescribed dose, on average, is around 115 Gy, and therefore it is predicted to last for about a week. However, we have to be aware of the fact that the predicted periods would actually have to be higher because of the reduction of the seeds' activities as time goes on. To validate our results, we consider a comparison to those of ref. [11]. In that reference, they use seed activities between 1.8 and 2.5 mCi and number of seeds up to 40. Their initial dose rate is about 350 mGy/h, which when used to estimate the period for delivering 115 Gy dose, will give about two weeks. Taking into account that our seed activities range from 2.5 to 3.5 mCi, and the number of seeds ranges from 60 to 120, this is quite acceptable, because using less activity and a smaller number of seeds leads to smaller dose rates and accordingly longer periods to deliver the prescribed dose.

7. Conclusion

Radiation doses that would be received by the prostate and some other close organs in a prostate brachytherapy process with cesium-131 have been predicted by utilising the Monte Carlo code MCNP5. The simulation codes adopted the human body mathematical description made by the Oak Ridge National Laboratory. The simulation results of the dose rates are quite acceptable compared to those of the other estimations. The period expected for the brachytherapy process, till it almost reaches an end, has been evaluated for one of the cases studied. From the obtained dose rates, one can see that the brachytherapy operation with cesium-131 is apparently safe for healthy organs close to the prostate. In other words, no damage is expected to happen to the normal organs [27] while curing the prostate by the brachytherapy process, which is expected to last for a period ranging from a few days to a few weeks depending on the prescribed dose, the number of seeds and their activity. The calculated radiation dose rates are found to be almost insensitive to the way of spreading the seeds in the prostate. Moreover, due to their small size, it is shown that the seeds could be well approximated by point sources. It is a very good and useful approximation, as it can be used to simplify the simulation processes and quicken their run on the computer. The results obtained in this article encourage researchers to do more research on these types of operations that take place in the field of radiation therapy and medical physics in general. A forthcoming study will consider a comparison to the use of other radionuclides that are applied in prostate brachytherapy.

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