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Dosimetric comparison between low dose rate and high dose rate brachytherapy for prostate cancer: a Monte Carlo study

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Abstract

This study performs a dosimetric comparison between low-dose-rate brachytherapy with I-125 and single-fraction high-dose-rate brachytherapy with Ir-192 for the treatment of prostate cancer. The dose distributions in the prostate as well as the delivered dose to the organs at risk surrounding the prostate were obtained by Geant4 Monte Carlo toolkit. The results indicate that very low-activity HDR brachytherpay with Ir-192 sources delivers a lower dose to the organs at risk than I-125 LDR brachytherapy with equal seed activities. Therefore, the significance of performing high-activity HDR brachytherapy in a fractionation scheme is further emphasized.

Keywords: Brachytherapy, Prostate cancer, Dosimetry, Monte Carlo, Geant4

Introduction

Prostate cancer is the fourth most common cancer globally in 2020, in which over 1.4 million new cases have been reported [1]. Brachytherapy is one of the most effective treatments for prostate cancer. Low-dose-rate (LDR) brachytherapy is performed using I-125 and Pd-103 seeds, and high-dose-rate (HDR) brachytherapy is performed using Ir-192 sources [2]. Monte Carlo codes play a significant role in dose and risk estimation in brachytherapy treatment procedures, and focus on the challenges which appear in each method. LDR brachytherapy is a proven approach for prostate cancer treatment in which tiny radioactive seeds are implanted in tumors either permanently or temporarily. In contrast, the HDR approach is a superior alternative to LDR techniques, which reduce the surrounding organ doses by taking advantage of the fractionation scheme. Literature has emphasized the importance of estimating the delivered dose in each modality and comparing the dose outputs, specifically for prostate cancer [3]. The aim of this study is to perform a dosimetric comparison between LDR and *single-fraction* HDR brachytherapy in prostate cancer with emphasizing the delivered dose to the related organs at risk (OARs), using Geant4 [4] Monte Carlo simulation toolkit.

Materials and Methods

Geant4.10.7 with Livermore low energy physics, "G4EmLivermorePhysicsList", was implemented in this study. The G4EmLivermorePhysicsList package uses the accurate standard and low-energy models which includes photoelectric effect, Compton scattering, Rayleigh scattering, bremsstrahlung, ionization and fluorescence emission. Simulation was performed by modeling the MIRD male phantom [5], to calculate the dose delivered to OARs. We extended the MIRD male phantom to include the prostate, which is defined as an elliptical volume of soft tissue (density=0.9869 g/cm^3) with dimensions of 4.39×4.39×5.28 mm^3. Also, the urethra was added to the phantom as a cylindrical volume of soft tissue with a radius of 0.25 mm and a height of 5.26 cm. In the case of LDR brachytherapy, 119 I-125 seeds (Amersham 6711 model [6]) were placed in prostate with center-to-center spaces of 1 cm and 0.5 cm in axial and transversal planes, respectively. Five planes were considered along the z-axis, and eight planes were considered along the x- and y- axes. In the case of HDR brachytherapy, 16 Ir-192 sources (Isodose Flexisource model [7]) were placed in prostate with center-to-center spaces of 2 cm and 1 cm in axial and transversal planes, respectively. In this case, two planes were considered along the z-axis, and six planes were considered for both x- and y- axes. All sources were kept away from the urethra for at least 1 cm. Note that the position of sources in this simulation is based on a typical treatment planning system that is not optimal for all patients. The 3D dose distributions were obtained using Geant4 mesh capability which divides the prostate volume into 0.1×0.1×0.1 mm^3 voxels in three dimensions. The number of primary particles was 1.5×10^7, and all statistical errors in the simulation were below 1% in all OARs except urethra. For urethra the statistical error was below 8%. The dose rate (DR) is calculated by equation 1:

$$DR\ (Gy/s)=(D_0/N_0)\times A_0\times N_s\times F, \quad (1)$$

in which N_0 is the number of primary particles, D_0/N_0 (Gy/particle) is the dose deposited per particle, A_0 (Bq) is the source activity, N_s is the number of seeds, and F is the number of particles emitted per decay. F equals to 1.476 and 0.978 for I-125 and Ir-192, respectively.
The accumulated dose ($t\rightarrow\infty$) is obtained by equation 2:

$$D_{tot} = DR/\lambda, \quad (2)$$

in which λ is the decay constant of each radioisotope.

Results and discussion

The 3D dose distributions at the central plane in the prostate for I-125 (LDR) and Ir-192 (HDR) sources are shown in Figures 1 and 2, respectively. The isodose contours are normalized to the dose covered 90% of the prostate volume as the reference dose [8].

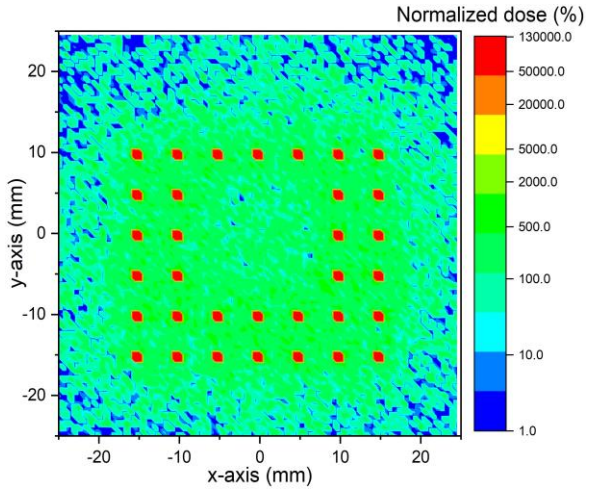

Figure 1. The dose distribution of LDR I-125 seeds at the central plane in the prostate.

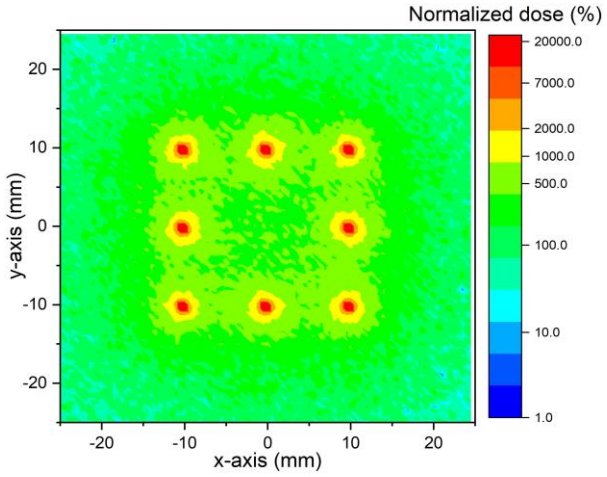

Figure 2. The dose distribution of HDR Ir-192 sources at the central plane in the prostate.

The DRs delivered to the prostate as well as the surrounding OARs for 119 LDR and 16 HDR sources are tabulated in Table 1. Note that the nominal source activites, i.e., 0.5 mCi for I-125 seeds, and 10 Ci for Ir-192 seeds were not taken into account for the calculation of DR, instead the same activites of 0.1 mCi was considered. we reduce the actitiviy of the seeds to 0.1 mCi as suggested by [8] for the possible permanent utilization of Ir-192 sources. Therefore, we considered that all sources are permanently implanted in the prostate. It can help us to have a better comparison for such sources. Table 2 represented the total accumulated dose in Gy. Note that the dose values are listed as both the raw values and the normalized ones. The normalized values are listed in brackets.

Table 1. The dose rates (Gy/s) in the prostate and the surrounding OARs for I-125 and Ir-192 implants obtained by equation 1.

Organ	I-125 (sd*)	Ir-192 (sd)
Prostate	1.70E-6 (0.06%)	3.79E-6 (0.1%)
Urethra	1.24E-6 (7.1%)	2.97E-6 (5.0%)
Bladder	5.06E-8 (0.4%)	2.52E-7 (0.4%)
Testes	5.02E-8 (0.6%)	2.47E-7 (0.6%)
Pelvis	3.85E-10 (1.0%)	2.10E-8 (0.3%)

*sd=standard deviation

Table 2. The total dose (Gy) in the prostate and the surrounding OARs for I-125 and Ir-192 seeds obtained by equation 2. The normalized values are in brackets.

Organ	I-125 [Normalized %]	Ir-192 [Normalized %]
Prostate	1.47E-4, [100]	4.05E-4, [100]
Urethra	1.08E-4, [78.3]	3.17E-4, [73.3]
Bladder	4.38E-6, [6.64]	2.69E-5, [2.97]
Testes	4.35E-6, [6.50]	2.63E-5, [2.95]
Pelvis	3.34E-8, [0.56]	2.27E-6, [0.02]

At first glance, as shown in the dose distributions in Figures 1 and 2, the normalized isodose contours for Ir-192 source are extended to farther distances due to the high range of particles emitted from the Ir-192 source. Thus, the high gradient dose of I-125 seed may help better sparing of nearby OARs. This is also shown in Table 1. But the normalized values shown in Table 2 indicate that sparing of OARs nearby prostate may be improved by using very low-activity of HDR permanent sources. This is in consisted with [8]. Thus, the permanent implantation of very low-activity I-192 sources may be superior than the permanent implantation of I-125 with the same activity of the seeds. We ignored the relevent radiobiological issues in this simulation. It will be studied in our future studies.

Conclusions

From the simulation viewpoint, HDR brachytherpay with very low-activity Ir-192 sources delivers a lower dose to the OARs adjacent to the prostate than LDR brachytherapy using I-125 seeds, provided that the seed activities are the same. This result highlights the importance of the fractionation scheme in usual HDR brachytherapy deliveries.

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