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A DOSIMETRIC STUDY OF PROSTATE BRACHYTHERAPY USING MONTE CARLO SIMULATIONS WITH A VOXEL PHANTOM, MEASUREMENTS AND A COMPARISON WITH A TREATMENT PLANNING PROCEDURE

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In prostate brachytherapy treatments, there is an initial swelling of the prostate of the patient due to an oedema related to the insertion of the seeds. The variation of the prostate volume can lead to variations in the final prescribed dose in treatment planning procedures. As such, it is important to understand their influence for dose optimisation purposes. This work reports on a dosimetric study of the swelling of the prostate in prostate brachytherapy using Monte Carlo simulations. Dosimetric measurements performed on a physical anthropomorphic tissue-equivalent prostate phantom and thermoluminescent dosimeters (TLDs) were used to validate the MC model. Finally the MC model was also used to simulate prostate swelling in a real treatment planning procedure. The obtained results indicate that the parameters mentioned above represent a source of uncertainty in dose assessment in prostate brachytherapy, and can be detrimental to a correct dose evaluation in treatment plannings, and that these parameters can be accurately determined by means of MC simulations with a voxel phantom.

INTRODUCTION

Prostate brachytherapy is used to treat prostate cancer by placing a set of sealed radioactive sources inside the tumourous prostate. Seed implantation and treatment planning procedures in prostate brachytherapy have evolved considerably since its onset as a widely used tumour treatment procedure. Current brachytherapy procedures make use of 3D imaging techniques to determine the prostate volume that is crucial to define the seed distribution. In addition, the application of transrectal ultra-sound probes allow for the real-time visualisation of seed implantation. As a consequence, a more accurate knowledge of prostate volume and shape, as well as the seed positioning inside it, is achieved. This allows for a better informed choice of the treatment seeds distribution (peripheral or uniform loading or other), and helps to reduce damage to the healthy tissues and optimises the dose delivered to the tumour, leading to significantly improved treatment planning procedures[1].

Seeds containing ^{125}I sources are widely used in permanent prostate implants. The ^{125}I seeds considered in this study consist of small cylindrical titanium capsules, inside which there is a smaller gold (or silver) rod, where the active ^{125}I radionuclide is adsorbed on its surface. For low energy brachytherapy source dosimetry ($E<50$ keV) the TG43-U1 protocol[2] establishes recommendations for the experimental methodology and Monte Carlo calculations. In addition, a recommended emission spectrum is provided, in particular for ^{125}I (which has maximum emitted energy of 35.5 keV). On the other hand, it establishes the consensus values for the parameters and functions needed for the calculation according to the TG43 methodology, which is the one followed by most of the planning systems[3]. Depending on the prostate volume, the number of implanted seeds in a brachytherapy treatment may range from 60 to 120[3, 4]. The seeds used in this study are the Amersham 6711 brachytherapy seeds.

Several studies have focussed on studying the dosimetry of single or multiple brachytherapy sources, by making use of the AAPM-TG-43 formalism. This formalism is very robust and well established. Abundant work in the literature is found in regards to the determination of the different dosimetric parameters, by making use of different algorithms or MC codes, in water and other media. Moreover, ^{125}I brachytherapy seeds have been widely studied using different Monte Carlo simulation programmes[5, 6]. However, a treatment planning simulation should be as realistic as possible, taking into account the most accurate depiction of the human anatomy, and time-dependent factors not directly taken into account in typical prostate brachytherapy treatment planning procedures. In fact, there is evidence that small variations in the prescribed treatment dose relative to the actual dose can lead to significant changes in the recurrence rates of patients(7). This emphasises the need to understand the effect of realistic volume variations in the prostate, among other factors. To the best of the authors' knowledge, very few studies have considered more realistic phantoms of the human body. One of the possible ways to reproduce the realistic treatment planning conditions is to use a voxelized phantom, created from a patient CT or MRI images files. To the best of the authors' knowledge, there have been very few dosimetric studies in this field making use of VOXEL phantoms(8, 9).

Taking this into account, this work reports on the study of the influence of the prostate oedema in the final dose delivered to the prostate, using the aforementioned techniques.

MATERIALS AND METHODS

Dosimetric measurements

For the experimental setup, a geometric prostate phantom was developed. The phantom was constructed from square slabs with 30 cm side length made of RW3 (PTW—Freiburg Lörracher Strasse 7, 79115 Freiburg, Germany, model Plattenphantom 29672), which were cut into smaller square slabs of 7 cm side length. Each of these slabs has a thickness of 0.5 cm, and by piling up 14 of these slabs, a cubic phantom representing the prostate was obtained. Each slab contains a 13×13 square matrix of small holes (0.05 cm radius), which are 0.5 cm apart from each other. This geometry, shown in Figure 1, was established in order to maintain the same reference points as in the frame of reference used in the planning system to guide the seed insertion in the prostate. For the measurements, the seeds are placed inside a specific hole, with thermoluminescent dosimeters (TLDs) (Harshaw TLD-100 chip with 1 mm $\times$ 1 mm $\times$ 4 mm) being placed in the holes surrounding the seed, according to the position where the absorbed dose was to be measured. As it has an effective atomic number of 8.2, the TLD-100 can be considered tissue-equivalent, and therefore it only possesses weak energy dependence for low energy photons(10). Dose evaluations inside the prostate phantom TLDs were carried out only once. However, in order to evaluate the TLD response uncertainty, a reproducibility study of the TLD response was previously conducted. This study was developed for a ^{60}Co source, a dose of 1cGy and five exposures under identical conditions. Since the TLDs were calibrated using a ^{60}Co source, a correction factor of 1.42 was applied to the TLD readings to account for the different response of TLD-100 to the photons emitted by ^{60}Co and by ^{125}I. This value was taken from the literature, and the average uncertainty for such correction factors ranges from 0.05 % to 2 %(11, 12).

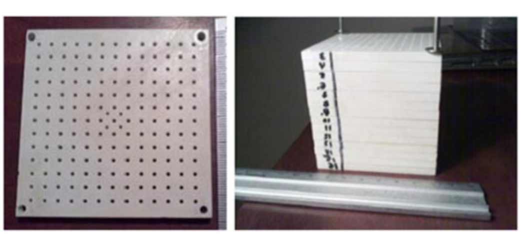

Figure 1. Prostate phantom constructed from square slabs.

A planar view of the phantom setup is depicted in Figure 2. The positions of the seeds are represented in blue and the positions where the absorbed dose to water was assessed are in red. The remaining holes were left empty and hence filled with air. In order to validate the computational model, the experimental setup described above was simulated and the computational results were then compared with the measurements. Finally, in order to validate the MC simulations using the GOLEM phantom, the same geometry setup as shown in Figure 2 was replicated inside the prostate of the GOLEM phantom (but using the elemental composition of it) using MCNPX 2.7, and the results were compared with the previous ones.

Monte Carlo simulations

The Monte Carlo simulations were performed with the Monte Carlo N-Particle eXtended (MCNPX

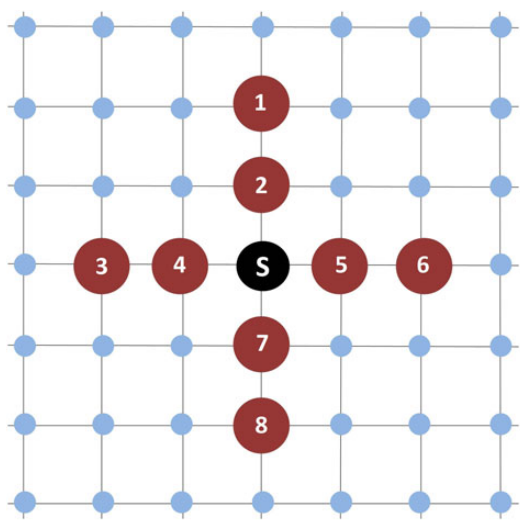

Figure 2. Planar view of the phantom with the inserted source and TLD's.

2.7)[13] code, which was developed at the Los Alamos National Laboratory. The code uses MC methods to transport particles through a 3D geometry defined by the user. Cross-section libraries are used to simulate the particles interactions, and when these are not available for a certain type of particle and energy, physical models are used. Radiation protection, dosimetry and medical physics are some of the several applications fields of this MC code. The simulations were performed with the default physical parameters for photon and electron transport, and the ENDF/B-VI libraries for the scattering cross sections were used.

First, the parameters that characterise the computational model of the brachytherapy seed to be used were calculated using MCNPX 2.7. These parameters are the dose rate constant, Λ, radial function, g(r) and anisotropy function, F (r, φ). Then, the simulation of the experimental setup was performed, in order to validate the MC model consisting of the seeds in a specified arrangement and the GOLEM voxel phantom. After the validation of the computational model of the brachytherapy seed, MCNPX 2.7 and the GOLEM voxel phantom were used to study the dose delivered to the prostate in brachytherapy treatments when the volume of the prostate is varied. Finally, the real treatment procedure was simulated using MCNPX 2.7 for three different prostate volumes: 38.01, 52.01 and 57.02 cm^3.

For each simulation, the number of simulated particles was appropriate to obtain statistical uncertainties below 0.5 % (1σ standard deviation). All these simulations are described in detail in the following sections.

The GOLEM voxel phantom[13] is a whole body male adult phantom with a weight and height similar to the ICRP reference data for the adult male[14]. The voxel dimensions are $2.08 \times 2.08 \times 8.0$ mm^3 and the phantom includes 121 organs. Golem's prostate has a volume of 52.10 cm^3 and consists of soft tissue with a 1.05 g cm^{-3} density (Figure 3).

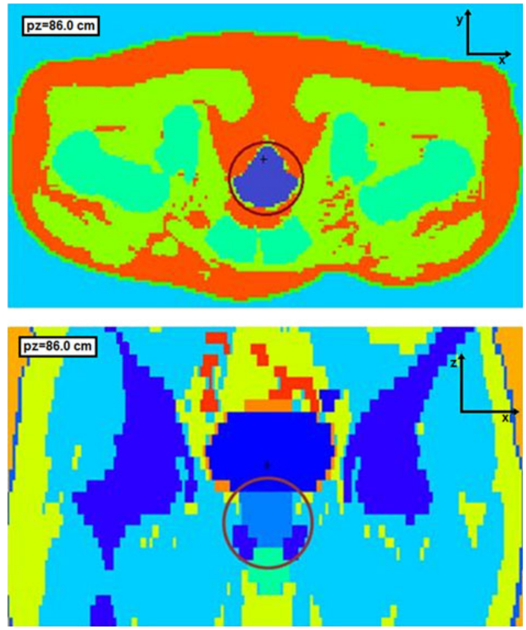

Figure 3. GOLEM voxel phantom. The prostate is encircled.

Table 1. Results for g(r) obtained in this work and their comparison with results from[6].

r (cm)	0.25	1.0	3.0	5.0	8.0	10.0
this work	1.104	1.000	0.623	0.359	0.146	0.0784
Rivard *et al.*[6]	1.069	1.000	0.643	0.370	0.151	0.0820
Deviation (%)	3.2	0.0	−3.2	−3.0	−3.4	−4.6

Table 2. Results for the anisotropy function F (*r*, *φ*), obtained in this work and their comparison with results from[6].

	ϕ_{an}(r)	ϕ_{an}(r)	ϕ_{an}(r)
r (cm)	0.25	2	7
This work in solid water™	0.950	1.026	0.965
Rivard[6] in liquid water	1.052	0.946	0.951
Deviation (%)	−11 %	8 %	1 %

Brachytherapy seed characterisation

The results obtained in the dosimetric characterisation of the Amersham 6711 brachytherapy seed are the values for the radial function g(r) for different distances, for the 1D anisotropy function in solid water™ (composition by mass fraction: H:8 %, C:67.2 %, N: 2.4 %, O: 19.8 %, Ca: 2.3 %, Cl:0.1 % and density 1.015 g cm^{-3}), as defined in AAPM-TG43[3]. The obtained results were compared with consensus results[6]. The comparison is shown in Tables 1 and 2.

The dose rate constant Λ was also determined. The authors obtained a value of $\Lambda = 0.9773$ cGy h^{-1} U^{-1} (±3 %). This is in good agreement (<5 % deviation) with the value obtained in a similar study[6].

RESULTS AND DISCUSSION

Dosimetric measurements and Monte Carlo simulations

Table 3 presents the comparison between the results obtained with the TLD measurements, the MC simulations in the cubic prostate phantom, and the same setting inside the prostate of the GOLEM voxel phantom. The results of the simulations in the cubic phantom are between 1 % lower and 14 % higher than the measured dose values, and the results of the simulations in the voxel phantom are between 1 % and 9 % higher than the measured doses.

Considering the uncertainties of the dose values, the results are in reasonable agreement and provide thus an experimental validation for the Monte Carlo simulations using the GOLEM phantom. Since the authors have considered the experimental values as those against which they validated their simulations, the ratios in the last column are expressed in terms of simulated/experimental values. Uncertainties from simulations are merely statistical (1σ).

Variation of the prostate volume

As mentioned before, the influence of the prostate volume on the absorbed dose delivered to the prostate was studied by changing the voxel dimensions. Volumes of 30.02 cm^3, 35.00 cm^3, 40.00 cm^3, and 45.00 cm^3 were considered beside the original volume of 52.10 cm^3, using 65 geometrically detailed seeds in a uniform arrangement. The simulation results are displayed in Table 4. As expected, the total absorbed dose to the entirety of the prostate volume decreases with increasing prostate volume. Assuming that 30.02 cm^3 was the initial prostate volume, and no swelling, and that the prostate was to be treated with 65 seeds, the simulated dose would be of 125.58 Gy. If the prostate swells by around 42 % after the insertion of the seeds, equivalent to a post-insertion prostate volume of 52.10 cm^3, the total absorbed dose to the prostate with the same loading distribution and number of seeds is 90.30 Gy, which is 28 % lower than the originally simulated 'prescribed' dose (Table 4). This means that the patient receives a dose which is 28 % smaller than the desired dose during the period in which the prostate is swollen, that is, in average, about 2 weeks. To note that in order to obtain the exact absorbed dose delivered to the prostate, the different stages of the prostate swelling (initial insertion, swelling and deflation) have to be considered dynamically, not instantaneous as in the present study. A more realistic approach would reflect the course of both the swelling and the deflation with time, which was beyond the scope of this work. Simulating the total absorbed dose to the prostate taking into account the immediate swelling and deflation of the prostate (step-function) in each of the simulated prostate volumes, an absorbed dose of 120.28 Gy was calculated, which is 4.22 % lower than the initial simulated absorbed dose of 125.58 Gy (without the swelling).

Comparison with a treatment planning procedure

A real clinical treatment was simulated exactly as it was performed. In Figure 4 is shown the real treatment planning and in Figure 5 the implementation in

Table 3. Comparison of TLD measurements and Monte Carlo results considering the cubic prostate phantom. Simulations uncertainty is statistical and below 0.5 % (1σ).

Point	Experimental		Simulations (cubic phantom)		Simulations (voxel phantom)		Ratio	
	Dose (Gy)	Unc. (%)	Dose (Gy)	Unc. (%)	Dose (Gy)	Unc. (%)	Cubic phantom simulation/Exp	Voxel phantom simulation/Exp
1	1.186	3.32	1.299	3.83	1.274	2.08	1.10	1.08
3	1.165	4.66	1.325	3.81	1.266	2.09	1.14	1.09
6	1.207	3.66	1.191	4.01	1.281	2.08	0.99	1.07
8	1.245	4.94	1.242	3.94	1.263	2.09	1.00	1.02

Table 4. Comparison of total dose values for seeds described in detail and point sources in the simulation of a real treatment. Simulations uncertainty is statistical and below 0.5 % (1σ).

Volume (cm^3)	Description	Mass (g)	Absorbed dose per seed (Gy/seed)	Total absorbed dose (Gy)	Comparison (%)
38.01	Detailed seeds	39.911	1.32	110.96	10.75
	Point sources	39.911	1.48	124.33	
52.01	Detailed seeds	54.705	1.12	94.23	12.57
	Point sources	54.705	1.28	107.77	
57.02	Detailed seeds	59.866	1.07	89.77	11.78
	Point sources	59.866	1.21	101.75	

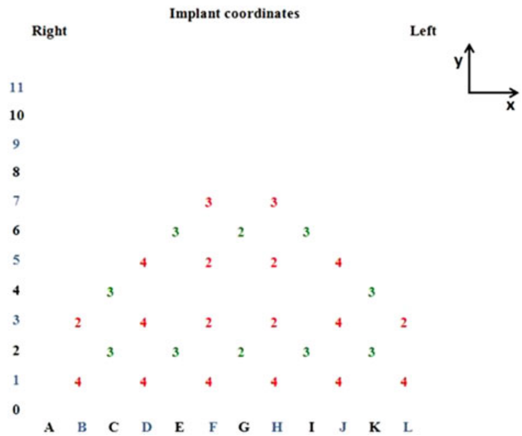

Figure 4. Real treatment planning of the seeds' position.

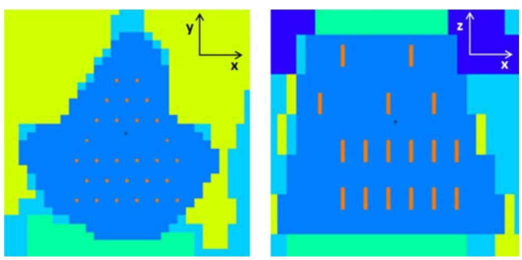

Figure 5. Seeds inside GOLEM's prostate.

the voxel phantom. Eighty-four seeds were implemented in GOLEM's prostate in a uniform arrangement, for prostate volumes of 38.01, 52.01 and 57.02 cm^3, assuming both the point source approach, as in the medical treatment planning system, and a detailed simulation of the seed geometry, as explained previously. Table 4 shows these results.

The dose values resulting from the Monte Carlo simulation are lower than the doses evaluated for the real treatment planning. Also, the dose to the prostate assuming point sources is around 10.75 –12.57 % higher than when assuming a real description of the seeds. This may be explained by the interseed effect, where volumetric neighbour seeds will absorb a part of the radiation emitted by one seed, whereas when considering point sources this does not happen.

For a detailed seed description and assuming an instantaneous swelling of the prostate for 2 weeks (57.02 cm^3 volume), followed by an instantaneous deflation, the total absorbed dose delivered to the prostate is 3.51 % lower (107.77 Gy) than assuming a constant volume of 38.01 cm^3, which is what is assumed in the treatment planning. The value obtained in the simulation where the swelling is considered, i.e. the more realistic simulated scenario, is 25.16 % lower than the prescribed dose of 144 Gy determined with the treatment planning software.

CONCLUSIONS

In a prostate brachytherapy treatment planning the prostate swelling can be a source of uncertainties that should be taken into account[15, 16]. The accurate determination of the prostate volume after implantation of the seeds of a patient using either CT-scans or ultra-sound can prove to be a difficult task. Furthermore, the volume may vary from the time that determination was performed to the time of the implant. After the implantation, not only the prostate swells, as the seeds will inevitably deviate from their originally planned positions, influencing the dose to the prostate. In this work a first step is given in trying to quantify the dose variation due to the prostate swelling. The authors used a simplified model of the swelling, which consists of a step-function (the prostate swells immediately, and then immediately returns back to its original volume after the average period of the swelling—2 weeks). In order to test this model a real clinical treatment planning procedure was simulated and both results compared. When assuming the same conditions of the treatment planning system (that the volume of the prostate remains unchanged and that the seeds are point sources) there is a deviation of ∼14 % between the computational results and the prescribed dose of the treatment planning software, which indicates that in this particular case, with the model implemented here, the treatment planning system is overestimating the dose. Yet, with the same conditions of the treatment planning system, when a prostate swelling from 38.01 cm^3 to 57.02 cm^3, for 2 weeks is considered, the delivered dose is 120.94 Gy, which is 16 % lower than the prescribed dose. This value, when assuming a detailed seed description, is 107.77 Gy, which is 25 % lower than the prescribed dose. Future work would involve quantifying the effect of seed migration due to the swelling and more realistic models for the prostate swelling other than a step-function.

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