Monte Carlo iodine brachytherapy dosimetry: study for a clinical application

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Abstract. At present, all clinical algorithms used in brachytherapy are based on the TG-43 algorithm, which has the advantage to offer very fast calculation time. However, this formalism has many simplifications, assuming for example the patient tissue composition equivalent to water. For low energy brachytherapy seeds such as iodine seeds, it is of interest to evaluate the dosimetric differences between calculations based on Monte Carlo simulations (considered the gold standard) and the TG-43 formalism. For a 6711 model 125I seed calculated photon spectra were compared to spectra measured with a CdTe spectrometer. Good agreement was found except for the lowest energy peak which seems to be over-estimated by the experiment due to the contribution of the spectrometer CdTe diode to the measurement. Dose distributions in water are measured with EBT Gafchromic film and compared to the Monte Carlo calculation. A very good agreement is found. Finally, the method to create a MCNPX input file from computed tomography (CT) scanner images is explained and some preliminary isodose distributions are presented.

1. Introduction
The dose distributions of commercially available treatment planning systems (TPS) in brachytherapy are calculated using the TG-43 formalism [1]. In this, the AAPM task group 43 defined an equation to calculate the dose at any point in a water phantom. This equation takes into account different parameters, such as the spatial distribution of the activity in the seed, the photon absorption in the seed and water, the distance from the seed, etc. For a tumor seed loading consisting of multiple seeds, the dose is calculated for the individual seeds and the resulting distributions summed. This procedure is fast, however, inter-seed attenuation effects are ignored. Some authors [2-4] have shown that the dose at the periphery of the iodine implant was over-estimated by 6% when the interseed attenuation was ignored. Moreover, the TG-43 formalism considers the patient equivalent to a water sphere. The different tissue compositions are not taken into account. As a result of this, about 4% dose
overestimation would be noticed at the periphery of the iodine implant when the tissue is assumed equivalent to water [3, 5]. Therefore, the approximations due to the TG-43 equation introduce errors in the patient dose distribution calculation, in particular for low energy seeds using isotopes such as $^{125}$I or $^{103}$Pd. A solution to take into account the interseed attenuation and the patient tissue composition would be to carry out Monte Carlo (MC) dose calculations. Therefore, we are designing a TPS based on a MC code for low energy brachytherapy seeds. The start of this project consists of the detailed studies of the different iodine seed characteristics and the dose calculation using a MC code. In addition, in this paper, the model 6711 $^{125}$I seed characteristics are studied: the photon spectrum of the seed and the dose distribution in water are calculated and measured. Then, the first results are presented of a fictitious clinical example of a breast implant with 64 model 6711 seeds.

2. Material and methods

2.1. Monte Carlo simulations

2.1.1. Generalities. The used MC code was the MCNPX code version 2.5.0 [6]. The physical processes modeled were photoelectric effect (the fluorescent rays are apportioned among the x-ray lines $K\alpha_1$ ($L_3\rightarrow K$), $K\alpha_2$ ($L_2\rightarrow K$), $K\beta$ ($M\rightarrow K$ and $N\rightarrow K$)), pair production, coherent (Rayleigh) scattering and incoherent (Compton) scattering which are described by the MCNPX ‘detailed physics’ treatment (in contrast to the ‘simple physics’ treatment which does not take into account the fluorescent photons and incoherent scattering). Due to the low energy of iodine emission photons, the secondary electrons were not transported (for 30 keV photons in water, the electron range is smaller than 2 $\mu$m). The kerma approximation was considered to be valid for all simulations ('MODE P' and 'PHYS:P 100 0 0'). The MCPLIB04 photon cross section library, derived from the ENDF/B-VI.8 data library that was derived from EPDL97, was used [7]. Simulations were carried out with the incident photon number such that the statistical error on calculated values in the area of interest (where the isodoses were calculated) was below 2 %.

The 6711 source modeling (Amersham Health, Princeton, NJ, USA) consisted of a 3 mm long right circular cylinder of silver with 0.5 mm diameter and encased inside a cylindrically symmetric titanium shell of 0.06 mm thickness and 3.5 mm length. Each of the two quasi-hemispherical ends has been reproduced as a 0.4 mm radius half-sphere sitting on a 0.1 mm high cylinder. The iodine has been distributed uniformly on a 1 $\mu$m thick AgBr-AgCl layer, which was coated on the silver rod (figure 1). The halide layer was assumed to consist of equal parts of AgBr and AgCl [8-10].

![Figure 1. Geometry and dimensions of the model 6711 iodine seed in the MC simulations.](image)

2.1.2. Photon fluence spectrum simulation in air. The energy photon spectrum of the model 6711 iodine seed was calculated using the actual $^{125}$I photon spectrum (19 x-rays and 1 $\gamma$-ray [11]) and the simplified spectrum recommended by the TG-43 formalism update (4 x-rays and 1 $\gamma$-ray). The photons exiting the seed geometry were counted in energy bins of 0.05 keV width on an infinite plane located at 1 cm above and parallel to the seed in the air. The F1 MCNPX tally (which is the number of
particles crossing a surface) was used. The number of source photons was $1 \times 10^8$. The statistical error was below 2% except for some bins, but the photon number in these bins was insignificant.

2.1.3. Two-dimensional dose calculation in water. The model 6711 seed inside a 6 French plastic tissue-equivalent catheter was modeled at 0.25 mm above and parallel to the surface centre of an EBT type high-sensitivity radiochromic film (International Specialty Products, Wayne, NJ, USA) in a 30 cm x 30 cm x 30 cm water tank. The 5.94 cm x 5.94 cm x 0.0234 cm rectangular EBT film was simulated with all layers accounted for (figure 2).

![Figure 2. EBT GafChromic film structure/dimensions.](image)

Rectangular voxels with a size of 0.06 cm x 0.06 cm x 0.0017 cm were created in each active layer and defined as MCNPX repeated structures (10,000 voxels were defined in each active layer). Even if the thickness of the active layer is very thin, the electron range for 30 keV photons is much smaller than the voxel thickness (only 0.96 µm in the clear polyester layer). The kerma approximation is, therefore, valid. The dose with the F6 tally was calculated in each voxel ('lattice tally'), then averaged two by two between corresponding voxels (the same x and y) of the active layers. The F6 tally is a track length estimator which, after multiplication by the heating number $H(E)$, estimates the energy deposition. Afterwards, a Matlab program (The MathWorks, Natick, MA) was written to normalize each dose by the dose deposited on the transverse axis of the seed at 1 cm and obtain the isodoses.

2.1.4. Clinical application of a breast brachytherapy. CT images of a breast cancer patient were used to create the MCNPX input file. The actual treatment is carried out with $^{103}$Pd seeds, but, in order to keep the same model of seed studied before, the 64 seeds present in the scanner images were considered for this fictitious study to be iodine model 6711 seeds. The voxel size of the images was 0.094 cm x 0.094 cm x 0.5 cm. From a Matlab program, the part of the images where the seeds are contained was selected to limit the number of voxels (about 500,000 voxels). Then, the Hounsfield Units (HU) corresponding to the seeds were replaced by the HU corresponding to fat. This prevents, during the next step, bone material being assigned to structures in the breast. The next step consisted in converting the HU of the selected part of the images ("Hounsfield map") in different material numbers ("material map") according to the CT calibration curve (figure 3).

The MCNPX input file was created defining 6 materials (air, lung, adipose tissue, soft tissue, bone cartilage and bone). Several densities were assigned to the materials (2 for air, 3 for lung, 1 for adipose tissue, 3 for soft tissue, 4 for bone cartilage, 1 for bone). In fact, it is not possible to define a continuous density for the materials with the MCNPX code. Then, the 64 model 6711 seeds were superimposed on the material map at the locations determined from the CT images by a C++ program. This method to create the input file allows taking into account the interseed attenuation and the tissue inhomogeneities. The dose with the F6 tally was calculated in each voxel and the results were processed by a Matlab program to normalize each dose by the maximum dose and to obtain the isodoses.

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1 The CT images were supplied by Dr. JP Pignol and B Keller of Sunnybrook Health Sciences Centre at Toronto.
Figure 3. The procedure to create the MCNPX input file from the breast brachytherapy CT images.

2.2. Energy photon spectrum measurement in air
An XR-100T-CdTe spectrometer (Amptek, Bedford, MA, USA) was used to determine the photon energy spectrum in air of the model 6711 seed. The detection volume of this detector was a 3 x 3 x 1 mm³ CdTe Schottky diode with a 400 V nominal bias voltage. The crystal was mounted on a thermoelectric (Peltier) cooler in order to reduce the leakage current and improve the charge transport properties (approximately -20°C) [12]. The model 6711 seed was located in air inside a catheter. The spectrometer was aligned on the transverse axis of the seed at about 100 cm distance. A 2 mm thick tungsten collimator with a 2 mm diameter hole was used. The energy calibration of the spectroscopic system was accomplished with γ rays from a 133Ba calibration source (energy range: 0-40 keV). The channel width was about 0.05 keV per channel. The measured x-ray spectrum was corrected with a stripping method using the response function calculated with the EGSnrc MC code [13].

2.3. Dose measurements in water
A circular EBT Gafchromic film was located inside a water tank, and sealed with a tape to prevent water from leaking into the film. A single seed (apparent activity: 8.8 mCi) was positioned inside a catheter placed on the film. The same setup was used without the source for the control film. The irradiation time was 24 hours. The films were scanned before and after irradiation with an Agfa Arcus II flat-bed document scanner [14]. Using the calibration curve obtained from a 102Ir source [15], the net optical density was converted into dose. Then, the isodoses were normalized to the dose at 1 cm on the transverse axis of the seed.
3. Results and discussion

3.1. Photon energy spectrum of the model 6711 seed

3.1.1. Comparison seed spectrum for the two iodine input spectra. Figure 4 shows the photon spectra exiting the model 6711 as calculated with MCNPX using the $^{125}$I spectrum recommended by the TG-43 update [1], and the actual spectrum of $^{125}$I [11]. The spectrum was normalized to unity at the 27.4 keV peak. The rays below 5 keV are due to the $K_\alpha$ and $K_\beta$ transitions in titanium. The photons near 22 keV and 25 keV are silver $K_\alpha$ and $K_\beta$ characteristics x-rays, respectively. All other rays are directly due to the $^{125}$I radionuclide decay.

The two spectra are identical, except for the peak at 31 keV. With the actual iodine spectrum, the spectrum presents two rays in the energy bins: 30.9 keV-30.95 keV and 30.95 keV-31 keV with respectively 0.098 and 0.190 normalized photon number. With the simplified iodine spectrum, only one ray is present in the energy bin: 30.95 keV-31 keV with 0.291 normalized photon number. Therefore, with the iodine simplified spectrum, the rays at 30.9 keV-30.95 keV energy bin are offset 0.05 keV. The differences are very small and the two spectra can be considered identical.

![Figure 4. Photon spectrum for model 6711 seed calculated with MCNPX from the $^{125}$I actual spectrum and the simplified spectrum recommended by the TG-43 update. The spectra were normalized to unity at the 27.4 keV peak.](image)

3.1.2. Comparison between the calculated and measured spectrum. Table 1 compares the calculated spectrum of the 6711 seed to the spectrum measured with the CdTe detector. The agreement between the calculation and the measurement is reasonable, except for the peak at the lowest energy.
Table 1. Comparison between the photon spectrum calculated using MCNPX and the spectrum measured with the CdTe detector.

| Energy (keV) | Normalized photon number | Measurement - MCNPX |
|-------------|--------------------------|---------------------|
|             | MCNPX | Measurement |                 |
| 4.5         | 0.010 | 0.210 | 0.200 |
| 22.1        | 0.255 | 0.314 | 0.059 |
| 24.9        | 0.082 | 0.075 | -0.007 |
| 27.5        | 1.0 | 1.0 | - |
| 31.0        | 0.288 | 0.248 | -0.040 |
| 35.5        | 0.104 | 0.094 | -0.010 |

It was noticed that when a slab of 3 cm of solid water was introduced between the detector and the seed the peak contribution at 4.5 keV remained constant. So, this difference between the calculation and the measurement could be attributed to an element in the detector which contributes to the 4.5 keV peak. This element seems to be the tellurium in the detector diode, which exhibits L-transitions at 4.34 keV and 4.61 keV. Because L-transitions are not taken into account in MCNPX, for this part of the study we used the EGSnrc code [16]. The simulation confirms the tellurium diode contribution for the peak at 4.5 keV. This effect must be studied in detail with a more realistic detector geometry simulation.

3.2. Dose distributions in water: comparison between calculations and measurements

The isodoses normalized by the dose at 1 cm on the transverse axis of the seed calculated by MCNPX and measured by EBT Gafchromic film in a water tank are presented in figure 5. The agreement between the calculation and the measurement is very good (within 2% in general).

Figure 5. Isodoses normalized by the dose at 1 cm on the transverse axis of the seed calculated by MCNPX and measured by EBT Gafchromic film in water. The ellipse in black represents the orientation of the seed.
The most important differences (up to 10%) are noted on the longitudinal axis of the seed. According to the study carried out by Dolan et al. [10], these differences are mainly due to a possible 0.4 mm offset of the vertical position of the silver rod in the Ti shell and the end weld thickness variations (±0.15 mm) when the seed is produced by the manufacturer.

3.3. Clinical application of a breast brachytherapy: the preliminary results

![Figure 6](image.png)

Figure 6. Two image slices with the isodoses normalized by the maximum dose of a fictitious breast brachytherapy treatment with 64,671 seeds. The first slice is the central CT image of the treatment plan and the second slice is located 5 mm below the central image towards the patient’s feet.

Figure 6 presents the isodoses normalized by the maximum dose of a breast brachytherapy treatment with 64,671 seeds calculated with MCNPX. The interseed attenuation and the tissue inhomogeneities are taken into account in this dosimetry study. It can be noticed that the isodoses for 10% and 20% are present in a rib portion. In future research, the MCNPX code will be used as a reference and a fast MC code, such as PTRAN_CT [17] will be studied to design the TPS.

4. Summary

The $^{125}$I simplified spectrum recommended by the TG-43 update formalism can be used in Monte Carlo simulations since no differences in the photon spectrum of the model 6711 seed were obtained. The spectral measurement with the CdTe detector confirmed the calculations. A contribution for the peak at 4.5 keV of tellurium transitions in the detector diode is suspected. The study of dose measurements in water showed that the EBT Gafchromic film is an appropriate dosimeter for low energy brachytherapy seeds and that agreement with MCNPX simulations is good. A method to create a MCNPX input file taking into account the interseed attenuation and the tissue inhomogeneities was developed.

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