Diffusion of ^{220}Rn and ^{212}Pb in diffusing alpha-emitter radiation therapy dosimetry with Geant4

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INTRODUCTION

Diffusing alpha-emitter radiation therapy (DaRT) utilizes short-lived alpha-emitting atoms generated from the decay of ^{224}Ra. The radioactive daughters, ^{220}Rn and ^{212}Pb diffuse within tumor tissue. This diffusion results in a high-dose region that extends a few millimeters around the source, effectively overcoming the limited tissue penetration range of α −particles[1-3]. However, the extent of diffusion of α-emitting atoms varies based on the tumor type and between the patients, leading to a heterogeneous dose distribution. Furthermore, existing dosimetry software is unable to simulate this environmental diffusion and accurately compute the absorbed dose in the surrounding medium.

AIM

To develop a Monte Carlo-based dosimetry package to simulate the decay of ^{224}Ra, its daughters, and the interaction of the decay products with matter considering the environmental diffusion of ^{220}Rn and ^{212}Pb.

METHODS

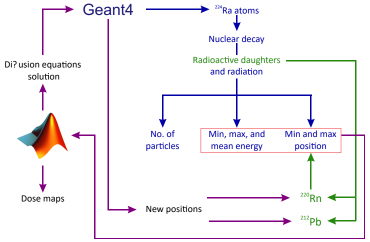
1. Solve the diffusion equations of ^{220}Rn and ^{212}Pb provided by Arazi et al.[1] using an in-house Matlab script and use the solution as an input to an in-house Geant4-based dosimetry package called Alpha Dosimetry Calculation (AlDoC):

$$\frac{\partial n_{Rn}}{\partial t} = D_{Rn}\nabla^2 n_{Rn} + S_{Rn} - \lambda_{Rn} n_{Rn}$$

$$\frac{\partial n_{Pb}}{\partial t} = D_{Pb}\nabla^2 n_{Pb} + S_{Pb} - \lambda_{Pb} n_{Pb} - \alpha_{Pb} n_{Pb}$$

2. Use the AlDoC toolkit to simulate:

- Geometry and material of a hollow DaRT seed (length: 10 mm, inner Ø: 0.4 mm, outer Ø: 0.7 mm, ρ = 7.92 g/cm^3)
- Decay chain of ^{224}Ra
- Retrieve: Number of particles generated and their energy
- Obtain the energy spectra of the entire decay chain of ^{224}Ra
- Transport ^{220}Rn and ^{212}Pb to the new positions based on the solution of their diffusive equations
- Score the absorbed dose in the surrounding medium using a voxelized geometry
- Generate 3D dose maps to observe the distance the –particles can reach from the seed



RESULTS

The results of the simulations such as the spectra emitted during the entire decay chain and dose maps at different distances from the seed are shown in the following figures.

The energy spectra of ^{224}Ra are shown in Figure 1. These results were compared to values reported by the IAEA Live Chart of Nuclides database [4]. Figure 1a represents the alpha energy spectrum which had a difference of 0.006-0.015% with the database. *Figures 1b-1d* are the β-particle energy spectrum of ^{212}Pb, ^{212}Bi, and ^{208}Tl, each with a 4.81%, 0.179%, and 0.240% difference range, respectively. The γ-photon energy spectrum shown in Figure 1 e) also had a good agreement with the IAEA database values having a difference of up to 0.081%.

Figure 2 shows the resulting dose distribution from only the α-particles emitted from the α-emitter daughters of the ^{224}Ra decay at different distances from the center of the DaRT seed. The absorbed dose values decrease with distance in the three directions (x, y, z), indicating that the α-particles can reach a distance between 3 and 4 mm from the seed. These results agree well with published work [5].

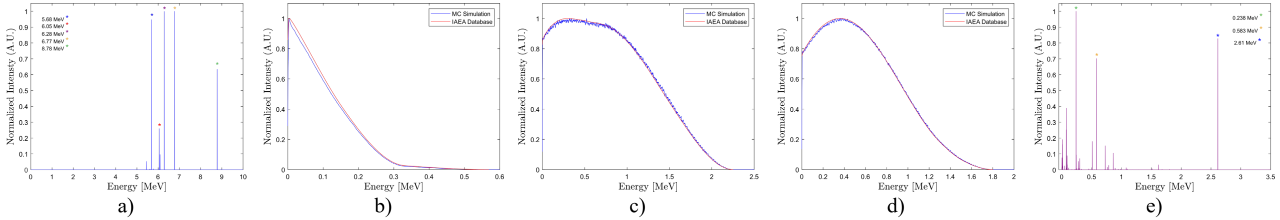


Figure 1. Normalized energy spectra of (a) α-particles, (b-d) β-particles, and (e) γ produced during the decay of ^{224}Ra. Figures b-d show the simulated energy spectra (blue solid line) compared to reported data from the IAEA (red solid line).

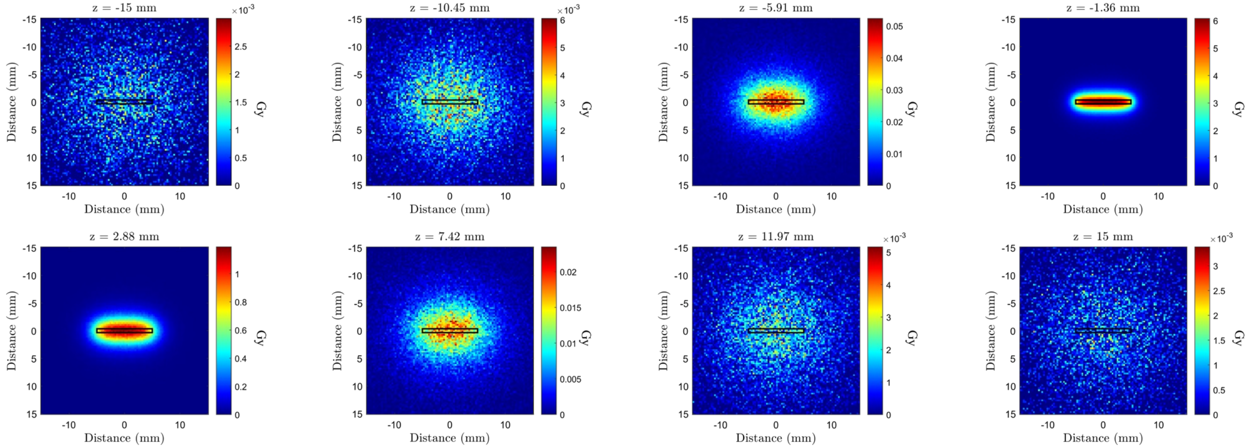


Figure 2. Dose distribution around the seed at different distances taken over the z-axis of the simulated world going from -4 mm up to 3 mm away from the center of the seed (represented as the black rectangle).

CONCLUSIONS

In this work, the diffusion of ^{220}Rn and ^{212}Pb from the ^{224}Ra decay chain was implemented in the user code of AlDoC, extending the distance at which α-particles deposit their energy. This extension reached a distance of ~4 mm from the seed, similar to the ones reported by the literature. The energy spectra of the DaRT seed obtained with this code matched literature values within an acceptable difference. This software can be used in other α-particles dosimetry applications.

REFERENCES

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ACKNOWLEDGEMENTS

The authors thank the fundings and resources provided by the CONACyT Mexico, Institute TransMedTech Montreal, Digital Research Alliance of Canada, and the Jewish General Hospital foundation.