Determination of Absorbed Dose to Water for the DaRT Brachytherapy Source in Monte Carlo

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INTRODUCTION

- Diffusing alpha Radiation Therapy (DaRT) is a ^{224}Ra source electroplated onto a stainless-steel wire that is coated with a polymer such that the only radionuclides that leave the containment is the first daughter ^{220}Rn and subsequent progeny [1].
- Alpha-emitting radionuclides in the past have not been used in brachytherapy treatments of solid tumors because the range of 5-9 MeV alpha-particles in tissue is roughly <0.09 mm [2].
  - However, initial investigations of DaRT dose deposition shows that the diffusive flow of the daughter radionuclides can extend the dose as far as 7 mm away from the source depending on tissue type [3-5].
- This source has received two breakthrough device designations from the FDA: (1) treatment of skin cancer and (2) treatment of patients with recurrent glioblastoma multiforme (GBM).
- The DaRT source has just begun its second clinical trial in the US for treatment of Squamous Cell Carcinoma (SCC) with its current source strength being quantified as activity in units of Becquerel (Bq) [1,6].
  - While this quantity is of interest for applications like Radiopharmaceutical Therapy, where the time integrated activity (TIA) is converted to absorbed dose, the usefulness for brachytherapy applications is not as relevant.
- In order to provide a source strength quantity that quantifies the energy deposition per decay, an absorbed dose to water formalism has been developed and validated in Monte Carlo for the DaRT source.
- At the University of Wisconsin Medical Radiation Research Center (UWMRRC), absorbed dose to water has been measured for a ^{210}Po pure alpha-emitting radionuclide in an extrapolation ionization chamber. A modified version of this chamber serves as a potential future measurement platform.

METHODS

- TOPAS Monte Carlo simulations were used to estimate signal and correction factor magnitude for the DaRT source in a windowed extrapolation ionization chamber geometry.
  - The initial extrapolation ionization chamber measurements at UWMRRC were acquired with a windowless design, however, due to the DaRT source curved geometry and polymer coating the surface cannot serve as the high voltage electrode to establish the electric field.
- Geometry optimization was found through minimization of correction factor magnitude and maximization of signal for a 3 µCi source in the windowed extrapolation ionization chamber. This was done by adjusting the size of the collecting electrode, source to mylar distance, mylar thickness, and distance between the mylar and collecting electrode (air gap).
- The absorbed dose to water at a point 0.5 mm from the center of the source normalized by activity, $\frac{\dot{D}_{water}}{A_0}$, formalism for the DaRT source is proposed as:

$$\frac{\dot{D}_{water}}{A_0} = \frac{k_{MC,\alpha}\left[\left(\frac{\overline{W}}{e}\right)_{air} \cdot \bar{S}_{air}^{water}\right]_{\alpha} + k_{MC,\beta}\left[\left(\frac{\overline{W}}{e}\right)_{air} \cdot \bar{S}_{air}^{water}\right]_{\beta}}{A_0 \cdot \rho_0 \cdot Coll_{area}} \cdot \left(\frac{\Delta I}{\Delta l}\right)_{l \to 0} \cdot (k_{meas}) \cdot (k_{MC})$$

  - Where $k_{MC,\alpha,\beta}$ is the Monte Carlo weighting factor for alpha particle and beta particle dose contribution, respectively, $\left[\left(\frac{\overline{W}}{e}\right)_{air} \cdot \bar{S}_{air}^{water}\right]_{\alpha,\beta}$ is the average energy required to create an ion pair in air and stopping power ratio of water to air for alpha and beta particles.
  - A_0 is the initial activity of the source, ρ_0 is the air density at standard temperature and pressure, $Coll_{area}$ is the effective area of the air cavity, and $\left(\frac{\Delta I}{\Delta l}\right)_{l \to 0}$ is the change of ionization current as a function of air gap, l.
  - k_{meas} and k_{MC} are the measurement-based and Monte Carlo based correction factors that are summarized in Table 1.

Correction Factors:

Component of	Correction Factor	Description	Equation
k_{meas}	k_{tp}	Temperature and pressure	$k_{tp} = \frac{273.2 + T}{273.2 + 22} \cdot \frac{101.33}{P}$
	k_{recom}	Initial and general recombination	$k_{recom} = \frac{1}{Q_{sat}} = \left(\frac{1}{Q_{sat}} + \frac{\alpha}{V} + \frac{\beta}{V^2}\right)e^{-\gamma V}$
	k_{pol}	Polarity	$k_{pol} = \left\lvert\frac{M^+ - M^-}{2M^-}\right\rvert$
k_{MC}	$k_{backscatter}$	Backscatter from collecting electrode	$k_{backscatter} = \frac{D_{vol,air,air}(l)}{D_{vol,air,copper}(l)}$
	k_{div}	Accounts for loss of particles as air gap changes in extrapolation	$k_{div} = \frac{D_{vol,air,air}(l \to 0)}{D_{vol,air,air}(l)}$
	k_{window}	Entrance window attenuation	$k_{window} = \frac{D_{vol,air,copper}(l)}{D_{vol,mylar,copper}(l)}$
	k_{vol}	Conversion from volume dose to point dose	$k_{vol} = \frac{D_{point,air,air}(vol \to 0)}{D_{vol,air,air}(l \to 0)}$

Table 1. Description and equations for the correction factors.

RESULTS

- Optimal correction factor magnitude was found for a 2 mm by 3 mm rectangular collecting electrode, 500 µm source to mylar distance, 3 µm aluminized mylar thickness, and air gap distances ranging from 300-500 µm, shown visually in Figure 1.

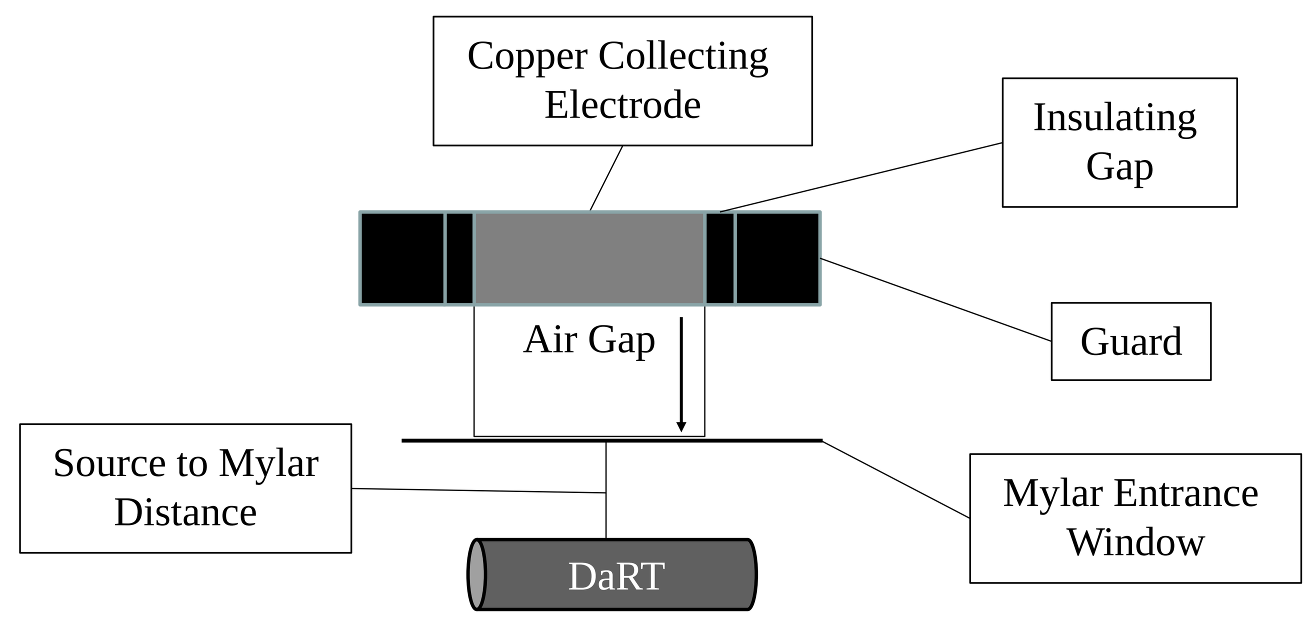

Figure 1. Windowed extrapolation ionization chamber geometry for absorbed dose to water measurements of the DaRT source.

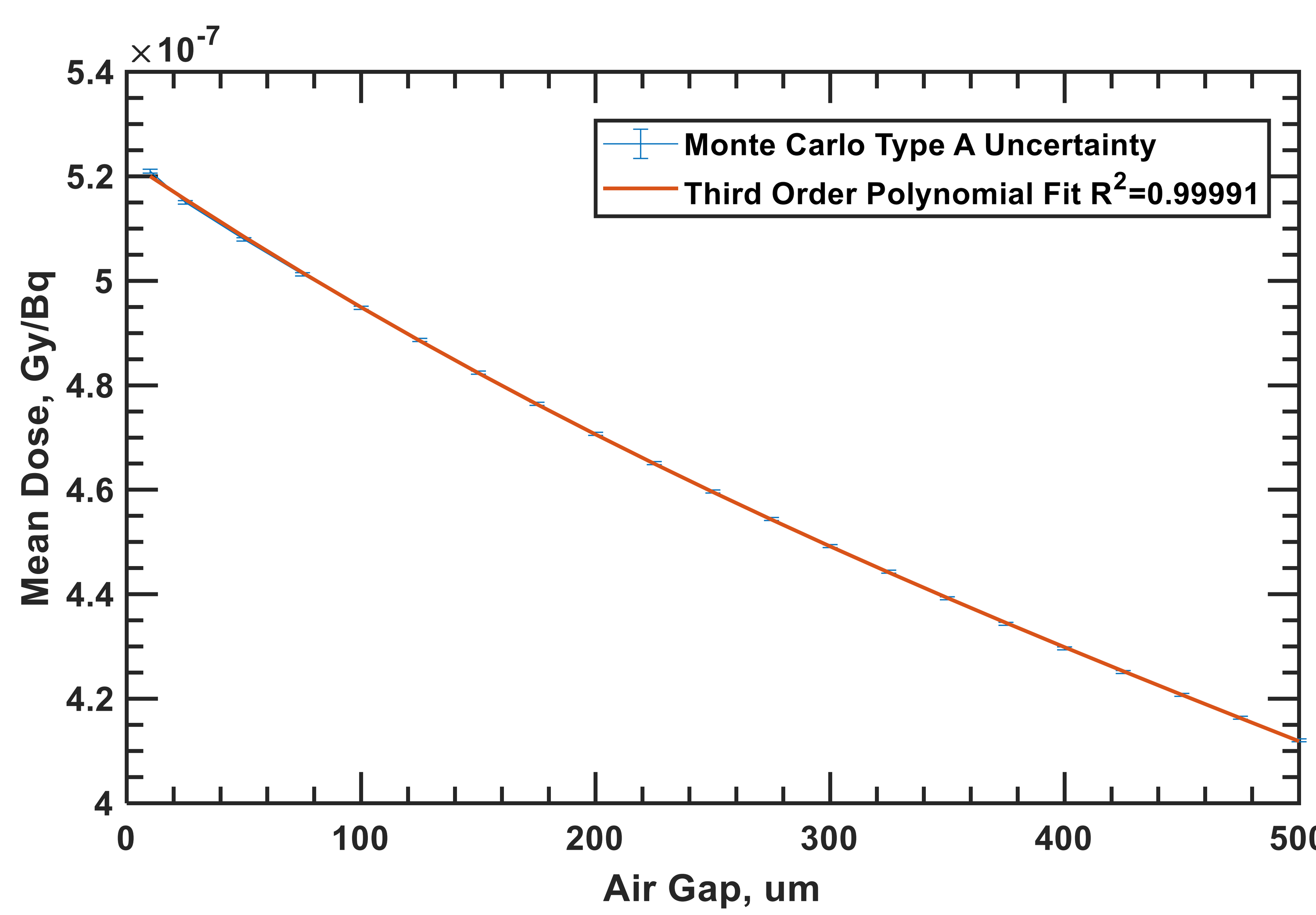

Figure 2. Dose to air as a function of air gap distance, with a third order polynomial fit to account for divergence relative to a 0-distance air gap.

- Figure 2 shows the effects of side losses caused by the divergence effect when extrapolating, with a third order polynomial fit applied. Table 2 shows a compilation of the values and uncertainties from the results of Monte Carlo simulations for each correction factor.

Correction Factor	k_{meas}			k_{MC}			
Air Gap (um)	k_{tp}	k_{recom}	k_{pol}	$k_{backscatter}$	k_{div}	k_{window}	k_{vol}
300 µm				0.996 (0.08%)	1.160 (0.09%)	0.931 (0.08%)	
325 µm				0.996 (0.07%)	1.173 (0.08%)	0.931 (0.08%)	
350 µm				0.996 (0.07%)	1.186 (0.08%)	0.931 (0.08%)	
375 µm				0.996 (0.07%)	1.199 (0.08%)	0.932 (0.08%)	
400 µm	Obtained During Physical Measurements			0.996 (0.07%)	1.213 (0.08%)	0.932 (0.08%)	1.230 (0.73%)
425 µm				0.996 (0.07%)	1.226 (0.08%)	0.933 (0.08%)	
450 µm				0.996 (0.07%)	1.238 (0.08%)	0.933 (0.08%)	
475 µm				0.997 (0.07%)	1.251 (0.08%)	0.933 (0.08%)	
500 µm				0.997 (0.07%)	1.264 (0.08%)	0.933 (0.08%)	

Table 2. Magnitudes and uncertainties for Monte Carlo based correction factors at each measurement air gap.

CONCLUSIONS

- A method for the measurement of absorbed dose to water for the DaRT source has been determined and geometry optimized.
- An absorbed dose to water standardization and characterization would provide a more clinically relevant quantity of source strength for the DaRT source.

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