Evaluation of GEANT4 Monte Carlo platform for absorbed dose calculation using alpha-emitting radionuclides

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Purpose: Targeted radionuclide therapy (TRT) is a systemic therapy based on radiopharmaceuticals that are directly injected into the patient's bloodstream. TRT with alpha particles leverages the high linear energy transfer (LET) and short range of alpha particles in tissue when compared to beta particles. Dosimetry in TRT involves calculation of absorbed dose or microdosimetric quantities, such as lineal or specific energy, using computational methods that employ platforms with distinct transport physics, nuclear decay data, and interaction cross-section data. Therefore, there is a need to generate experimental data that can be used to validate the various existing dose calculation platforms. Monte Carlo (MC) codes, such as GEANT4, are often employed for dosimetric calculations in TRT. Hence, the purpose of this work was to use an extrapolation ionization chamber (IC) to measure absorbed dose to air from alpha-emitting radionuclides to experimentally validate the GEANT4 MC code. The comparison of experimentally-measured and MC-calculated absorbed dose to air was performed using a pure alpha emitter ie. ^{210}Po.

Methods: Figure 1 illustrates the cylindrical geometrical setup chosen in this work as well as the printed circuit board (PCB) utilized in the IC. The absorbed dose to air per unit radioactivity at each air gap can be measured by:

$$\dot{D}_{air}(l) = \frac{1}{A_o}\frac{\left(\frac{\overline{W}}{e}\right)_{air}}{\rho_o \pi r^2}\frac{I}{l}\left(k_{pol}k_{recom}k_{TP}k_{elec}\right) \tag{1}$$

where A_o is the radioactivity of the alpha-emitting radionuclide, ρ_o is the air density at standard temperature and pressure, r is the radius of the cylindrical air cavity, $(\overline{W}/e)_{air}$ is the mean energy required to liberate an ion pair in dry air, I is the ionization current, and l is the air gap between the collector and source surfaces. k_{pol} is the polarity correction that accounts for the difference in signal due to the polarity of the applied bias:

$$k_{pol} = \left|\frac{Q^+ - Q^-}{2Q^-}\right| \tag{2}$$

where Q^+ and Q^- are the positive and negative charges, respectively, collected by the IC. k_{recom} is the recombination correction that corrects for the incomplete signal collection due to recombination effects:

$$k_{recom} = \frac{Q_{sat}}{Q} \text{ with } \frac{1}{Q} = \left(\frac{1}{Q_{sat}} + \frac{\alpha}{V} + \frac{\beta}{V^2}\right)e^{-\gamma V} \tag{3}$$

where Q_{sat} is the saturation charge, Q is the collected charge, and V is the applied voltage. The terms α, β, and γ are fitting parameters. The saturation charge was determined by fitting the experimental data to the model shown in equation 3. k_{TP} is the temperature and pressure correction that accounts for the difference in the mass of the air cavity due to non-standard temperature and pressure:

$$k_{TP} = \frac{273.15+T}{273.15+22} \times \frac{101.33}{P} \tag{4}$$

where T is the temperature in degrees Celsius and P is the pressure in kPa. k_{elec} is the electrometer correction that converts the displayed current or charge values to the true values.

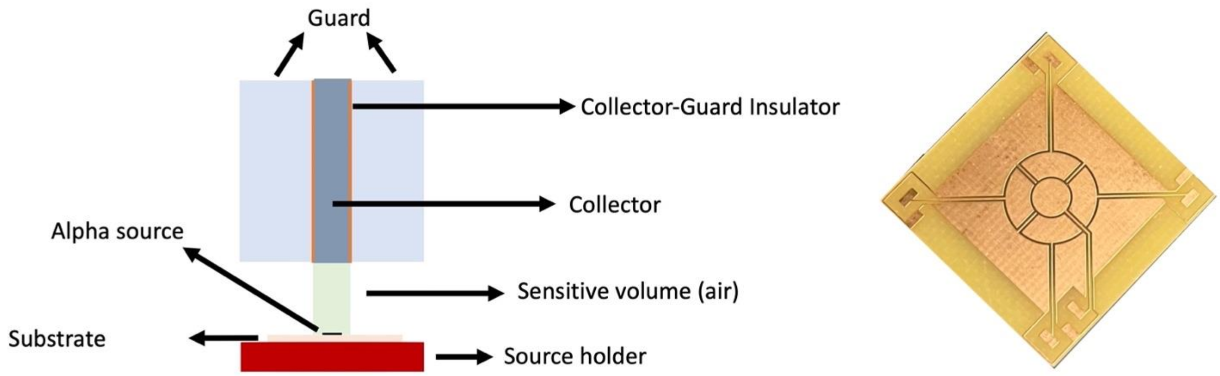

Figure 1. The measurement schematic (left) and the printed circuit board (PCB) IC (right) are shown.

The PCB was produced by electrochemical etching of conventional circuit board materials (electroless nickel immersion gold over FR-4 fiberglass). The collector was 4.5 mm in diameter and enclosed by a guard ring extending radially beyond the collector by at least 6.5 mm. The differential capacitance between isolated guard sectors aided in establishing parallelism between the source and collector. The absorbed dose to air was measured using a ^{210}Po source with a 5.305 MeV alpha emission and 1.253 μCi activity. Four independent measurement trials were conducted by measuring the ionization current in the air cavity. Voltages in the 1-200 V range were employed for a 0.3 mm air gap to calculate the k_{recom} correction. An electric field strength of 150 V/mm was selected and the air gap was varied between 0.3-0.525 mm in 0.025 mm increments. The charge was collected using a MAX4000 electrometer. The experimental setup was modeled in GEANT4 v10.6 MC code. A physics list consisting of *G4RadioactiveDecay*, *G4Decay*, *G4HadronElasticPhysicsHP*, *G4HadronPhysicsQGSP_BIC_HP*, *G4IonElasticPhysics*, *G4IonQMDPhysics*, and *G4StoppingPhysics*. The atomic de-excitation was turned on and the production thresholds were set to 1 μm. The internal GEANT4 decay data were used to simulate the ^{210}Po source. Absorbed dose to air per unit radioactivity was calculated for air gaps in the 0.3-0.525 mm range.

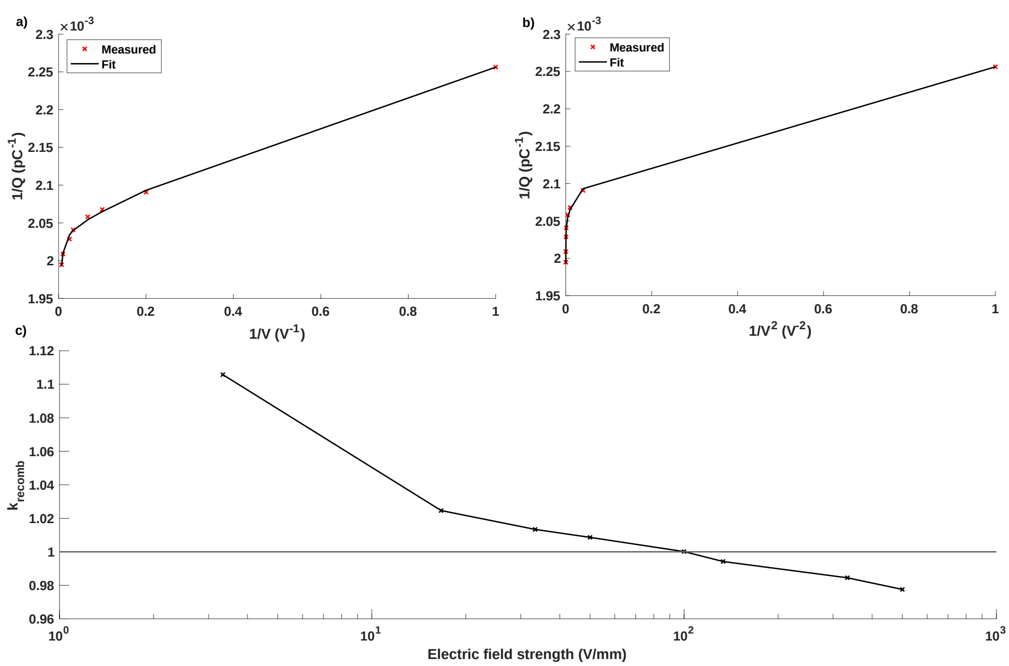

Figure 2. The fitted recombination model using measured charge as a function of a) $1/V$ and b) $1/V^2$. c) k_{recom} as a function of electric field strength.

Results: Figure 2 reports the recombination correction for various electric field strengths. The chosen field strength of 150 V/mm led to a correction of <0.5%. For electric field strengths >200 V/mm, the charge multiplication effects were observed. Contrarily, the recombination effects of up to 10% were noted for field strengths <10 V/mm. The measured absorbed dose was found to be lower than the MC-calculated dose. A mean deviation of 4.20% was found between the two datasets. The MC-calculated absorbed dose agreed with the experimental data within 5% across all air gaps. The total combined uncertainty, compiled in table 1, in the measured dose was calculated to be ~4% at k=2.

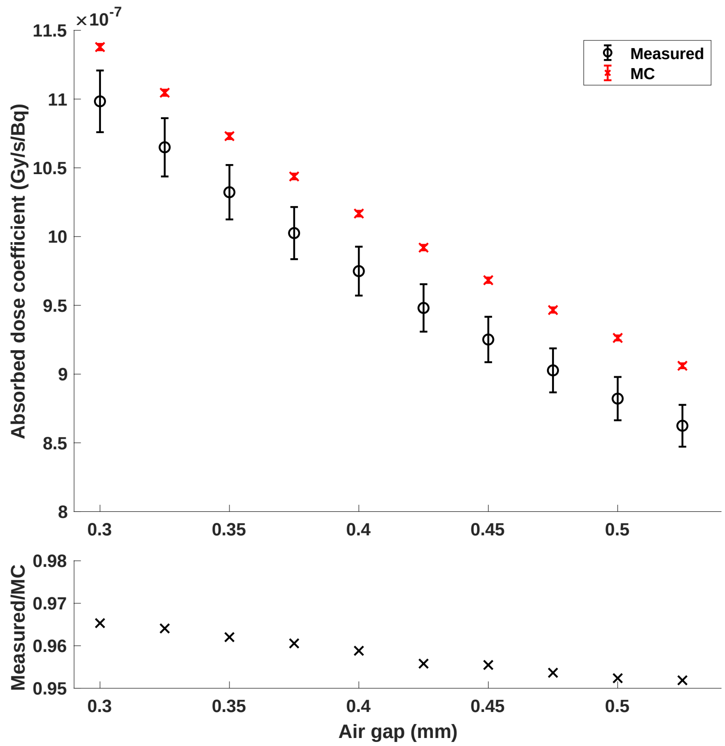

Figure 3. The measured and MC-calculated absorbed dose to air from ^{210}Po source at 0.3-0.525 mm air gaps.

Table 1. The uncertainty budget for measured absorbed dose to air for a 0.3 mm air gap.

Component of uncertainty	Type A (%)	Type B (%)
Net current	0.13	
Current repeatability	1.70	
Air density correction		0.10
Recombination correction		0.10
Average energy per ion pair		0.20
Effective Radius of the cavity		0.40
Radioactivity		1.00
Combined uncertainty (k=1)	2.04	
Combined uncertainty (k=2)	4.08	

Conclusions: Experimental validation of the GEANT4 MC code was performed using absorbed dose measurements for a pure alpha-emitting radionuclide. The MC results agreed with the experimental data within 5%.

Relevance to CIRMS: This work is part of a doctoral thesis aimed at constructing absorbed dose standards for alpha-emitting radionuclides utilized in TRT. This work fits the mission statement of CIRMS since it develops absorbed dose measurement strategies for TRT agents and aims to standardize the absorbed dose calculation methods for all TRT treatments. The first author is an aspiring academic/clinical medical physicist with research focused on radiation metrology.