Validation of the Monte Carlo Detector Effects Model for the UCT POLARIS Compton Camera

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Abstract. The benefit of proton therapy will only truly be realized once an experimental in-vivo dose verification system has been developed. The use of a Compton Camera (CC) allows detection of the secondary radiation, specifically Prompt Gammas (PG), produced at the location of the dose deposition. The UCT Polaris detector is composed of two separate stages with two CdZnTe positron-sensitive crystals per stage, configurable in an orthogonal or face-to-face alignment. Previous work has shown that the CdZnTe crystals experience significant deadtime when exposed to a high dose-rate proton beam. The Monte Carlo Detector Effects (MCDE) model was developed to replicate these deadtime effects. The goal of this work was to adapt the MCDE model to the UCT Polaris detection system, to allow for new detector configurations and broaden the applicability of the model to high-activity gamma sources. The MCDE model results are compared to measured data from a short-lived ^{68}Ga positron source in face-to-face configuration. The observed differences between the measured and simulated results point to an overestimation in the underlying Geant4 model and to a change in one of the timing parameters used in the MCDE model. A two-parameter optimization code was run to improve the overall comparison between simulation and experiment, providing the most extensive validation of the MCDE model to date.

1. Introduction

Compton Cameras (CCs) have been studied extensively as a tool for verifying the in vivo range of proton beams delivered to patients during proton radiotherapy, through the imaging of prompt gamma rays emitted during tissue irradiation as reviewed by Polf and Porodi [1]. Of particular interest are CCs with CdZnTe crystals, that are characterised by high position and energy resolution [2]. Experimental studies conducted with proton beams in laboratories and clinical radiotherapy facilities demonstrate that in-vivo imaging is feasible ([3], [4]). However, at clinical dose rates the detector efficiency for multiple scattering events becomes too low for accurate reconstruction of the dose range.

In order to investigate the detector efficiency, Maggi and Polf developed a quantitative Monte Carlo and Detector Effects (MCDE) model for simulating gamma ray interactions with a CdZnTe CC detector [5]. The MCDE model enabled an analysis of deadtime effects and false coincidence events in the detector, by simulating the effects of electronics on data capture. The model was validated by comparison to a proton beam experiment in a PJ3 detector with 16 PolarisJ CC modules in a two plane configuration. In our paper we show that the MCDE model generalises to arbitrary detector configurations, by adapting it to the UCT PolarisJ Compton Camera detector. We demonstrate the broader applicability of the model, by replicating an experiment with a high-activity ^{68}Ga positron source. The true and simulated detectors are compared with respect to their characteristic deadtime behaviour. The model is further optimised to improve the overall comparison between simulation and experiment.

2. Method

2.1. MCDE: A Brief Overview

A flowchart diagram of the MCDE model is drawn in Figure 1 [5]. In the data input stage, the experimental setup of interest is replicated with a Geant4 Monte Carlo model that simulates the interactions of gamma rays with the Compton Camera's CdZnTe crystals after emission from a radioactive source or beam target. The positions and deposited energies of single, double and triple scatter events (D_n) are used as idealised raw data for the MCDE model. In the initialisation stage, the positions are assigned time stamps t_n drawn from an exponential distribution, with a rate parameter corresponding to a desired dose rate or source activity. The position data is then discretised and indexed by pixel, crystal and module number. During detector timing and readout, the simulation models the detector response as a three-stage cycle: each module first detects a scattering event, then records interactions over a small timing window. The modules enter deadtime to process the event, and subsequently reactivate to listen for new events. The timing and readout section accounts for physical effects that distribute and dampen energy depositions in the CdZnTe crystals, of which dominant factors are the anode potentials, charge drift and the formation of electron clouds. Account is also made for timing delays associated with the proprietary electronics in the PolarisJ modules. The final output of the MCDE model is a list of position data, energy depositions and timestamps for all events recorded by the detector.

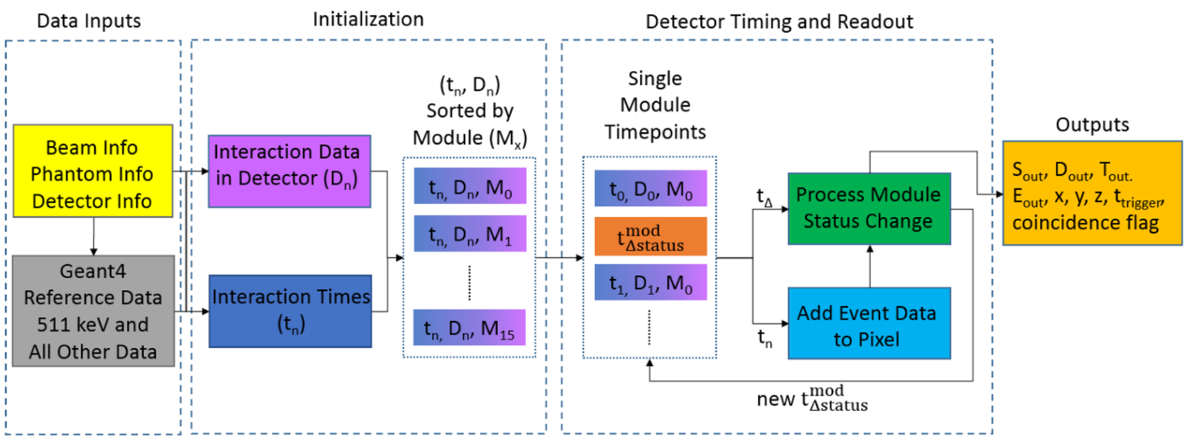


Figure 1: High level flowchart for the MCDE model [5].

2.2. Adapting MCDE to the UCT PolarisJ Compton Camera

The original MCDE model was hardcoded for a two-plane detector setup [5] as discussed in the introduction. The UCT Polaris detector is composed of two separate stages with two CdZnTe positron-sensitive crystals per stage, configurable in an orthogonal or face-to-face alignment. Neither alignment was compatible with the original model. Compatibility was achieved by transforming all position data, from either orthogonal or back-to-back alignments, to a standard configuration with the modules placed side-by-side on a fixed plane. The position discretisation was then adapted for the two-module case. The solution is justified on the basis that the MCDE model is blind to the relative configuration of the modules after simulating the interactions in the Geant4 model, as long as the modules do not intersect. For dose range reconstruction, an inverse transformation was applied to the event data after simulating detector timing and readout. Additional modifications were made to handle cases where the PolarisJ modules have either two or four crystals, and adjust the positions of anode planes in the detector.

2.3. Recorded Event Rate vs. Activity of a ^{68}Ga Positron Source

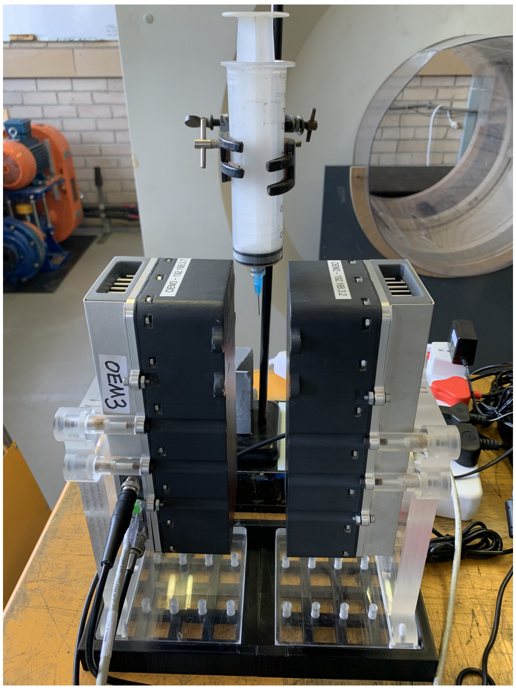


Figure 2: Image of the experimental setup for PG imaging of a ^{68}Ga point source [6].

A measurement-simulation comparison was drawn for an experiment with a short-lived ^{68}Ga point source [6] starting at an initial activity of 4.72±0.24 MBq (see Figure 2). The aim of the experiment was to identify the relationship between the expected rate of raw singles events in the CCs (n) and the recorded event rate (m), as a function of the activity A. The graph of event rate $m(A)$ versus A is called the deadtime curve. The relationship between event rate m and expected rate n, in the range of activities studied, was captured by a non-paralysable deadtime model [7]

$$n = \frac{m}{1 - m\tau_{np}} \tag{1}$$

where τ_{np} is a non-paralysable deadtime parameter unique to the detector. The setup was replicated with 5×10^7 simulated decays in the Geant4 model. The MCDE model was run at 200 source activities evenly spaced between 1 and 5000 kBq, using a small fixed sample of the simulated dataset. For the MCDE model, the expected event rate was calculated directly from input parameters, whereas for experiment the expected event rate was estimated with a linear fit to data at low activity (160-220 kBq). Scattering events with more than three interactions were excluded from the measured event rate calculation for both cases.

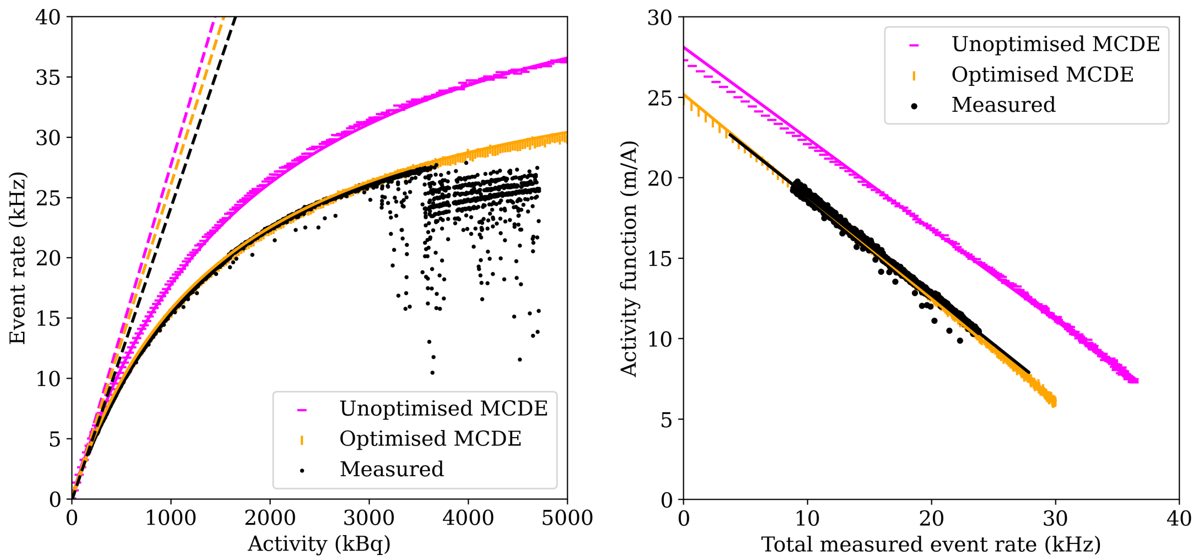
The real and simulated detectors were compared with respect to their non-paralysable deadtime parameters τ_{np}. This follows from applying a weighted linear fit $y = am + b$ to the activity function $\frac{m}{A}(m)$, which yields the estimate $\tau_{np} = -a/b$.

2.4. MCDE Model Optimisation

A two-parameter optimisation was carried out to improve the comparison between measurement and simulation for the MCDE model. One parameter was a linear shift to the total deadtime experienced by the detector for each recorded event, which naturally affects the rate at which events are recorded by the detector. The second parameter is a factor correction applied to the number of scatter events recorded in the Geant4 simulation: this accounts for over - or underestimates in the number of interaction events that take place in the CC for a given activity. The objective function for minimization was the chi-square value of the distance between the simulated deadtime curve and a small sample of data points from the experimental deadtime curve. The local minimum of the objective function was estimated by a brute force evaluation of its value for a small region of the parameter space.

3. Results and Discussion

Figure 3a shows a comparison between the measured and simulated deadtime curves for the ^{68}Ga positron source experiment, and Figure 3b shows the corresponding activity functions along with the fits used for estimating the non-paralyzable deadtime parameters τ_{np}. The estimated deadtime parameters are $\tau_{np} = 2.4544 \pm 0.0016 \times 10^{-5}\mathrm{s}^{-1}$ (Measured), $\tau_{np} = 2.01 \pm 0.27 \times 10^{-5}\mathrm{s}^{-1}$ (Unoptimised MCDE) and $\tau_{np} = 2.52 \pm 0.41 \times 10^{-5}\mathrm{s}^{-1}$ (Optimised MCDE).

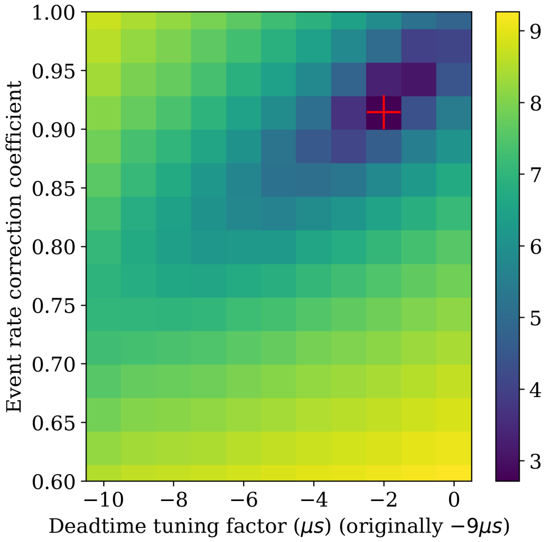


(a) (b)

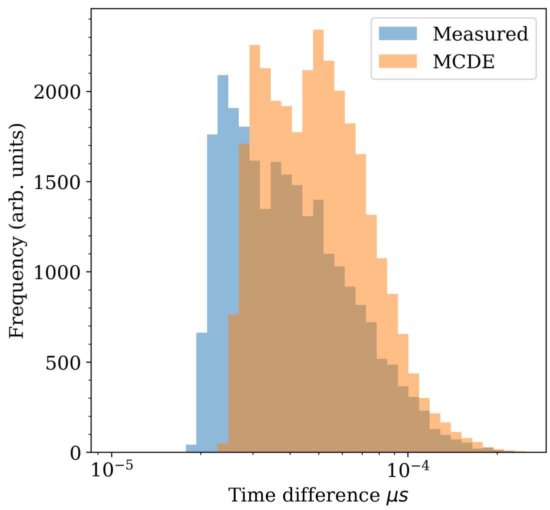
Figure 3: (a) Measured and simulated raw singles event rates as a function of activity for a ^{68}Ga point source. Expected rates n are drawn with dashed lines, event rates m with scatter points, and non-paralysable deadtime model fits with solid lines. (b) Activity functions of measured and simulated event rates.

In the range 0 to 3500 kBq, the measured deadtime curve increases monotonically and plateaus without becoming paralyzed. Beyond this range, the deadtime curve drops sharply and forms a physically implausible set of parallel curves; the distinct change is attributed to buffer overflow effects from streaming the event data, as well as paralyzable deadtime effects. The MCDE model qualitatively reproduces this curve, with the exception of the region exceeding 3500 kBq: a sufficient explanation is that the MCDE model does not account for buffer overflow. Quantitatively, the model overestimates the meaured event rate by a factor on the order of approximately 20%.

We claim that the differences in event rates are fully explained by two parameters: the time spent in deadtime, and overestimation of gamma ray interactions with the detector in the Geant4 simulation. In Figure 4, a phase diagram is drawn for the objective function of the discrepancy between simulated and measured deadtime curves, as a function of the two parameters. In order to optimise the comparison, the deadtime tuning factor needs to increase, and the event rate correction factor needs to decrease. The former implies that the MCDE model deadtime per event is too short, and the latter indicates that the Geant4 model simulates too many events for a given source activity. The optimisation yields closely matching event rates between measurement and simulation, as well as strong agreement between the estimated parameters τ_{np}. We attribute the event overestimation to simplifying assumptions in the Geant4 model. In particular, the model excludes the syringe needle used to hold the point source (see Figure 2) which potentially absorbs emissions in a significant solid angle about the source.



(a)



(b)

Figure 4: (a) Phase diagram of the logscaled weighted chi square value of the difference between the measured and simulated deadtime curves, as a function of the deadtime tuning factor and the event rate correction coefficient. The optimal parameters are a tuning factor of -2μs and correction of 0.914. (b) Time differences between subsequent events recorded by the true and optimised MCDE detectors.

In general, however, the optimisation is not fully explanatory. For example, the change in the deadtime tuning factor results in a significant mismatch of minimum time differences between the measured and simulated data (Figure 4b). Ongoing work aims to improve the objective function for optimisation, by including additional weighting to minimise deviations between the measured and simulated time difference distributions.

4. Conclusion

The Monte Carlo Detector Effects (MCDE) model was adapted to the UCT Polaris Compton Camera, and shown to be effective in modelling the detector's deadtime characteristics when exposed to a ^{68}Ga point source. The unoptimised model demonstrates non-paralysable deadtime behaviour in agreement with the Compton Camera, but overestimates the recorded event rate. A brute force optimization indicates that discrepancies result from event rate overestimation in the Geant4 model and biased per-event deadtime during detector timing and readout. The MCDE model will be further optimised for use in investigating positron sources.

References

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