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Review Article

Monte Carlo Simulation Modeling Techniques to Measure & Understand Instrument Dead Time in PET Images

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Abstract

Monte Carlo simulation modeling is one of the newest approaches to helping biomedical imaging professionals measure, model, and analyze how noise and instrument dead-time works and negatively affects the great capability of Positron Emission Tomography with a Discovery Simulation Tomography camera. Dr. Bastein Guerin and Dr. Georges El Fakhri used and modified Simulation System for Emission Tomography (SimSET) software and Geant Analysis for Tomography Emission (GATE) simulation software to create a NEMA image quality phantom The NEMA image quality phantom helped replicate how noise and instrument dead time is created and functions during Positron Emission Tomography scans in the 2D and 3D operation modes. Using the SimSET and Geant Analysis for Tomography Emission software, Dr. Guerin and Dr. Fakhri were able to generate and validate data results that illustrated how modeling dead-time can help account for other non-uniform dead-time behaviour in multiple structures of blocks that are not geometrically cylindrical or symmetrical. By applying statistical weights using a variance reduction technique in the SimSET and Geant Analysis for Tomography Emission simulation software, single coincidence circuitry can also process all detected coincidences with the object and scanner. Their approach using Monte Carlo simulation modeling can help create more capable PET scanners can better reduce noise and instrument dead time in the future.

Keywords: Positron Emission Tomography; Geant Analysis; Monte Carlo Modeling

Introduction

Significance of Monte Carlo Simulation Modeling for PET

Positron Emission Tomography (PET) scanners were originally designed to image the anatomy and function of two vital organs, the brain and the heart, using the "decay qualities of short-living radiotracers" [1]. In PET, the radiotracers are "injected into patients with higher activity levels and can lead to increasing random events of noise, scatter, and dead time" [1] making it much had to track the photon using the positron from the Line of Reconstruction. PET usage in 3D has continuously gathered positive interest in it because of its detection efficiency but it positive traits will always be judged in difficult manner because of negative drawbacks, mainly PET's high-noise components and instrument dead time, stemming from scattered and random coincidences. This negative trait continuously effects image quality and modality processing time. With improving computational simulation techniques and technology, the Monte Carlo simulation method gardners promising interest because it can provide a direct and independent approach in being able to "estimate the factors and components of noise and instrument dead time using random selection and meticulous probability distributions" [1].

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In 2008, researchers Dr. Bastein Guerin of the University of Paris-France and Dr. Georges El Fakhri of Harvard University Medical School published validated results of a simulation study analyzing the system relationship of pixelated block detectors, random coincidences, light sharing crystal elements and dead-time in 2D and 3D Positron Emission Tomography imaging using the Simulation System for Emission Tomography (SimSET) Monte Carlo Simulation software, created by University of Washington Imaging Research Laboratory, against the Geant Analysis for Tomography Emission Monte Carlo Simulation Code [2].

Analysis of Monte Carlo Modeling, SimSET & GATE Simulation Software

Monte Carlo Simulation & the Simulation System for Emission Tomography (SimSET: Dr. Guerin and Dr. Fakhri chose to utilize the Monte Carlo simulation because it is effective when it comes to modeling photon interactions between the target object and PET detector. The Monte Carlo simulation software, SimSET, provides the computational capabilities to measure the reference activity and attenuation distributions of the target object and PET detector in conjunction with the scattered, unscattered, and random coincidence distribution. SimSET can assist in the "tracking and analyzation of of PET detected voxel-based activity and attenuation distributions operating in 2D and 3D nodes" [2]. There were previous studies that tested and validated the capabilities of SimSET, specifically towards modeling "photon transport in non-uniform attenuation distributions" [3-5], but a great obstacle with SimSET was the holistic over-measurement of the PET scanner Block-Design Performance due to SimSET's lack or inability to model the pixelated detectors, light-sharing among crystal elements, random coincidences, and detector dead-time [6]. Expert research has shown that Block Design PET Scanners has "limited spatial resolution because of crystal element size" [7] and "the light-sharing read-out which makes use of less than one photo-multiplier tube (PMT) per every crystal-element" [8]. Block Design PET Scanners also possess worse quality "system sensitivity because of the presence of gaps between the blocks in the PET scanner construction set up" [9]. In specific regards to better measurement and potential of measuring dead time in correlation with random coincidence value of the specific attenuation or activity level distribution, the SimSET software and Monte Carlo simulation enables the high quality modeling of PET Image acquisitions at the high count rate level and even the Noise Equivalent Count (NEC) rate" [10].

How SimSET Software & Monte Carlo Simulation Modeling Was Utilized to Target & Measure Instrument Dead Time: The first specific stage where SimSET was used to measure the Instrument Dead-Time in PET Scanners was creating Photon Propagation. The Photon Propagation has three phases, [a] Photon Generation, [b] Photon Propagation in the Object & Septa, and [c] Photon Propagation in the detector.

[a] With SimSET's Photon Generation, co-incidence events were generated to computationally replicate positron range and photon non-colinearity of the PET scanner. Dr. Guerin & Dr. Fukhri had to model the photon transport mechanism by measuring and replicating the particle transport phenomena throughout the target object and the septa and then had to follow up by propagating the photon transportation all throughout the detector with the purpose of modeling the PET detector effects and binning. According to the Bassler Company, the binning technique "combines the information of an adjacent pixel into resulting information depending on the 3 binning modes of Horizontal Binning, Vertical Binning, and Full Binning" [11]. The Binning technique ultimately produces a "reduced pixel resolution by the factor of the binning type, but in addition, sum total the performance of each and every pixel" [11].

[b] For the Photon Propagation in the Septa & Object, Dr. Guerin & Dr. Fukhri were able to "modify their version of the SimSET software to permit the independent tracking of photons that originated from the same annihilation site" [2]. To be accurate and precise in estimating and measuring single events and coincidence events, Dr. Guerin & Dr. Fukhri decided to simulate any single photons that were not detected. The simulation step was not currently or originally performed in SimSET because of the purpose of reducing the number of events that need to be tracked and shortened for the simulation time. This step helps with computational calculations of the PET scanner dead time and and random coincidences [2]. For the Photon Propagation of the Septa, Dr. Guerin & Dr. Fukhri "modelled the photon propagation using Monte-carlo techniques and accounted for parameters of septal penetration, photoelectric absorption, and the Compton and coherent scattering" [2]. The SimSET software was also modified to be able to store any photon propagation "single events that reached the detector in a list-mode format files based on coincidence categorization" [2].

[c] To complete the creation, replication, and modeling of the Photon Propagation, Dr. Guerin & Dr. Fukhri used the list-mode file created from the Object Scepta Photon Propagation Step to as the way to input for second overall step of the simulation process that models the propagation in the blocks [2]. Dr. Guerin & Dr. Fukhri decided to model only one block of the full PET detector to reduce the amount of simulation time while also increasing the optimization of this modeling step [2]. The SimSET software rotated the incoming photon tracks into the block frame of reference post detector progration only then to be rotated back into their original frame position and location. Dr. Guerin & Dr. Fukhri used the software then modeled the other blocks' propagations by "rotating the photons' tracks into the new block's frames for each single time they entered a new block to allow the amount of photons to scatter in multiple contiguous blocks" [2]. There was predicted evident backscatter that followed this rotation step from the opposite blocks, but Dr. Guerin & Dr. Fukhri decided to forgo modelling this aspect because tracking the photons inside the target object and inside the detector performed in a separate manner. This methodology process could only allow one passing of photons through the attenuation distribution [2].

Purpose of the GATE Software & Validation Usage

Any associated error from the absence of not modeling the backscatter events was analyzed and evaluated using the GATE software and the Dr. Guerin & Dr. Fukhri provided that defining just one of the blocks, instead of the entire full ring of blocks, minimized the computational memory processing power and more accurately defined the geometric characteristics of one block compared to a multiple block ring structure" [2].

The GATE software that was used is a standard validation Monte Carlo software that models the properties of photon transport, electron transport, X-ray production, and Delta Ray production" [12]. The GATE software helps model wide ranges of acquisition geometries and read-out schemes that are used in Positron Emission Tomography (PET) [12]. GATE's limitation is adapting to the absence of sampling methods because they yield very long simulation times when modeling complex activity distributions with a clinically relevant number of counts" [13].

The GATE software was mainly used by Dr. Guerin & Dr. Fukhri to validate the tracking of the photon propagation of the detector. Dr. Guerin & Dr. Fukhri used the GATE software to validate the tracking of the photon propagation in the pixelated detector through comparing the energy spectra that was obtained in GATE and the simulation when the Discovery Simulation Tomography (DST) camera measurements was modeled [2]. The energy spectra were able to be modeled by Dr. Guerin & Dr. Fukhri using the current version of SimSET that the team used. Dr. Guerin & Dr. Fukhri were able to compare absolute single event rates that were detected from GATE and the resulting simulation to model the dead-time and random coincidence [2].

Dead-Time Modeling Technique of SimSET Simulation Software

Dr. Guerin & Dr. Fukhri were able to use the SimSET software to mathematically compute and model instrument dead-time by computationally creating a mathematical equation to calculate the dead-time fractions within every block structure in accordance to dead-time free photon fluence rate [2]. The dead-time modeling technique helped with accounting for paralyzable dead-time with finite integration time of pulses, a further aspect of the dead-time fraction rates [2]. Dr. Guerin & Dr. Fukhri used a variation reduction technique where all dead-time events were detected and statistical weights were applied to all of the dead-time events and fraction rates [2]. Dr. Guerin & Dr. Fukhri observed and noted that a statistical weight that was smaller than the numeric value of one that was applied to them to better reflect their probability of potentially not being detected due to dead-time. In Positron Emission Tomography, a specific camera called the Discovery Simulation Tomography camera, is one of the newer camera models used with PET technology and its resolution is consistent with the expected image results for its type of detector design" [14]. In this simulation models, Dr. Guerin & Dr. Fukhri noted that the "Discovery Simulation Tomography (DST) camera did not have any buckets, which permitted only single coincidence circuitry to process all detected coincidences" [2]. Dr. Guerin & Dr. Fukhri used the SimSET software to model the dead-time in coincidence processors along with a modified non-paralyzable model that was applied to total prompted coincidences rate [2]. Any and all dead time losses that were caught, measured, and analyzed were able to be modeled by team by using the SimSET software. The team mathematically "multiplied the dead-time free coincidence rates by the live-time fraction of the processor (equal to 1 dead-time fraction), a process studied and proposed by the research of Dr. Erikkson" [15].

Dr. Guerin & Dr. Fukhri were able to further apply the modeling process and effects to "simulate PET scanners with the coincidence buckets by matching each and every bucket with the same or similar electronic dead-time parameters" [2]. By doing this, the team was able to analyze the dead-time in each bucket as a variable based on the number of coincidences processed by the bucket per second" [2], and would therefore provide a standard, accurate, and precise way of measuring instrument dead-time in PET scanners with a block design setup.

Image Quality Results from SimSET/GATE Simulation Software

According to the researcher's experimental results the "measured and simulated values were in good agreement numbers wise and they were able to indicate that the noise levels in simulated and measured images were near identical " [2]. The only potential slight was that Dr. Guerin & Dr. Fukhri found from the results that the "difference between the noise structures in the simulated and measured images, especially in 3D mode" [2], potentially because of the researcher's normalization and correction measures for dead-time, scattering, and random noise creation events. The best result in terms of accuracy for the simulated images in terms of NEMA count rate for the NEMA phantom created by the SimSET software was the data generated from modeling for dead-time, noise, and scatter "activities in the clinical range and up to 80 kBq/cc in 3D mode" [2]. The accuracy for the NEMA count rates was better than 13% while the discrepancies between the NEMA phantom count rates that were obtained both with and without variance reduction technique for modeling dead-time was less than 1%" [2].

Conclusion

The future challenge of incorporating Monte Carlo simulation software like SimSET and GATE to assist in reducing the obstacles of dead-time in PET is that the NEMA count rates or total count rates is that instrument dead-time sometimes does not fit into the types of paralyzable and non-paralyzable dead time [2]. Another challenge is that Monte Carlo simulation software not being able to yet model and adapt to "pulse pile up (degradation of the energy and spatial resolutions) and saturation of the electronic system" [2] according to the simulation research can cause new pathways for inaccuracy in using Monte Carlo simulations to measure and reduce instrument dead time and noise.

The research of Dr. Guerin & Dr. Fukhri does show a validated, and even more important, a realistic positive use of how Monte Carlo modeling can measure, attain better understanding and create potential new ways of reducing noise and instrument dead-time to help improve the already high effectiveness of Positron Emission Tomography. With this modeling and simulation approach, biomedical images experts and medical healthcare professionals can better "account for non-uniform dead-time in blocks when simulating objects that don't possess a cylindrical geometry" [2]. Biomedical imaging experts and medical healthcare professionals will be able to better reduce different activity levels of instrument dead time and noise at different locations, specifically with the current Discovery Simulation Technology (DST) camera used in PET imaging.

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