A SIMULATION MODEL OF THE COUNTING-RATE RESPONSE OF CLINICAL PET SYSTEMS AND IT'S APPLICATION TO OPTIMIZE THE INJECTED DOSE

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ABSTRACT

The design principles of clinical PET data acquisition protocols require images of high statistical quality, while the scanning time remains relatively short and the total amount of radioactive dose does not exceed a level, above which significant count losses are observed. This can be satisfied by determining a range of injected dose levels where the performance parameter of Noise Equivalent Count Rate (NECR) is maximized. However certain patient- and scanner-related parameters can shift the range. We propose a methodology to design a model of the NECR response to certain patient-scanner parameters, based on validated simulations of imaging systems and realistic human phantoms. We used Geant4 Application for Tomography Emission and investigated the relationship between the NECR and the patient size, the coincidence time window of the scanner, the dead-time of the system's electronics and the energy window.

Index Terms— Positron Emission Tomography, Monte Carlo methods, optimization methods, dose, simulation, biomedical imaging

1. INTRODUCTION

The total amount of injected radioactive dose in Positron Emission Tomography (PET) studies is very important when designing efficient clinical PET data acquisition protocols. The objective is to acquire projection data of the highest possible statistical quality, so as to be able to reduce the scanning period significantly, while the final image quality is maintained. PET is a statistical imaging technique, where the presence of noise is inevitable [1]. In order to limit the negative effect of noise and improve the statistical quality, the number of detected true coincidences must be increased against the number of scatter and random coincidences. An option would be to increase the total injected activity. However higher activity levels are not necessarily associated with higher statistical quality, due to increased random coincidences and counting losses caused by the dead-time and pile-up effects on detectors. On the other hand, lower activity levels might not induce high enough count rates to ensure a statistically significant projection data set for the short acquisition times required by clinical protocols. Thus, a trade-off is observed between the statistical quality of the projection data and the acquisition time. Therefore a short optimal range of activity level values exists, where the counting rate response of a PET system is high enough to ensure acquisition of projection data of good statistical quality in a short amount of time. In order to determine this optimal activity range, we first need to characterize and quantify the counting rate performance of a PET imaging system. In this study we have introduced the parameter of the Noise Equivalent Count Rate (NECR) which is applied as a metric of the statistical quality of the coincidence counts per unit scan time. The optimal mean dose range for a particular patient-scanner system is defined in this work as the range of the activity levels required to be injected to that patient in order to induce a maximal NECR value.

The optimal dose range may be different for each patient and is depending mainly on the size and the geometry of the attenuating media of the patient volume relative to the scanner. Many studies have considered evaluating the performance of a clinical scanner by estimating a NECR response curve. [2,3] Furthermore, in most of these studies, relatively simple body-like phantoms have been used in simulations and experiments to construct fixed statistical prediction models, whose results were later simply extrapolated to human studies without sufficient validation. In fact the human body consists of many layers of different attenuation index each and simple anthropomorphic phantoms based on basic geometric volumes cannot provide results that can be safely extrapolated to clinical studies.

More recent studies have shown that NECR can be calculated through a series of appropriate phantom measurements or simulations and expressed as a function of the singles rate, which is largely independent of the geometry and size of the scanned object. [1, 4] However, there exist customized acquisition protocols for specific cases, where different system parameters, such as energy window settings, are applied. In this case a clinical dose administration protocol designed with the above methodology would fail, as it requires all the digitizer settings of the scanner to be constant.

Hence, a promising alternative methodology would be to simulate an appropriate series of scans with state-of-the-

art voxelized anthropomorphic phantoms using a validated model of a scanner system where the effect of many system- or patient-related parameters to the NECR can be investigated independently to each other. This will allow the prediction of the optimal mean dose range for every patient and system configuration prior to the actual scan.

In this paper we will present a simulation study of the effect of specific parameters to the NECR of a clinical PET system. Finally we will propose a simulation methodology to estimate the optimal mean injected dose based on the results and conclusions of the study

2. MATERIALS AND METHODS

In this work we used Geant4 Application for Tomography Emission (GATE), a well validated Monte Carlo simulation package, to model a series of scans of NCAT phantoms of varied size and activity. GATE can provide the user with the required trues, scattered and randoms rate data in order to directly calculate the NECR each time. [5] Moreover this simulation package offers the ability to control various digitizer, source, timing and geometry parameters of the simulation and determine the independent effect of each one to the modeled NECR response.

Furthermore the NCAT phantom was selected among many other voxelized phantoms because of it's capability to change its size in a homogeneous manner so as to sufficiently reflect the differences in size and geometry of the body of patients with different weight. All 64 slices from 64^{th} to 127^{th} slice of the original NCAT phantom were included in the simulation (Fig. 1). Each slice had dimensions of 96x96 voxels. The activity map was generated by initially setting a uniform background activity concentration over all the tissues of the previous phantom and by subsequently adding a 32 times higher signal activity concentration over the regions of the heart, bladder, kidney and spleen (Fig. 2).

Figure 1. Transaxial (left), sagittal (center) and coronal view of the central slice of a large NCAT phantom (attenuation map)

The NECR value for each of the following acquisitions was calculated by the following equation:

$$NECR = \frac{T^2}{T + S + R}$$

Variables T, S and R represent the mean true, scattered and random coincidence event rates respectively. The randoms rate was simulated directly with GATE.

Figure 2. Transaxial (left), sagittal (center) and coronal view of the central slice of a large NCAT source distribution (activity map)

First of all several hypothetical dead-time model versions, of an actual commercial clinical PET system, have been chosen to be simulated for this study so as to comparatively evaluate their NECR performance. For this purpose, we used an already validated GATE model of the Biograph LSO PET/CT scanner. [6]

The Biograph scanner is equipped with LSO detectors and Pico-3D electronics allowing it to operate with a relative short dead-time system response of approximately 300nsec. The effect on NECR response of different possible electronics configurations were modeled through the utilization of specific dead time responses of 150ns, 450ns, 600ns, 750ns and 900ns at the same GATE model. The comparative study of these model versions will provide a clear assessment of the significant improvement of new generation electronics in terms of NECR performance and will help illustrate how this performance enhancement affects the optimized dose.

Furthermore, three sizes of NCAT phantoms (large, medium and small) were generated and studied in correlation with the rest of the parameters investigated. The relative difference between the two long or short rib axes was approximately selected to be 15% and the respective activity and attenuation maps are presented in Figure 3. These three NCAT phantoms have been designed to resemble three characteristic sizes of human body associated with three common human body weights.

Figure 3. Transaxial view of the central slice of the large, medium and small NCAT phantoms (attenuation map)

Additionally, three different 2τ coincidence time windows have been applied to determine their effect on the NECR response and, indirectly, the optimal total injected dose range. The NECR achieved in the case of the standard 4.5nsec time window was compared against the equivalent NECR for a 3nsec and 6nsec window, respectively, at the same GATE model. The range defined above contains the lengths of most of the coincidence time windows applied to modern clinical PET scanners nowadays. Thus, this

comparison will provide a sufficient generalization of the important relation between the count-rate response and the coincidence time window of a clinical PET system.

In many cases, the lower energy threshold (LET) of an energy window might be decreased, in order to enhance the sensitivity of the system by allowing a wider energy spectrum, or might be increased so as to reduce the noise caused by low-energy scattered gamma rays. Consequently the NECR of a system would be affected accordingly. More specifically, four energy windows with a constant upper threshold of 650keV and varying lower threshold (375,400,425,450keV) were used.

3. RESULTS AND DISCUSSION

First of all the effects of the patient weight on the NECR and the optimal dose range for the Biograph were investigated. As we can see from Fig. 4, the NECR becomes higher, when smaller sizes of NCAT phantom are imaged. This is an expected behavior since the attenuation of the emitted gamma rays is reduced in smaller phantom sizes, allowing more trues and reducing, at the same time, the total number of scattered and random coincidences.

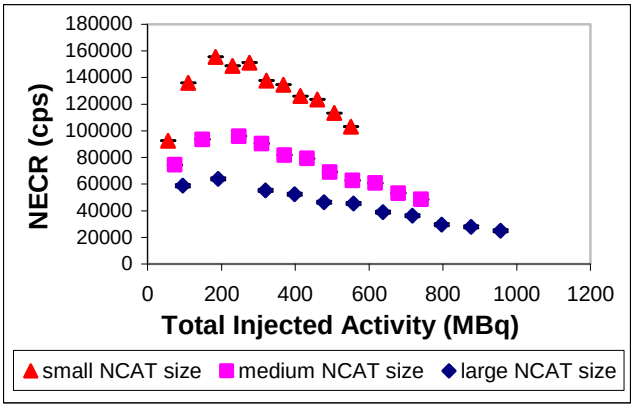

Fig. 4. Biograph NECR vs. total injected dose when three different sizes (small, medium, large) of NCAT phantom sizes have been used, application of the 425-650keV energy window, standard dead-time 300nsec are selected and 4.5nsec coincidence window.

Furthermore, according to figure 5, the estimated mean optimal dose is inversely proportional to the patient's size as expected for the same reasons as above. However, it becomes clear by observation of all relevant results of the study that the dependence between the two parameters is only minor. A standard coincidence time window of 4.5ns was used above. However, the NECR response was improved by 35% when a hypothetical 3ns coincidence window was applied, according to Fig. 6. This behavior demonstrates the importance of the development of new generation electronic coincidence systems allowing for shorter coincidence windows and, subsequently, better NECR performance. Generally, random events and pile-up effects are dramatically reduced when shorter coincidence windows are supported by the scanner, resulting in higher NECRs and, thus, higher optimal dose values, as it can also be concluded by Fig. 7.

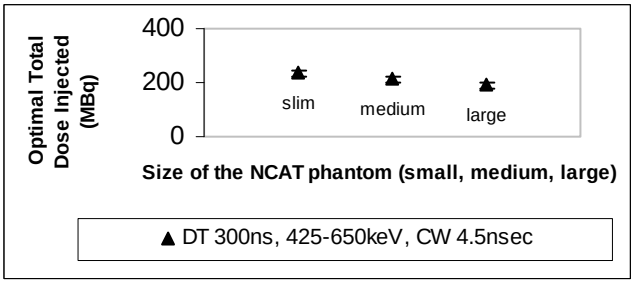

Fig. 5. Estimated optimal injected dose for three different NCAT sizes when a 425-650keV energy window, a dead-time response of 300ns and a coincidence time window of 4.5ns is used.

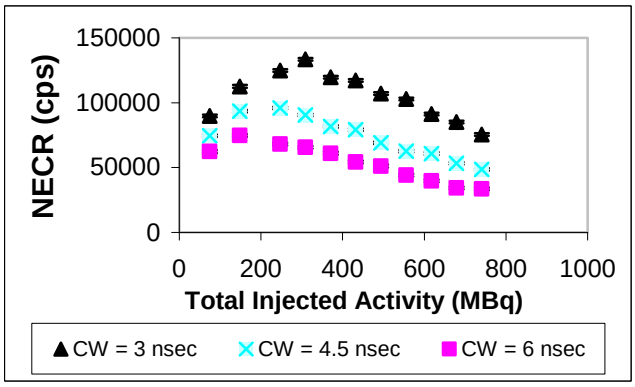

Fig. 6. Biograph NECR vs. total injected dose when different coincidence time windows are applied. A medium-sized NCAT phantom is used with a 425-650keV energy window and a standard dead-time of 300ns.

Additionally, in figure 8, the NECR responses of several hypothetical dead-time models of the Gate model of Biograph are plotted together for the purpose of a comparative analysis. NECR is increased by 30% when the dead time is dropped from 300ns to 150ns. The latter is the estimated total dead-time response of most state-of-the-art clinical PET scanners. The use of advanced electronics with shorter dead-time allows a clinical scanner to achieve significantly higher NECR values for the same amount of dose.

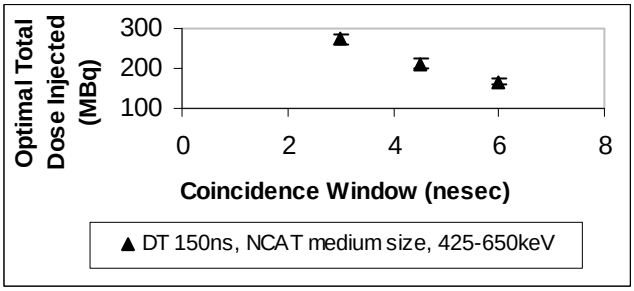

Fig. 7. Estimated optimal injected dose for three different NCAT sizes when a 425-650keV energy window, a dead-time response of 300ns and a coincidence time window of 4.5ns is used.

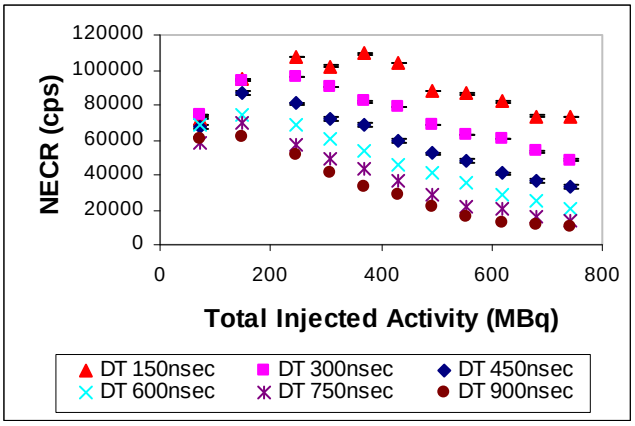

Fig. 8. Comparative diagram of the NECR curve vs. total injected dose for 6 different dead-time responses. A medium-sized NCAT phantom size has been used with an energy window of 425-650keV, and a standard coincidence time window of 4.5ns.

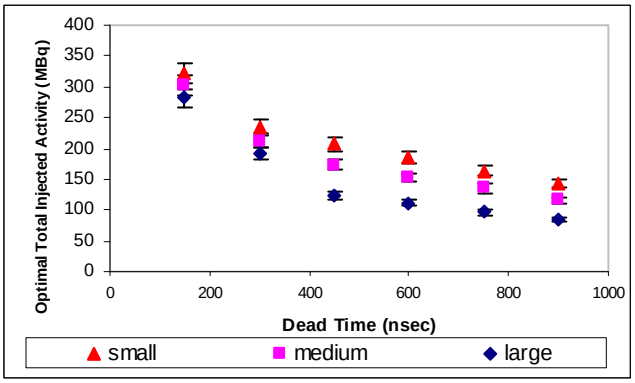

Fig. 9. Estimated optimal injected dose for three different body sizes, as a function of the dead time response, when a 425-650keV energy window and a 4.5ns coincidence window were applied.

Moreover, the peak NECR of a faster dead-time system is appearing at a much higher dose level, according to Fig. 9. A reduction from a 300ns to 150ns dead-time response results in an increase of the potential optimal injected dose by approximately 50%.

The energy window of 425-650keV had been selected for all the previous simulation series. In the following section the LET of the window of the Biograph was modified and the respective effects are presented at Fig. 10. When the LET is raised from 425 to 450keV a slightly better NECR value was measured over the entire range of dose levels because more randoms and scattered events were rejected with respect to trues. However the optimal dose range is only slightly affected (Fig. 11).

The conclusions and results of this study can be further expanded and analyzed in order to construct a statistical model that would be capable to estimate in good approximation the optimized dose for every patient based on its size, weight as well as the scanner characteristics. Our aim is to build a reliable statistical model that would be able to predict, in a clinically efficient way and within a tolerable degree of uncertainty, the optimal dose range for every patient.

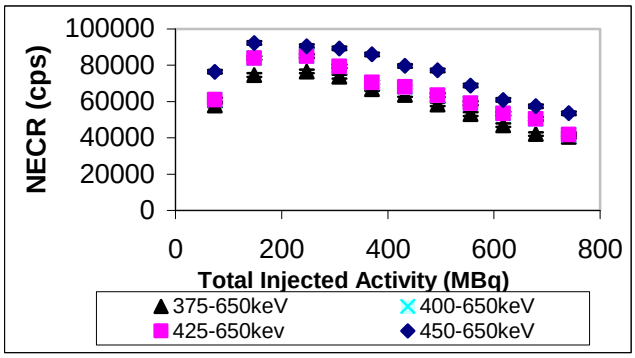

Fig. 10. Biograph NECR vs. injected dose for various energy window lengths. A medium size NCAT, a coincidence window of 4.5ns and a dead-time response of 300ns have been selected

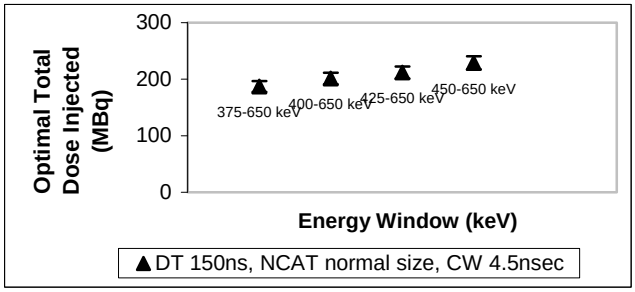

Fig. 11. Estimated optimal injected dose for four different energy window sizes, when a dead-time response of 150ns, a medium-size NCAT phantom and a coincidence window of 4.5ns is used.

11. REFERENCES

[1] Watson CC, Casey M, Bendriem B, Carney J, Townsend D, Eberl L., Meikle S., DiFilippo F., "Optimizing injected dose in clinical PET by accurately modeling the Counting-Rate response functions specific to individual patient scans", *The Journal of Nuclear Medicine*, vol 46, no 11, Nov 2005

[2] Bailey DL, Jones T., Spinks TJ, et al, "Noise equivalent count measurements in a neuro-PET scanner with retractable septa", *IEEE Trans Med Imaging*, 1991;10: p256-260

[3] Stearns CW, Cherry SR, Thompson CJ, "NECR analysis of 3D brain PET scanner designs", *IEEE Trans Nuclear Science*, 1995;42: p1075-1079

[4] Watson CC, Casey ME, Beyer T, et al, "Evaluation of clinical PET count rate performance", *IEEE Trans Nuclear Science* 2003;50:p1379-1385

[5] S. Jan et al. "GATE: a simulation toolkit for PET and SPECT", *Phys. Med. Biol*. 49 (2004) 4543-4561

[6] N. Karakatsanis et al, "Comparative evaluation of two commercial PET scanners, ECAT EXACT HR+ and Biograph 2, using GATE", *Nuclear Instruments and Methods in Physics Research, Section A*, Vol. 569, Issue 2, pp 368-372, 2006