A Methodology for Optimizing the Acquisition Time of a Clinical PET Scan Using GATE

Nicolas A. Karakatsanis, *Member, IEEE,* George Loudos, *Member, IEEE*, Konstantina S. Nikita, *Senior Member, IEEE*

***Abstract*– The acquisition time of a PET scan is a critical parameter when designing imaging protocols for clinical nuclear medicine studies. The statistical quality of the projection data increases when longer acquisition times are selected. However, very large scanning periods can limit the number of PET studies performed and, moreover, increase the probability of motion artifacts. The competing objectives of good statistical quality and short acquisition time are both depending on the counting rate performance of the system. The noise equivalent count rate (NECR), which measures the rate in which statistically important coincidence events are counted by a PET system, is employed in this study to quantify the counting-rate performance. Thus, higher NECR values allow for acquisition of relatively larger number of true coincidence counts at the same scanning time. NECR is directly depending, for a particular patient-scanner system, on the amount of radioactive dose injected into the patient and acquires a peak value for a certain range of dose values. Thus, a minimal acquisition time can be achieved by estimating this optimal dose range prior to a scan. In this simulation study we propose an alternative optimization methodology. Initially, a regular low dose is selected and used as a constant. Then the NECR response is modeled, using Geant4 Application for Tomography Emission (GATE) simulation package, as a function of the parameters of the patient's body size, the coincidence time window, the dead-time response and the energy window. Subsequently, the optimal scanning time is estimated, based on the simulated NECR, as the minimal scanning time necessary to acquire 20 million noise equivalent counts (NEC) per bed position. For this purpose, we employed a validated Biograph PET/CT scanner model, where six hypothetical dead-time responses were simulated as well as three coincidence time windows. Finally, we used three NCAT phantoms of different size, and four energy windows.**

I. Introduction

THE acquisition time of a PET scan is a critical parameter when designing imaging protocols for clinical nuclear medicine studies. The emission of positrons is a physical random process that follows the Poisson distribution. Therefore, PET is, by definition, a statistical imaging technique, where the presence of noise is unavoidable. In many cases the objective is to limit the negative effect of noise and, thus, improve the statistical quality by increasing the number of detected true coincidences rate relative to scatter and random coincidences rate.

In this study we quantify the counting rate of a PET system by employing the performance parameter of noise equivalent count rate (NECR), which measures the rate in which statistically important coincidence events are counted. Thus, higher NECR values indicate superior counting rate performance and therefore allow for acquisition of relatively larger number of true coincidences against random and scatter coincidences during the same scan time. This can be achieved either by injecting a certain amount of radioactive dose, within a range of optimal dose values, to the patient, or by selecting an optimal scan time. In both cases the key factor to determine the optimal values is the NECR and it's relationship with certain patient- and scanner-specific parameters.

If the scan time per bed position is considered a constant parameter, then the injected dose can be regulated so as to achieve high statistical quality for the given scan time. More specifically, the total injected activity could be increased, resulting in a higher rate of positron annihilations and consequent gamma emissions. However very high activity levels are not necessarily associated with high statistical quality in the projection data due to increased random coincidences and counting losses caused by the dead-time and pile-up effects on detectors. On the other hand, low activity levels might not induce high enough count rates to ensure a statistically important projection data set for the acquisition times usually required by modern clinical protocols.

Thus, if one considers the total amount of injected activity as a variable and the scan time as a given constant, a narrow optimal range of activity level values exists, for which the counting rate response of a PET system is high enough to ensure projection data of high statistical quality within the relatively short and constant acquisition times required by modern protocols. The optimal dose range for a particular patient-scanner system can be defined as the range of the activity levels required to be injected to the patient in order to induce a maximal NECR value [1].

The NECR and, as a result, the optimal dose range can be affected by certain parameters related with the patient, such as the size and the geometry of the body, and the scanner settings, such as the energy window, the coincidence time window and the dead-time response. Ideally, for a given set of scanner settings, the curve of the NECR vs. the injected dose should be calculated for each patient in order to estimate the optimal dose range prior to injection. However this method

Manuscript received November 9th, 2009.

N. A. Karakatsanis and K. S. Nikita are with the Department of Electrical and Computer Engineer, Biomedical Simulations and Imaging Laboratory (BIOSIM) of the National Technical University of Athens, 9 Iroon Polutechniou St., 15780, Athens, GR

G. Loudos is with the Medical Instruments Technology Department of the Technological Educational Institute of Athens, Ag, Spyridonos Street, Egaleo, 122 10, Athens, GR

9781-4244-3962-1/09/$25.00 ©2009 IEEE

cannot be applied in clinical studies because it would require a very long acquisition time. Moreover, the activity distribution over the patient body is changing significantly over long scanning periods, resulting possibly in significant variations of the activity present in the FOV at each bed position.

Many studies have considered evaluating the performance of a clinical scanner by estimating a NECR response curve [2-5]. For example, the National Electrical Manufacturers Association (NEMA) NU 2-2001 standard suggests the use of a simple cylindrical phantom to model the human body for the evaluation of the NECR performance of a PET system [6]. Additionally, 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.

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 dose range for every patient and system configuration prior to the actual scan. In a previous simulation study [7], it has been presented a model of the effect of specific patient and scanner parameters to the curve of NECR vs. the injected dose for a given constant scan time for the Biograph6 PET system. Based on the results and conclusions of this study, a simulation methodology has later been proposed to estimate the optimal injected dose range prior to an actual clinical PET scan, when the particular imaging system, or certain variant configurations of it, are employed [8].

II. Materials And Methods

The previous simulation methodology proposes the adjustment of the injected dose based on certain patient and scanner parameters in order to maximize NECR. However, the dose administered to patients is a parameter that needs to be specified prior to the injection and the scan itself, allowing no margins for miscalculations or modifications of the data acquisition protocol at a later phase of the imaging procedure after the injection.

Furthermore, in certain cases, the previous methodology is possible to suggest an optimal dose range that will contain relatively high values (>400MBq). Those values can be associated with radiation safety issues for some patients. This is particularly true for the case of certain patient-scanner systems with high NECR, such as when a PET system with a relatively low dead-time is employed for the imaging of slim patients. On the other hand, the equivalent curves of NECR vs. injected dose for these cases are nearly flat around these dose values implying that a dose of significantly lower value can be used with only a minor degradation of the NECR and the statistical quality.

For these reasons, in this study we present a methodology to estimate the optimal scan time for a given injected dose, instead of the optimal dose range for a given scan time. Now, we can repeat the previous analysis assuming the injected dose as a constant and the scan time as a variable, which needs to be optimized to achieve a certain level of statistical quality. The NECR remains here the key factor to determine the optimal scan time, however, the optimization criteria is no longer the maximization of the NECR, but the record of a minimum number of 20 million Noise Equivalent Counts (NECs) for each bed position containing the imaging targets of the scan. The above threshold of NECs per bed position is considered to be an adequate number of counts for each bed position of a whole body PET scan and ensures high statistical quality assuming Poisson statistics and reasonable amount of noise. Therefore, the optimal scan time for a particular bed position is defined in this study as the minimum amount of acquisition time required to scan this bed position and collect 20 million NECs.

According to the properties of the Poisson statistics, the selection of a longer acquisition time per bed position will enhance the statistical quality of the projection data through the reduction of the percentage uncertainty. On the other hand, very large scanning periods can limit the number of PET studies performed at a clinical facility on a daily basis and, moreover, increase the probability of patient stress and of consequent motion artifacts. However, the knowledge of the NECR as a function of a number of certain parameters, which will be examined later in this study, can allow for the prediction of the optimal scan time per bed position, as defined above, according to the following equation:

$$\text{Scan\_time}_{OPT}\left(\text{sec}\right)=\frac{20\times10^{6}\left(NECs\right)}{NECR\left(NECs/\text{sec}\right)} \quad (1)$$

It is obvious from Eq. (1) that the optimization of the scan time requires the construction of a NECR model that will be able to estimate the NECR performance of a clinical PET system for a number of parameters. For this reason, a series of simulated scans were performed, in which the individual effect of each of the parameters of patient size, energy window, dead-time response and coincidence time window on the NECR of a Biograph6 PET/CT scanner model were investigated.

Initially, a regular total injected activity of 150MBq was selected and used as a constant parameter for all the simulated measurements of this study. This value was chosen according to the results and conclusions of the dose optimization study described previously [8]. It has been shown that such an activity level lies within the optimal dose range for most of the conditions usually applied at whole body PET clinical scans.

Afterwards, the NECR response was modeled, using Geant4 Application for Tomography Emission (GATE), which is a well validated Monte Carlo simulation package. GATE can provide the user with the required trues, scattered and randoms rate data in order to directly calculate the NECR each time. 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.

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. For this reason, it was inserted into GATE geometry description and a series of simulated scans were performed to model the NECR performance of the scanner for various representative patient sizes and geometries. NCAT is characterized by a detailed representation of both the attenuating volume and the activity distribution of the human torso, allowing the accurate modeling of realistic source and material distributions. All 64 slices from 64th to 127th slice of the original NCAT phantom were included in the simulation. 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 later adding a 32 times higher signal activity concentration over the regions of the heart, bladder, kidney and spleen.

The 64 slices were selected so as to cover the human body from the neck to the bladder. This area includes the majority of the tissues that demonstrate relatively high activity uptake and relatively similar attenuation factors. The brain was chosen to be excluded because of his lower overall attenuation factor whereas the bottom part of the body was not modeled in order to reduce the number of voxels employed and speed-up the simulation. Therefore the activity distributions used in this study were smaller in size than in a real whole-body scan and, given a certain activity concentration for each voxel, the total amount of injected activity is lower by a scale factor compared to actual total activity that should have been injected to a whole-body to induce the same NECR response. For this reason the total injected activity used in the simulation was corrected later by that scale factor to reflect the case of a whole-body clinical PET scan. Consequently all the estimated optimal activity ranges were shifted to higher values before presented in this study. The previously described attenuation and activity maps in transaxial, sagittal and coronal view are presented in Fig. 1 and 2 respectively.

Indeed, the combination of GATE and NCAT model tools provided to this study a flexible and stable environment where the user had the power to control any scanner or patient parameter of his choice.

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

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

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

$$NECR = \frac{T^2}{T + S + (k+1)R} \quad (2)$$

where T, S and R are the mean true, scattered and random coincidence event rates respectively. The factor k indicates the method applied to estimate the randoms and can accept values between 0 and 1, where near 0 values imply the estimation of randoms based on the singles rate and near unity values indicate an estimation method based on an unsmoothed delayed sonogram without interpolation.

In this study the parameter of NECR was estimated by Eq. (2) after setting *k=0* based on the simulated trues, scattered and randoms rate that were modeled with GATE. Thus the following equation was applied:

$$NECR = \frac{T^2}{T + S + R} \quad (3)$$

First of all several hypothetical dead-time model versions, of an actual commercial clinical PET system, have been chosen for simulation 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 [9, 10]. The Biograph scanner is equipped with LSO detectors and Pico-3D electronics, resulting in a dead time of 300nsec. The effect on NECR response of different possible electronics configurations was modeled through the utilization of specific dead time of 150ns, 450ns, 600ns, 750ns and 900ns. The comparative study of these model versions will provide a clear assessment of the importance of employing new generation electronics in terms of NECR performance improvement

reduction of scan time. In Fig. 3 the geometry configuration of the model of Biograph and the relative bed position of a large NCAT phantom are illustrated using the GATE visualization tool.

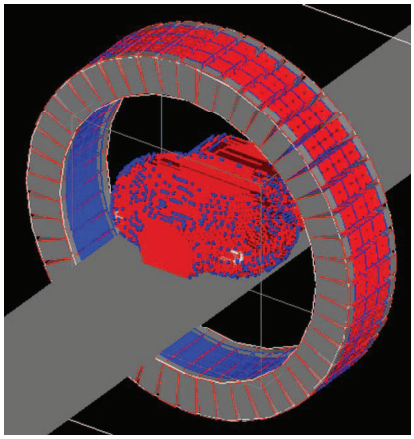

Fig. 3. Visualization of the geometric configuration of the GATE model of Biograph 6 and the relative position and size of the NCAT anthropomorphic voxelized phantom

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 attenuation maps are presented in Fig. 4. These three NCAT phantoms have been designed to resemble three characteristic sizes of human body associated with three common human body weights.

Fig. 4. 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 the optimal scan time. The NECR achieved in the case of the standard 4.5ns time window was compared against the equivalent NECR for a 3ns and 6ns window, respectively. 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.

Finally, the optimal PET acquisition time was estimated as the ratio of a constant NEC threshold of 20 million per bed position and the simulated NECR, for each one of the case above, according to Eq. (3).

III. Results And Discussion

First of all the effects of the patient weight on the NECR and the optimal acquisition time for the Biograph were investigated. As illustrated by Fig. 5, the NECR becomes higher, when smaller sizes of NCAT phantom are imaged, resulting in a proportional decrease of the estimated optimal acquisition time. In the previous study [8], where the objective had been to optimize the injected dose, it has been shown that the optimal dose range was not affected significantly by the size of the patient body. On the other hand, as we clearly see in Fig. 5, the optimal scan time is drastically affected by the patient size and, thus, this parameter is statistically significant and should be taken into account when optimizing the scan time. The reason for this observed difference in the impact of the same parameter to the optimal dose and scan time lies in the fact that the curve of the NECR vs. the injected dose is mainly shifted vertically rather than horizontally when the size of the patient changes, as illustrated by Fig. 6.

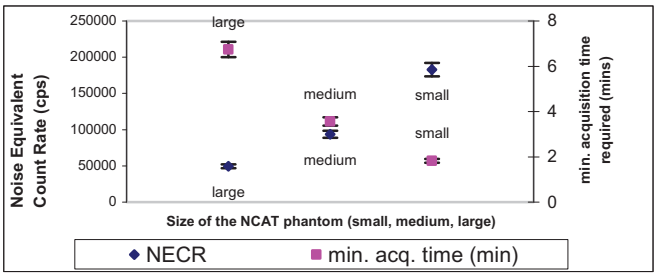

Fig. 5. Biograph NECR and optimal acquisition time vs. total injected dose for three different sizes (small, medium, large) of NCAT phantom (energy window of 425-650keV, coincidence window of 4.5ns and dead time of 300ns have been selected)

According to Fig. 7 when the coincidence time window of Biograph hypothetically drops from 4.5ns, which is the default value, to 3ns, then a non-negligible increase of the NECR and an equivalent shorter optimal scanning time is observed. The NECR response is also improved by 35% in this case, as it is illustrated by Fig. 8. This behavior demonstrates the importance of the development of new generation electronic coincidence systems allowing for shorter coincidence windows and, subsequently, better NECR performance [8]. 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, shorter optimal scan times.

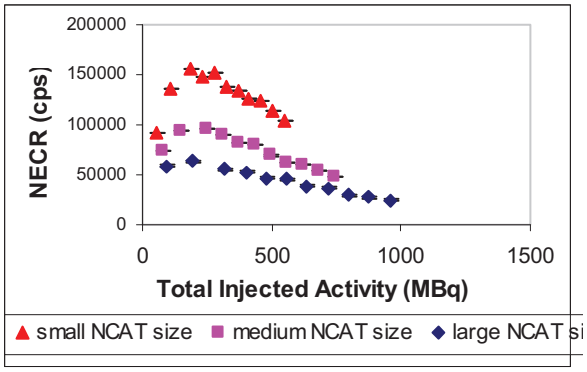

Fig. 6. Biograph NECR vs. total injected dose when three different sizes (small, medium, large) of NCAT phantom sizes have been used, application of the 425-650keV energy window, standard dead-time 300nsec are selected and 4.5nsec coincidence window.

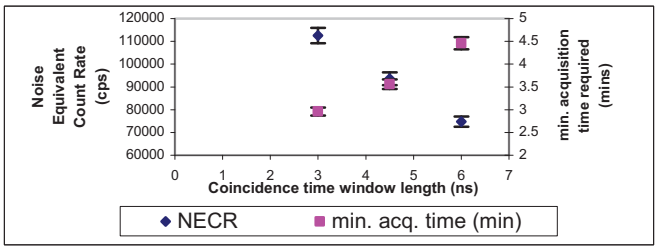

Fig. 7. Biograph NECR and optimal acquisition time vs. total injected dose for three different coincidence time windows (3ns, 4.5ns, 6ns) (medium size, energy window of 425-650keV, and dead time of 300ns have been selected)

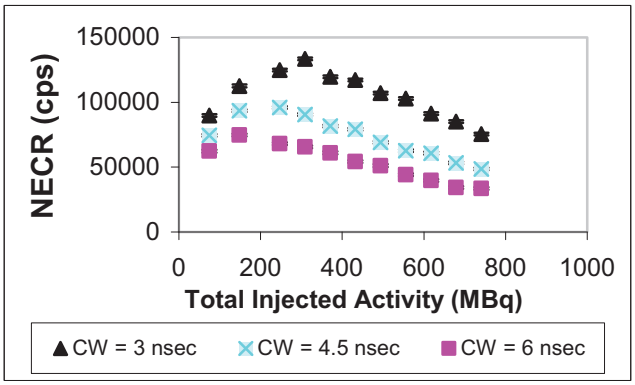

Fig. 8. Biograph NECR vs. total injected dose when different coincidence time windows are applied. A medium-sized NCAT phantom is used with a 425-650keV energy window and a standard dead-time of 300ns.

Moreover, Fig. 9 demonstrates the strong dependence of the NECR and the acquisition time on the system dead-time. Additionally, the NECR responses of several hypothetical dead-time models of the Gate model of Biograph are plotted together in Fig. 10 for the purpose of a comparative analysis [8]. 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 and thus acquire the same number of NECs in significantly shorter scan times.

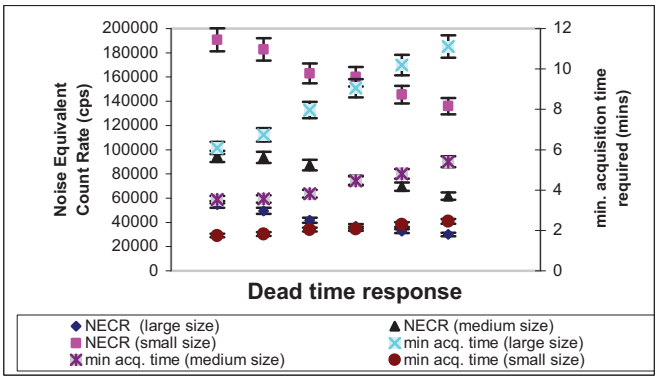

Fig. 9. Biograph NECR and optimal acquisition time vs. total injected dose for six different dead time responses (medium size NCAT, energy window of 425-650keV, and coincidence time window of 4.5ns have been selected)

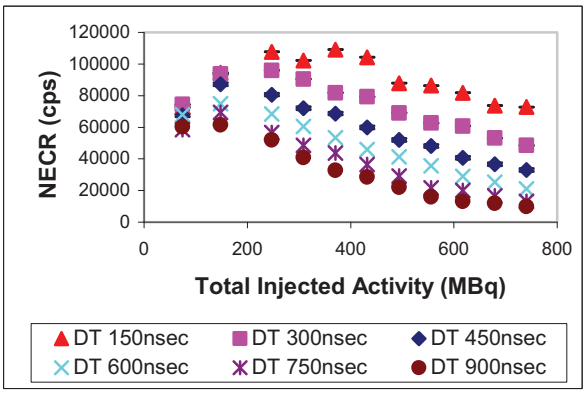

Fig. 10. Comparative diagram of the NECR curve vs. total injected dose for 6 different dead-time responses. A medium-sized NCAT phantom size has been used with an energy window of 425-650keV, and a standard coincidence time window of 4.5ns.

Finally, we observe, in Fig. 11, an enhancement of the NECR, when narrower energy windows are used, allowing for shorter scan durations. The energy window of 425-650keV is the energy window preferred in clinical studies and had been selected for all the previous simulation series. However, Fig. 10 illustrates the effect of different low energy thresholds (LETs) on the NECR and the optimal scan time. When the LET is decreased from 425keV down to 400, 375 and 350keV, a significant degradation of the NECR and an equivalent increase of the optimal scan time is observed. On the other hand, when the LET is raised up to 450keV, a slightly better NECR value is measured over the entire range of dose levels, as it is presented in Fig. 12, because more randoms and scattered events are rejected with respect to trues. This results in a slightly better NECR for the selected injected activity level of 150MBq and, therefore, to a minor improvement in the optimal scan time. However, the enhancement of statistical quality is only minor and, although the NECR response of the system is enhanced when LET=450keV, the overall performance of the Biograph is optimized, in most cases, when a LET of 425keV is applied.

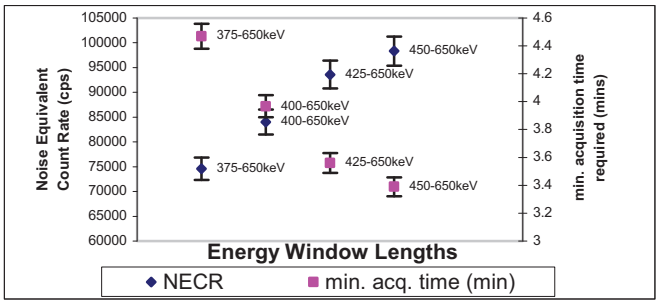

Fig. 11. Biograph NECR and optimal acquisition time vs. total injected dose for four different energy windows (medium size, coincidence time window of 4.5ns and dead time of 300ns have been selected)

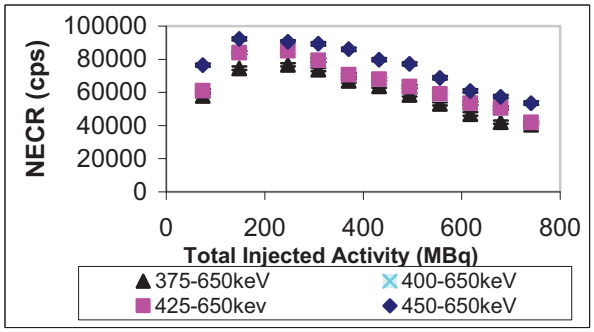

Fig. 12. Biograph NECR vs. injected dose for various energy window lengths. A medium size NCAT, a coincidence window of 4.5ns and a dead-time response of 300ns have been selected

A complete set of simulated NECR values and optimal scanning times has been generated, for all combinations of parameter values used previously, in order to create a sufficient data set that will allow for the building of a regression model or an artificial neural network, both capable of estimating the optimal acquisition time prior to a clinical scan. Our aim is to provide such an optimization model for nuclear medicine clinical applications.

The proposed optimization method examined here can be applied together with previously developed dose optimization studies [7, 8] to further enhance the flexibility of the data acquisition protocol, while ensuring high statistical quality in the generated projection data. Thus, the injected dose can be regulated according to the initial parameter values of the patient and the scanner using the methodology described for dose optimization. Later, after the injection of the optimal dose, which had been determined in the first step, the parameters of the patient and the scanner can be recalculated, together with the actual activity distribution over each bed position, and the methodology of scan time optimization can be employed to ensure high statistical quality for each bed position.

ACKNOWLEDGMENT

The authors would like to thank the OpenGATE collaboration for allowing us to use the GATE simulation software for the purposes of this study.

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