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Estimating Live-Time for New PET Scanner Configurations

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Abstract

We present the derivation of a live-time model for predicting count rates in computer simulations of PET scanners. Computer models are frequently used to investigate new PET scanner configurations, but they typically do not account for the count losses caused by scanner-specific electronics and processing. The live-time fraction depends strongly on the photon flux incident on the detector. We modeled the live-time of a clinical PET scanner by relating measured and simulated single photon fluxes. Our model used data from a specific scanner, but the approach is generally applicable.

We applied the live-time model to partial collimation on a PET scanner; in particular, a scanner with septa positioned between every third detector ring (“2.7D” acquisition mode). The photon flux was measured and simulated for conventional acquisition modes (2D, 3D), and simulated for partial collimation (2.7D). These data were used in the model to predict live-time for partial collimation. The model was then validated against measurements in 2.7D mode. At low activity the model was very accurate at predicting the live-time fraction. Over-estimation of count-rates by the simulations lead to an uncertainty in the live-model. The uncertainty increased with activity concentration, reaching 0.9% and 2.2% at 20 kBq/mL for singles and coincidence live-time, respectively. When applied to 2.7D mode, the model predicted coincidence live-time accurate to 2.2% and 10% at 5 kBq/mL and 20 kBq/mL in the phantom, respectively. The 2.7D singles-counting live-time was predicted to within 0.2% of the measured value for up to 20 kBq/mL in the phantom.

I. INTRODUCTION

Positron emission tomography (PET) scanners are limited in count rate capability due to the finite time required to process incoming detected photons. It is important to understand and quantify the count rate limitation of PET scanners because the limitations frequently occur in the count-rate region experienced during patient scanning. The loss of counts due to count-rate limitations must be corrected in order to generate an accurate image, especially for quantitative considerations. Methods for characterizing PET scanner count rates are described in [1–4]. Several factors in the data processing chain combine to govern the overall PET scanner count-rate. Due to the interaction of these multiple factors, the correction for count losses due to count-rate limitations usually must be derived from a combination of analytical models that describe the individual electronics components and empirical data derived from scanning phantoms at various input count rates. A fundamental determining factor in the count-rate limitation is the rate at which individual photons strike the system detectors, and whether they trigger the system to begin processing.

Computer modeling is a powerful tool for evaluating new PET scanner configurations. Computer simulations typically model the physics processes of gamma ray interactions and

scintillation photon propagation, but not the limitations of the counting electronics. In order to estimate count-rate performance of simulated scanners over a wide range of activities it is necessary to estimate the live-time effects independently of the computer simulation. The count-rate limitations of radiation detector electronics can be parameterized by paralyzable and non-paralyzable models [5]. However, as mentioned above, PET systems become sufficiently complex that in order to accurately correct for the count losses due to count-rate limitations the analytical expressions for live-time are augmented by measured effects. In PET imaging photon pairs are detected in coincidence so it is the coincidence count rate live-time that is relevant. However, random coincidences are commonly calculated from the single photon flux, so we must also characterize the live-time of singles counting in order to predict the random coincidence rate. The coincidence live-time and singles live-time are related, with coincidence live-time effects being worse due to the extra processing required to verify and process a coincidence event

We have used computer models to investigate performance parameters of new PET scanner configurations, namely intermediate degrees of collimation between 2D and 3D acquisition modes [6]. To estimate count-rate dependent parameters, such as the noise equivalent counts (NEC), it is necessary to know how the singles and coincidence count rates are affected by scanner live-time. We present a model to estimate PET scanner live-time fraction (LTf) that was developed to predict count rates for partial collimation. We present results for a specific scanner, but the method could be applied to other systems. Our aim is not to provide corrective factors for an existing system; rather we seek a predictive model for application to new scanner configurations that use known or predictable processing electronics.

II. MATERIALS AND METHODS

We used measured and simulated data to predict the live-time fraction for the Discovery STE PET scanner (70 cm diameter by 15.7 cm axial FOV, 24 BGO rings, GE Healthcare). The new configurations of the DSTE that we studied used variable numbers of septa between 2D mode and 3D mode. In this paper we focus on the case of septa between every third detector ring (2.7D mode) because we have measured data in 2.7D mode that can be used to verify our predictive live-time model. The results of applying the live-time model to partial collimation has been reported elsewhere [6].

The SimSET Monte Carlo simulation [7] was used to generate count-rate and energy spectra data from 2D, 2.7D, and 3D scanner configurations. One significant difference between the SimSET model and the DSTE scanner is the detector block format. The current version of SimSET does not model general PET block detectors, rather a PET ring is modeled as a solid annulus of detector material. As such, the simulation does not model the differences in energy spectra among the individual scintillation crystal elements within a block. These differences are potentially important to our understanding of the system live-time due to the fundamental dependence of the live-time on the distribution of incident photon flux. To augment the SimSET data we have measured the singles events energy spectra on the DSTE scanner in 2D and 3D modes.

The LTf of the scanner was measured in 2D, 2.7D and 3D modes. The general live-time model was derived from the 2D and 3D measurements before measurements were made in 2.7D mode. The model was applied to simulated 2.7D data to investigate the NEC on the DSTE in 2.7D mode. The encouraging results from that work motivated building and testing a 2.7D collimator for the DSTE [6]. From the measured 2.7D data we determined the corresponding system live-time and compared it to what our model predicted.

Live-time was derived from count-rate experiments conducted over a wide range of activities. Count-rate data were acquired according to the NEMA NU-2 2001 protocol using a 70 cm long, 20 cm diameter polyethylene cylinder with a 3 mm diameter line source (18-F) along its length, 4.5 cm from the axis of the cylinder. In addition, the count rates were measured in a larger cylinder phantom that was identical to the NEMA standard except with a 35 cm diameter.

Ideally, the measured count-rate in a scanner increases linearly with activity in the scanner field of view (FOV). The LTf is the fraction of the ideal event rate that is actually measured in practice. At low activities the ideal linear relationship is obeyed; count losses are negligible and the $LTf \approx 100\%$. This linear relationship can be extrapolated to higher activities to give 'ideal' count rates for all activities. We calculated the singles LTf vs. activity concentration by taking the ratio of the measured singles rates to the 'ideal' singles rates derived from the linear extrapolation. We obtained the coincidence LTf in the same way. We also obtained the coincidence LTf from the proprietary correction factors implemented on the DSTE. The measured coincidence count-rate curves reached a maximum, then began to decrease, characteristic of a paralyzable dead-time. In the count-rate region we considered the paralyzable model fit both singles and coincidence live-time curves well. As mentioned, the true LTf relationship is likely some combination of the analytical models. Since the paralyzable model appeared sufficient for the count-rates studied, it was used in the model, and it is given by

$$LTf_m(x) = \exp(-\alpha_m x) \quad (1)$$

where α_m is a dead-time coefficient fit parameter, and x is the activity concentration in the phantom. The index, m , on the dead-time coefficient signifies the scanner acquisition mode (2D, 3D, or other, e.g. 2.7D). This index is necessary when describing the live-time fraction as a function of activity concentration. Our hypothesis is that LTf is a function of photon flux incident on the detectors. If we designate the incident photon flux as Φ , then equation (1) can be expressed as

$$LTf(\Phi) = \exp(-\tau\Phi) \quad (2)$$

where now τ is the more familiar dead-time coefficient expressed in units of time, and is independent of acquisition mode. The relationship between the incident flux (Φ) and the activity concentration (x) is acquisition-mode-dependent. Equation (2) is the universal expression of live-time that we seek for application in models of new scanner configurations.

We obtained a relationship between the phantom activity concentration and incident flux via SimSET. This gave us a way to relate the mode-specific measured $LTf_m(x)$ (eqn. 1) to the general LTf expression (eqn. 2) for the conventional acquisition modes.

Our derivation of the live-time model used the following steps:

1. Measure the live-time fraction as a function of activity concentration in the phantom, $LTf_m(x)$, using the NEMA count-rate experiments. $m = 2D, 3D$.
2. Simulate the same experiment for conventional acquisition modes (2D and 3D). The simulations provide a relationship between the activity concentration in the phantom, x , and the photon flux incident on the detectors, $\Phi : \Phi_m(x)$, for conventional modes $m = 2D, 3D$.
3. Simulate the same experiment for new configurations (2.7D) to get $\Phi_{2.7D}(x)$.

4. Combine 1. and 2. to obtain the live-time fraction as a function of photon flux incident on the detectors, $LTf(\Phi)$. This can be done independently for 2D and 3D data, and the resulting $LTf(\Phi)$ should be the same in each case. Any deviation between $LTf(\Phi)$ expressions derived from 2D and 3D will be considered the error in the model. A likely source of such deviations is inaccuracy in SimSET's prediction of $\Phi_m(x)$.
5. Use the results of 3. to convert the $LTf(\Phi)$ derived in step 4. to $LTf_{2,7D}(x)$ in order to obtain live-time for the new configuration for a given activity in the phantom.

The incident photon fluxes are calculated as the sum of the energy spectra above a lower threshold. Our analysis accounted for the variable pulse height spectra found in different block crystals. SimSET models the detector as one large solid ring of BGO material so the pulse height variability due to crystal position within a block is not modeled. To compensate for this difference we adjusted the SimSET energy spectrum according to the variations in pulse height measured in each crystal on the DSTE scanner. Another variable is the energy resolution value in the different crystals within the block. SimSET was run with the mean scanner energy resolution specified in the configuration file. This variation was not modeled thus far. We plan to further modify the SimSET spectrum to compensate for this variation as well.

The association between photon fluxes predicted by SimSET and those measured on the DSTE varied, with SimSET tending to overestimate the count rate. This resulted in uncertainties in the generalized LTf model. We characterized the uncertainties with error bars on the predicted LTf values (see Fig. 3). The LTf model was compared to measured LTf for the case of a 2.7D collimator.

III. RESULTS

We first collected experimental count-rate data in 2D and 3D acquisition modes using the 20 cm and 35 cm diameter NEMA phantoms. An example of the measured coincidence count-rate is shown in fig. 1(a). In addition to the measured data points, fig. 1(a) shows the extrapolated 'ideal' count-rate line. The ratio of the measured data points to the corresponding values on the extrapolated line give the live-time fraction at a given activity concentration in the phantom. The live-time fraction for the case seen in fig. 1(a) is shown in fig. 1(b), as well as the singles and 3D LTf for the 20 cm phantom.

Fig. 2 shows the difference in measured and simulated energy spectrum shapes. The SimSET spectrum matches the spectrum measured from a central crystal in the block detector. The block spectrum is the sum of 48 crystal spectra with variable pulse heights as described earlier. The energy spectrum of each crystal is considered separately when qualifying an event for acceptance, but for purposes of triggering the system it is the global pulse-height distribution that is seen by the discriminator.

The number of incident photons was calculated by summing the SimSET energy spectra after adjusting the output SimSET spectrum according to the pulse-height variations measured on the DSTE as described in the Materials and Methods section. The values of the phantom activity and acquisition time are specified in each SimSET run. The calculated number of photons and specified activity concentration and acquisition time are combined to give the incident photon flux in counts-per-second per unit activity concentration. Using this calculation we converted the activity concentration axis in fig. 1(b) to incident photon flux. The result for the coincidence live-time fraction is shown in fig. 3.

Fig. 3 is a plot of eqn. 2, which we hypothesized to be independent of acquisition mode. Although the $LTf(\Phi)$ curves determined from the 2D and 3D data are close to each other, we

still see a difference in fig. 3. A likely source of the discrepancy is in the flux per unit activity values predicted by SimSET.

We applied the model derived in fig. 3 to the 2.7D case. The $LTf(\Phi)$ model shown in fig. 3 was adjusted to the activity concentration in the phantom, this time using the flux per unit activity conversion determined by SimSET for the 2.7D case. We also measured the $LTf_{2.7D}(x)$ in 2.7D mode. Both the modeled and measured coincidence LTf curves are shown in fig. 4.

The analysis was repeated for the singles live-time curves. Fig. 5 shows the modeled and measured singles LTf for 2.7D mode.

The entire analysis was repeated for the data acquired with the 35 cm diameter phantom. Fig. 6 shows the resulting modeled and measured coincidence and singles live-time fraction curves. In the case of the 35 cm diameter phantom the 2D and 3D live-time vs. incident flux curves ($LTf(\Phi)$) were much closer than for the 20 cm diameter phantom case (fig. 3). Error bars were calculated in the same way as for the 20 cm phantom case, but they are so small in the 35 cm case that they are not seen in fig. 6.

IV. CONCLUSIONS

Using measured and simulated count-rate experiment data we derived a generalized model of the global coincidence and singles live-time vs. activity for a PET scanner. The intent of the model is to predict live-time fractions for new, untested scanner configurations when clinically relevant activity concentrations are on the patient bed. In a separate report [6] we used the model to investigate the count-rate capabilities of a Discovery STE PET scanner equipped with partial collimation. In this work we presented the derivation of the live-time model.

The model depended on measured live-times and assumed that the live-time fraction is determined by the single photon flux incident on the detectors. For the activity range we considered, a paralyzable live-time function sufficiently described the measured live-time fraction curves. This function was then adapted to proposed new scanner configurations by relating the measured activity concentrations to incident photon flux via Monte Carlo computer simulations. The live-time model contains uncertainty due to discrepancies between simulated and measured photon fluxes. The simulated flux distribution was modified to better match the spectra measured on the scanner. Further modifications are possible that could potentially reduce the uncertainties in the live-time model. We also plan to calculate the effect of the uncertainty in the live-time estimate on parameters such as noise equivalent count rate with error propagation analysis.

The singles live-time fraction was modeled with excellent accuracy; $< 1\%$ error between modeled and measured singles live-time for both the 20 cm and 35 cm phantoms. Singles rates are needed to predict random coincidence rates on new scanners.

The coincidence live-time fraction was accurately modeled for low activity concentration; the % error in coincidence live-time was 2.2% at 5 kBq/mL and increased to 10% at 20 kBq/mL in the 20 cm diameter phantom. The corresponding %errors from the 35 cm diameter data were 1.4% and 5.6% at 5 kBq/mL and 20 kBq/mL, respectively.

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Fig. 1.

(a) Measured and extrapolated true + scattered coincidence count rate from the 20 cm diameter NEMA phantom in 2D. (b) Live-time fractions: ratio of measured to extrapolated count rates. The coincidence count LTf is less than the singles count LTf at a given activity due to the imposition of the coincidence timing window for coincidence events. The 3D LTf is less than the 2D LTf for a given activity because of the higher incident photon flux on the detector in 3D mode.

Figure 2.

The pulse-height distribution of the singles flux affects the Lf , as does the lower level trigger setting. In order to determine the flux rates for different configurations we considered differences between the measured global scanner spectrum and central crystal spectra, spectra for different collimators, and spectra for different sized phantoms. For the 20 cm dia. phantom: (a) Measured 2D energy spectra for the entire scanner and a block central crystal. (The scanner spectrum energy scale is calibrated by equating the photopeak of a central crystal to 511 keV.) and the SimSET spectrum. (b) SimSET singles energy for different collimation.

Fig. 3.

The 2D and 3D coincidence live-time fraction curves expressed as a function of incident photon flux. Our hypothesis is that these curves should lie on top of each other. Since they do not, our best estimate for the live-time model is the average of the 2D and 3D LTF curves. The error bars are simply the difference between the 2D and 3D LTF curves.

Fig. 4. Modeled and measured coincidence live-time fraction for 2.7D acquisition mode. The dotted line goes with the right-hand vertical axis and shows the % error between the model and the measured values.

Fig. 5. Modeled and measured singles live-time fraction for 2.7D acquisition mode. The dotted line goes with the right-hand vertical axis and shows the % error between the model and the measured values.

Fig. 6.

Modeled and measured coincidence and singles live-time fraction for 2.7D acquisition mode and the 35 cm diameter count-rate phantom. The solid lines are the models, the marker points are the measured values. The dotted lines go with the right-hand vertical axis and show the % error between the model and the measured values. In this case the error bars on the derived model are so small that they cannot be seen.