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Adjusting the Low Energy Threshold for Large Bodies in PET

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Abstract—**The performance of a PET scanner on three different phantom sizes was studied as a function of low energy threshold (LET). Phantom cross sections ranged from 20 cm diameter circular to 28 cm x 43 cm oval and LET's ranged from 350 keV to 475 keV, in 25 keV increments. System sensitivity, scatter fraction, and NEC were measured over a wide range of radioactivity levels. Increasing the low energy threshold lowered both sensitivity and scatter fraction. The statistical quality of the raw data was maximized for the 425 keV setting for all three phantoms. System stability and uniformity of response was also studied for 375 keV to 450 keV thresholds, and indicated acceptable performance for this system through 425 keV.**

I. Introduction

The low energy threshold (LET) in positron emission tomography (PET) is used to exclude scattered photons from being used to form counted coincidences. Because of the imperfect energy resolution of PET detectors, an LET that allows all true events will also allow many scattered events. In 2D PET, with relatively few scattered photons reaching the detectors, LET's as low as 300 keV have been used, with the priority being on maximizing sensitivity. With 3D PET, the much higher incidence of scattered events has justified the use of higher LET's. From the perspective of noise equivalent counts (NEC),

$$NEC = T/(1+S/T+R/T), \quad (1)$$

(where T, S, and R are the numbers of true events, scattered events, and random events on relevant lines of response, respectively). NEC can be increased even with lower T if it comes with a large enough decrease in scatter fraction or random fraction. Since the scatter fraction increases with increasing object size, the optimal LET may be higher for typical patients than for the 20 cm diameter test phantoms used for PET performance evaluation, and the optimal threshold may vary greatly enough with patient size that the use of multiple LET's on a system is worth investigating.

Previous studies have been reported that used 20 cm phantoms to LET optimization [1-3]. We have performed experiments with three different size phantoms to investigate NEC performance for a range of LET's and radioactivity levels.

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II. Methods

All data were acquired on a Discovery ST PET/CT system (GE Healthcare Technologies) [4]. This system has retractable septa, allowing 2D and 3D acquisition, and uses Bismuth Germanate (BGO) detectors whose average crystal energy resolution is approximately 17% FWHM. Data were acquired at low energy thresholds of 350, 375, 400, 425, 450, and 475 keV, with a single upper threshold of 650 keV. The standard LET for this system is 375 keV in both 2D and 3D modes.

A. System Sensitivity

System sensitivity was measured with a 70 cm long aluminum tube with an insert filled with 70 μCi ^{18}F. This represents a single measurement of the more involved NEMA NU2-2001 sensitivity prescription [5,6], whose purpose is to measure an absolute sensitivity. Since the purpose of this study was to compare sensitivities for different settings, a single measurement was determined to be simpler and still sufficient.

The rod was centered in the system field of view and data were acquired at each of the six LET's. Unlike the NEMA prescription, corrections were applied for random events, which were approximately 2%. After corrections for radioactivity decay were made, counts for each acquisition were divided by the counts for the 375 keV LET acquisition.

B. Scatter Fraction and Count Rates

Three phantoms were used for the scatter fraction and count rate tests. The first ("NEMA") was the 20 cm diameter, 70 cm long high-density polyethylene cylinder prescribed by the NU2-2001 protocol. This phantom has a 70 cm line source positioned 4.5 cm off-axis.

The second phantom was a fillable whole body ("WB") phantom with a 36 cm x 21 cm oval cross-section and a 80 cm length. A 70 cm line source was positioned internally, 7 cm laterally off the central axis. The remainder was filled with non-radioactive water.

The third phantom was the whole body phantom with an additional two layers of 3.8 cm diameter water-filled rubber hose wrapped around a 25 cm central section, as shown in Figure 1.

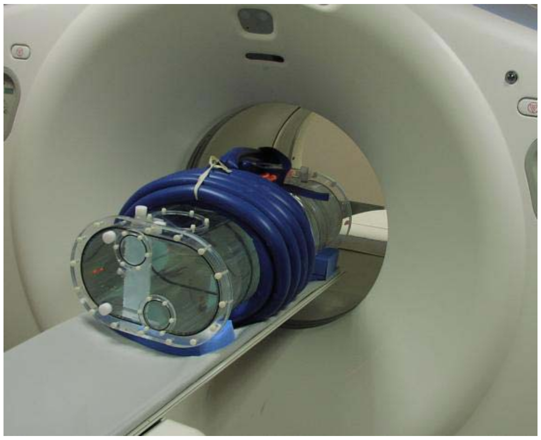

Figure 1. Augmented whole body phantom, shown on the scanner table out of the system field of view.

For each phantom, the line source was filled with ^{18}F solution. The phantom was centered in the field of view of the PET detectors, and scanning commenced with approximately 12 mCi in the line source. Taking into account the decay during a 45 min uptake period, and the radioactivity that goes outside the torso region (in the brain and extremities, and voided before the scan), this corresponds to approximately 25 mCi injection. The system cycled through 4 min 3D acquisitions at the 6 different LET's as the source decayed, with approximately one minute between acquisitions. Each LET setting was therefore sampled every half-hour. At the end of the acquisitions, a 20 min acquisition was performed for each setting. For these acquisitions, delayed coincidences were recorded in addition to prompts, to allow correction of the non-negligible (~2%) random events in the scatter fraction determination. For the whole-body phantom, a CT scan was performed with the phantom in place to define the body contour.

The raw data were taken off-line and processed. The 3D data were collapsed to 2D sinograms using single-slice rebinning. A mask was applied to the sinograms to retain only lines of response subtending or near the body. For the NEMA phantom, this mask was a 24 cm region centered on the phantom. For the elliptical whole body phantom, the mask was made from the CT images, converted into sinogram format as is done for attenuation correction. The subsequent processing was identical to the NEMA method, with the exception that the scatter fractions were determined from random corrected data. The analysis assumed a singles-based random correction, since this method is available on the system.

C. System Uniformity and Stability

In addition to the potential improvement in raw data statistics (NEC), raising the LET has several potential implications for system performance. Corner crystals yield less light than edge crystals, which in turn yield less light than inner crystals. Reduced light output implies lower energy resolution, which means that corner and edge crystals will be more affected by increases in the LET. In addition, raising the LET leads to more sensitivity to gain variations such as those caused by temperature fluctuations.

To investigate both the increasing non-uniformity of response across crystals in the block, as well as the potential instability of the system, blank scans were performed on the system at 375, 400, 425, and 450 keV on five different days over a period of 26 days. These blanks were acquired with an orbiting ^{68}Ge rod source normally used for system calibrations. These acquisitions were performed with septa in (2D) to control count rates, with the assumption that gain shifts and crystal-to-crystal variations with LET change would be evident in 2D as well as 3D. Each acquisition was 4 hours, so the entire procedure was 16 hours. The gain calibrations on this system are typically performed each Monday. The first and fourth of these blank studies were started on Monday evening after calibration, and second, third, and fifth were performed on the weekend.

III. Results

A. System Sensitivity

System sensitivity results are shown in Figure 2.

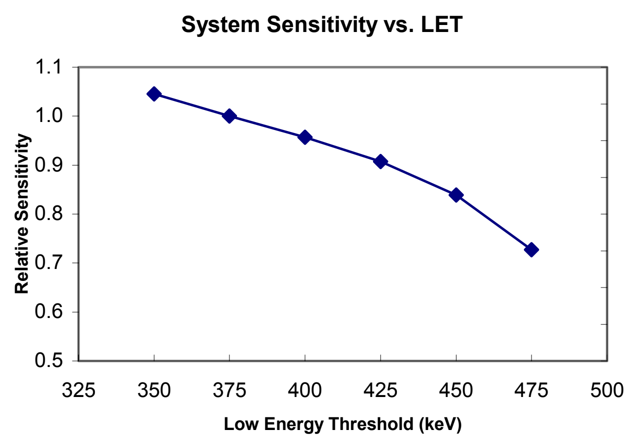

Figure 2. System sensitivity vs. low energy threshold, determined with line source in aluminum tube, and normalized to the system default 375 keV LET setting.

Sensitivity decreases approximately 5% per 25 keV change in LET for the lower energies, but the decrease is greater starting at 425 keV.

B. Scatter Fractions

Scatter fraction results are shown in Figure 3. The expected results are demonstrated. The scatter fractions are greater with increasing body size, and decrease with increasing LET.

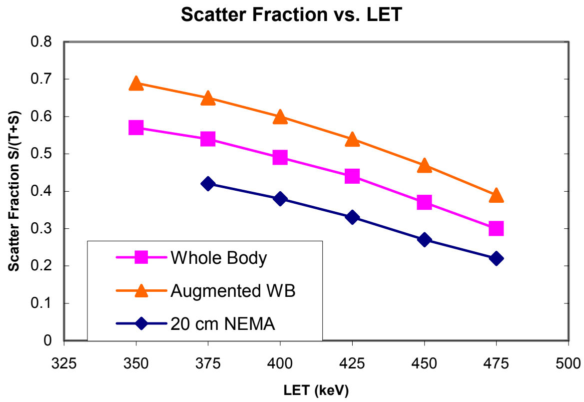

Figure 3. Scatter fractions vs. low energy threshold for the three phantoms.

C. Scatter fractions decrease approximately 10% per 25 keV change in LET.Count rate studies

Count rate results for the three phantoms are shown in Figure 4. Several trends stand out. First, the overall performance decreases dramatically as the phantom size increases. Second, there is a variation in performance as a function of LET. The variation is smallest for the NEMA phantom and increases with increasing phantom size. Third, the best performance, regardless of phantom, occurs at an LET of 425 keV. Finally, the ranking of the curves remains fixed up through the optimal activity level. Crossover of some curves at higher activity levels indicates that the benefit of higher LET on reduction of random events (non-linear with activity, vs. scatter events, whichare linear with activity) is a real phenomenon, but is not relevant here.

While the 425 keV LET performs the best, the 400 keV curve is second-best for the NEMA phantom, whereas the 450 keV curve is second-best for the augmented phantom. This indicates that there is a minor degree of body-size dependence to the LET optimization, and that if finer steps than 25 keV had been used, this experiment would likely have demonstrated the effect directly.

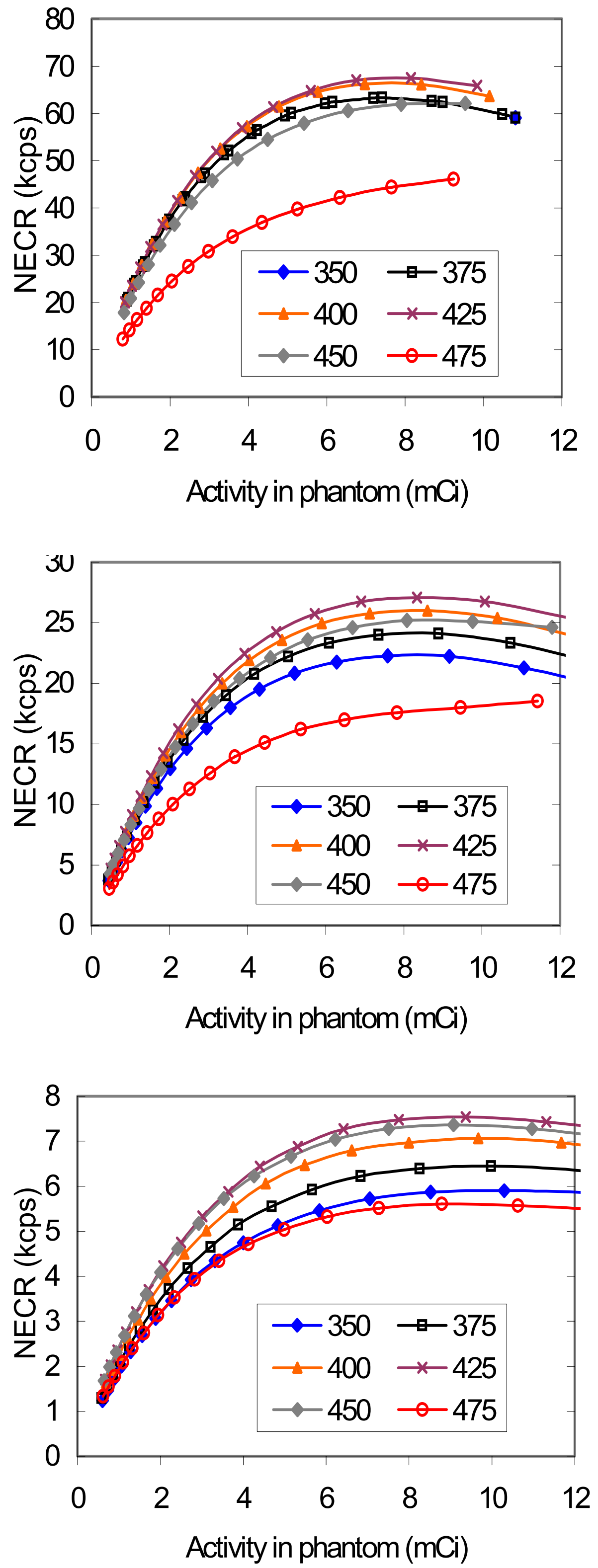

Figure 4. Scatter fractions vs. low energy threshold for the three phantoms.

D. System Uniformity and Stability

Blank scans from all four LET settings are shown from two of the days in Figure 5. Of the two days shown, the first blank is representative of four of the five days, which had good quality, and the second is the worst of the five days. There were several trends in the blank data. First, the count rates decreased with increasing LET, as expected given the sensitivity measurements. Second, the cross-hatch pattern became slightly more pronounced with increasing LET. Finally, as shown in the right column, the 450 keV LET setting was most vulnerable to regional and global gain drifts, with a substantially lesser degree of vulnerability for the 425 keV LET.

To demonstrate the change in uniformity more directly, Figure 6 shows the subtraction of higher energy LET sinograms from the 375 keV one. At this count density, there is no observable difference in uniformity between 375 keV and 400 keV. There are observable differences for 425 keV and 450 keV LET's, corresponding to the higher reduction in sensitivity for edge and corner crystals compared to inner crystals.

IV. Discussion

As expected, system sensitivity decreased with increased LET, while scatter fractions decreased. In the NEC formulation, small variations in large scatter fractions have a large impact on raw data statistics. The denominator of the NEC expression includes the term S/T. Expressed in terms of the scatter fraction *s.f.*=S/(S+T), this is

$$\frac{S}{T} = \frac{1}{1/_{s.f.} - 1}. \qquad (2)$$

For *s.f.*'s of 0.65 and 0.54 (the values for the augmented phantom at 375 keV and 425 keV), the term is 1.86 and 1.17, respectively, which makes a much larger difference in the NEC than does the ~10% loss due to sensitivity decrease (which affects the numerator directly.)

The count rate studies indicate that NEC is indeed improved with a higher LET. This is true not only for the small NEMA phantom, as other studies have found, but especially for the larger phantoms, more typical of patient sizes. The spread in NEC values as a function of LET increases with increasing body size.

The determination that the 425 keV LET was best for all phantom sizes used is certainly better for system operation than would have been a determination that the LET should be varied, depending on patient size, since this would require that a system be calibrated at different LET's. The hypothesis that different LET's might be appropriate for different body sizes would likely be correct, based on the relative ranking of the 400 keV and 450 keV NEC's with increasing body size, but a sampling finer than 25 keV would have to have been employed. The subsequent NEC improvement from adjustments finer than 25 keV, even if optimal, would be minor.

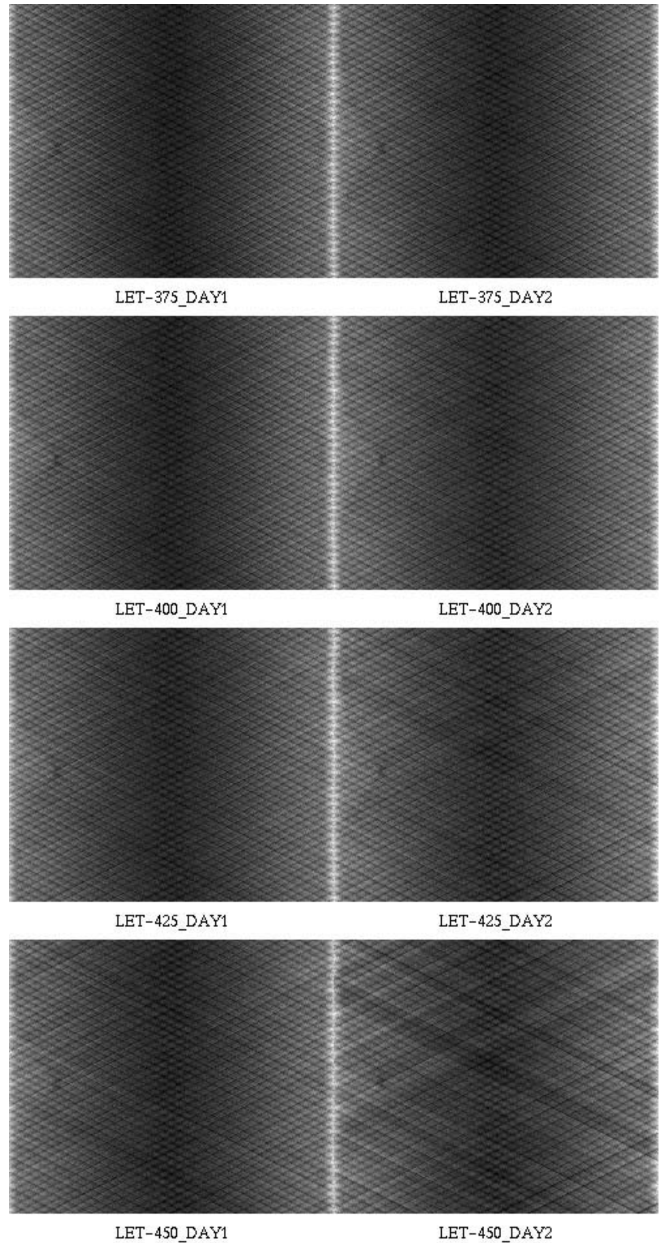

Figure 5. Blank sinograms for four LET settings for two of the five days sampled. The grayscale is maximized for each individual sinogram to emphasize any nonuniformities. At left are typical of the system performance. At right is the worst case.

The uniformity of system response, as indicated by blank measurements, degraded only slightly through 450 keV. More importantly, the system stability did suffer, perhaps unacceptably, at 450 keV for one blank measurement (likely due to larger-than-normal temperature fluctuations, which were unmonitored over the weekend while data were acquired), while the 425 keV performance seems adequate. These results reflect only the performance of a single system in a particular environment. More extensive evaluation is required before recommending that all systems of this model be operated at 425 keV.

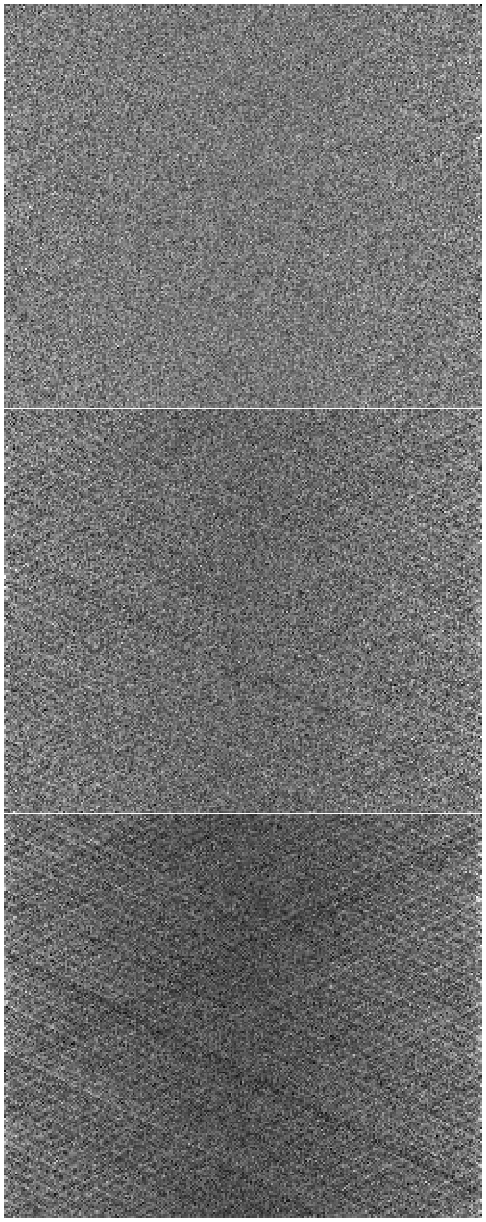

Figure 6. Blank sinogram subtractions: top is 375 keV – 400 keV; middle is 375 keV – 425 keV; bottom is 375 keV – 425 keV.

The recommended period for performing gain calibrations on this system is weekly. If use of a higher LET demanded more frequent calibrations (i.e., daily), that would be relatively easy to accommodate, since the procedure takes only a few minutes.

In addition to reducing scattered coincidences, increasing the LET should also lower the fraction of random events. Since the prevalence of random events increases faster than true events (unlike the scattered events, which are a constant fraction of true events), we expected that the relative ranking of the different LET's NEC might change with increasing activity, making higher LET's more favorable at higher rates. No change in rankings occurred for activity levels at or below the points for optimal system performance, so this effect was minor on this system.

V. Conclusions

Raw data statistics improve, for the range of body sizes studied, when the LET is increased from 375 keV to 425 keV. The improvement increases with body size. Use of this system at a 425 keV LET requires confirmation of stability and uniformity of response. Initial measurements on this system indicate that use of a 425 keV LET is feasible. More extensive evaluation on other systems of the same model in other settings are required before recommending this setting universally.

VI. Acknowledgments

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