Count-rate dependent event mispositioning and NEC in PET

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Abstract-- Most current PET detector designs suffer from event mispositioning at high count rates, as scintillation light from nearby and nearly simultaneous gamma ray conversions becomes mixed. We have used the NEMA NU 2-2001 70 cm test phantom and a Na-22 point source to quantify this effect as a function of activity on two block-detector tomographs (the Siemens/CTI HR+ and the General Electric Discovery LS), and two Anger-type PET tomographs (the Siemens ECAM DUET and the Philips CPET+).

After accounting for event losses due to dead time, we find that the number of counts on LORs passing through a cylinder of diameter and height equal to the point-source full width at tenth-maximum measured at low rate surrounding the point source decreases by between 9% (HR+) and 35% (CPET+) at the activity giving rise to peak Noise Equivalent Count (NEC) rate.

Mispositioned events act to reduce signal-to-noise ratio, both by reducing apparent activity at the originating location and by increasing the signal background. We have reformulated the conventional expression for NEC rate to account for this phenomenon. The new formulation of NEC, which we call NEC*, results in a lower peak value which in turn occurs at a lower activity concentration than for the conventional formulation.

I. INTRODUCTION

Most current PET detector designs suffer from event mispositioning at high count rates, as scintillation light from nearby and nearly simultaneous gamma ray conversions becomes mixed in the detector unit. This mixing is known as pulse pileup.

Event mispositioning for detection events which form part of scattered or random coincidences is probably of little importance, although it is possible that pileup for scattered coincidences may affect the accuracy of the scatter correction method employed. However, mispositioning of detection events that form part of true coincidences will lead to degradation of data quality [1].

The distance by which a piled-up “true event” (i.e., one which forms part of a true coincidence) is mispositioned is dependent on (1) the relative positions within the detector unit of the true event and the event(s) occurring in the detector while the light from the true event is being integrated, and (2) on the relative amounts of scintillation light generated by the gamma ray conversions involved. It is not obvious that a small mispositioning distance will be much more likely than a large one, and piled-up events may frequently be mispositioned across a significant fraction of the detector face. Thus, resolution loss as measured by the full-width at half-maximum (FWHM) of the detector point spread function (PSF) may not be the best way to characterize the effects of pile-up. However, event mispositioning will necessarily result in reduction in contrast and a decrease in signal-to-noise ratio (SNR). In this sense, the effect of event mispositioning on data quality is similar to the effect of scatter.

For PET scanners, data quality as a function of count-rate, or of activity, is usually measured using the Noise Equivalent Count rate (NEC) metric. NEC is formulated such that the SNR at the center of a uniform cylinder should be proportional to its square root [2]. However, NEC, and in particular NEC as measured using the NEMA NU-2 2001 methodology [3], does not account for the effects of event mispositioning, since the target region of interest (ROI) surrounding the emission line source used for the measurement is relatively large. Since NEC is used to compare performance of scanners with different detector designs, and to predict the optimum injected activity for human studies, this is potentially a serious limitation.

In this study, we characterize the effect of event mispositioning on point-source peak count-density and PSF as a function of activity for four clinical PET scanners. We also develop a pileup-corrected formulation of NEC (NEC*) that attempts to quantify the effects of the phenomenon in an easily implementable manner.
II. MATERIALS AND METHODS

A. Theory

The conventional formula for NEC is as follows:

\[ NEC = \frac{T^2}{T+S+2R} \tag{1} \]

where \( T \) is the true coincidence count rate, \( S \) is the count rate of scattered coincidences falling within the boundary of the object and \( R \) is the count rate of random coincidences falling within the boundary of the object (the factor of 2 accounts for the use of a delayed-window direct randoms subtraction method).

Mispositioned true events that have effectively lost all their positional information simply add to the signal background and may be treated in a similar way to scatter. We therefore write an expression for pileup-corrected NEC (\( NEC^* \)) as follows:

\[ NEC^* = \frac{T^*^2}{T^*+M+S+2R} \tag{2} \]

where \( M \) is the rate of mispositioned true coincidences falling within the boundary of the object, and \( T^* \) is the rate of true coincidences that have not been mispositioned.

Let us denote components of the NEC expression given in equation 1 and determined using the NEMA NU 2-2001 methodology by the suffix NEMA. The relationship between \( T_{NEMA} \) and \( S_{NEMA} \) is determined from a phantom experiment at low count rate, where the degree of event mispositioning is effectively zero. If we assume that event mispositioning does not significantly affect the rate of scattered coincidences falling within the boundary of the object, then we can say that

\[ T^* = T_{NEMA} - M \tag{3} \]

The relationship between \( NEC_{NEMA} \) and \( NEC^* \) may then be written as follows:

\[ NEC^* = SRC^2 NEC_{NEMA} \tag{4} \]

where \( SRC \), the source recovery coefficient, is given by

\[ SRC = \frac{T^*}{T^*+M} = \frac{T^*}{T_{NEMA}} \tag{5} \]

Determination of \( SRC \) for this formulation of NEC requires some method of dividing mispositioned events between those that have lost all positional information and those that have undergone only a small deviation in position and can still contribute to true signal. In this work we use the following (arbitrary) rule: events that are mispositioned beyond the full width at tenth-maximum (FWTM) of the PSF at low count rate are deemed to have lost all their positional information.

B. Scanners and Phantom Experiments

Measurements were performed on an EXACT HR+ (Siemens-CTI, Knoxville, TN), a Discovery LS (General Electric Medical Systems, Milwaukee, WI), a Philips CPET+ (Philips Medical Systems, Philadelphia, PA) and an ECAM DUET (Siemens Medical Solutions, Hoffman Estates, IL). Acquisition and scanner parameters are shown in Table 1.

<table>
<thead>
<tr>
<th>Scanner</th>
<th>Detector type, number and dimensions</th>
<th>Mode</th>
<th>Energy window (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR+</td>
<td>BGO block</td>
<td>Fully 3D</td>
<td>350-650</td>
</tr>
<tr>
<td>Discovery LS</td>
<td>BGO block</td>
<td>Fully 3D</td>
<td>300-650</td>
</tr>
<tr>
<td>CPET+</td>
<td>NaI Anger</td>
<td>Fully 3D</td>
<td>435-665</td>
</tr>
<tr>
<td>ECAM DUET</td>
<td>NaI Anger</td>
<td>Axial shields installed</td>
<td>434-588</td>
</tr>
</tbody>
</table>

Table 1. Scanner and acquisition parameters.

In each scanner we placed the NEMA NU 2-2001 70cm test phantom containing between 5 and 15 mCi of F-18 in the field of view and repeatedly scanned it using acquisition frames of duration between 10 and 20 minutes as the activity decayed away. This measurement will be subsequently referred to as exp-1. Exp-1 was then repeated with a Na-22 point source (diameter <2 mm, activity <10 microCuries) taped to the top of the phantom, opposite the phantom line source (subsequently referred to as exp-2). Prompt minus delayed channel coincidence sinograms were generated for all exp-2 acquisitions, except in the case of the CPET+, which does not have this capability. To simplify processing, all lines of response not parallel to the transaxial plane were discarded from the exp-2 data.

C. Data Processing

NEMA NEC calculations

Data acquired in exp-1 was processed using the standard NEMA methodology [3] to yield NEC rates as a function of activity in the 70 cm phantom.

Measurement of Full-Width at Tenth Maximum at low rate

For the lowest count-rate exp-2 dataset, all lines of response containing significant levels of true counts from the F-18 line source were set to zero. The sinogram containing the most counts from the point source was selected. In this sinogram, each projection was then shifted so that the maximum value was aligned with the center of the sinogram, and the projections were subsequently summed. The degree of shift necessary for each projection was recorded. Scattered coincidences (and, in the case of the CPET+, randoms) were removed by means of a NEMA-type background subtraction using a peak-width of 40 mm.
The point-source peak locations and heights were determined by fitting a parabola to the 3 highest points for each dataset, and the FWHM and FWTM were then obtained by linear interpolation.

**Determination of peak characteristics as a function of activity**

For all the exp-2 datasets, the projections passing through the point source were aligned using the transformation derived from the low count rate scans. Background coincidences were subtracted using a NEMA-type background subtraction for a range of peak widths incremented in steps of 0.5 mm. The total numbers of counts in the peaks were determined by summing data on all the lines of response (LORs) passing through a cylindrical ROI centered on the point source maximum and of diameter and height equal to the selected peak width. The axial peak location was determined by examining the sinograms close to the point source and computing the mean sinogram index weighted by the number of counts in each sinogram. Linear interpolation was used to determine the contribution to the peak for sinograms passing through the edge of the cylindrical ROI.

**Computation of dead time**

For the DUET, improved count rates in the large-area crystal are achieved by pulse pileup processing, rather than electronic pulse clipping. The detector is therefore only ‘busy’ when an integration is triggered by a photon conversion in the crystal. However, the entire detector subsystem is effectively “dead” to pulse pileup detection during the pulse rise time after an integration is triggered. As a result, local dead time is the same as system dead time, and linear regression may be performed on the total system count-rates obtained at low activity concentrations to determine the ideal count-rate at higher activities.

On the Discovery LS and HR+, in which the detector volume is physically segmented into blocks, and on the CPET+, in which the detector volume is electronically segmented by zone triggering [4], it is not necessarily the case that local dead time is the same as system dead time. To determine the appropriate dead time correction factors for the point source on these systems, local dead time was therefore estimated.

For the block based systems, this was done firstly by identifying the block combinations responsible for acquiring true coincidences arising from the point source. The total number of counts acquired on LORs from the block combinations was then computed for each scan and linear regression was performed on low count-rate data. In order to improve the fitting accuracy for the F-18 component (which dominated at medium and high rates but not at low rates), data from the LORs carrying most of the true counts from the point source were excluded from the fit.

This methodology was compromised on the CPET+ because of the presence of randoms in the data. Local dead time was therefore estimated by determining the number of true counts arising from the F-18 line source in sinogram planes containing the point source. NEMA-type methodology was used, but a very broad peak width (50mm) was employed to reduce losses due to mispositioning. Again, linear regression was performed on the low count-rate data.

The NEMA prescription for calculating dead time by linear regression requires the use of data for which randoms form less than 1% of the signal. However, it is not clear that this methodology will result in an optimum trade-off between noise and bias. We determined the optimum amount of low-rate data to include in the fit by sequentially adding more data points (starting data from the lowest count rate acquisitions), and computing the \( r^2 \) for the fit. Once sufficient points were included to overcome the initial instability in \( r^2 \), the number of data points that maximized the \( r^2 \) was chosen to determine the ideal count-rate behavior for the local system. A typical example of the relationship between and \( r^2 \) the number of data points is shown in figure 1.

**Computation of SRC and NEC*, and dead time corrected peak profiles**

For the computation of SRC, the height and diameter of the cylindrical ROI used to compute true peak counts were set equal to the low-rate FWTM of the scanner in question, rounded to the nearest 0.5 mm. For each exp-2 acquisition, true peak counts were corrected for dead time losses and divided by the true peak counts obtained from the lowest count rate acquisition to yield SRC as a function of activity. Peak profiles were corrected for dead time losses and plotted together for comparison. NEC* was then computed by matching exp-1 and exp-2 acquisitions with similar activity and multiplying the relevant NEC\textsubscript{NEMA} by the square of SRC.

**III. RESULTS**

Figures 2a and b show dead time corrected point profiles for the CPET+ and the HR+ for local dead time ranging from 0% to ~ 60%. In both cases a loss of peak height can be seen at higher dead times, but in the case of the CPET+ there is also significant peak broadening. Loss of peak height was seen for both the DUET and the
Discovery LS, but significant peak broadening at high rates was only seen on the DUET, and then primarily at the level of the FWTM. FWHM and FWTM are summarized in table 2 for all scanners.

Figure 2a. Dead time corrected point profiles for different percent dead times for the CPET+.

Figure 2b. Dead time corrected point profiles for different percent dead times for the HR+.

Figure 3. Source Recovery Coefficient as a function of peak width for the HR+. The low-rate FWTM for this scanner is 10 mm.

Figure 3 shows typical variations in SRC as a function of peak width. SRC changes quite rapidly with peak width when the peak width is small, but becomes less dependent on peak width as it increases. If the peak width is set very large (40 mm or so), the measurement becomes imprecise at high activities, as scatter from the F-18 source starts to dominate the point source profile.

Figure 4 shows NEC and NEC* as a function of activity for the four scanners. Peak NEC* is less than peak NEC for all scanners. It is also clear that for the Anger camera systems, peak NEC* occurs at a lower activity than peak NEC. Imprecision in the measurement makes the exact location of peak NEC* somewhat uncertain for the block detector systems, but NEC* would again appear to plateau at a lower activity than NEC. Peak NEC values are summarized in table 3. Dead times for the peak NEC values are given in table 4.

Table 2. Peak profile parameters for the different scanners.

<table>
<thead>
<tr>
<th>Scanner</th>
<th>FWHM (mm), 0% dead</th>
<th>FWHM (mm) at peak NEC NEMA</th>
<th>FWTM (mm), 0% dead</th>
<th>FWTM (mm) at peak NEC NEMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR+</td>
<td>5.0</td>
<td>5.2</td>
<td>10.1</td>
<td>10.2</td>
</tr>
<tr>
<td>Discovery LS</td>
<td>5.0</td>
<td>5.1</td>
<td>10.8</td>
<td>10.9</td>
</tr>
<tr>
<td>DUET</td>
<td>7.5</td>
<td>7.7</td>
<td>15.8</td>
<td>17.1</td>
</tr>
<tr>
<td>CPET+</td>
<td>6.8</td>
<td>9.2</td>
<td>14.8</td>
<td>19.9</td>
</tr>
</tbody>
</table>

Table 3. NEC parameters for the different scanners. Note that NEC for the CPET+ and the DUET are calculated assuming a noise–free randoms correction.

<table>
<thead>
<tr>
<th>Scanner</th>
<th>Peak NEC NEMA</th>
<th>Activity for peak NEC NEMA</th>
<th>Peak NEC*</th>
<th>Activity for peak NEC*</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR+</td>
<td>26.2 kcps</td>
<td>4.6 mCi</td>
<td>22.6 kcps</td>
<td>4.3 mCi</td>
</tr>
<tr>
<td>Discovery LS</td>
<td>23.1 kcps</td>
<td>4.0 mCi</td>
<td>18.9 kcps</td>
<td>3.1 mCi</td>
</tr>
<tr>
<td>DUET</td>
<td>2.3 kcps</td>
<td>2.9 mCi</td>
<td>1.8 kcps</td>
<td>1.9 mCi</td>
</tr>
<tr>
<td>CPET+</td>
<td>12.4 kcps</td>
<td>2.4 mCi</td>
<td>6.0 kcps</td>
<td>1.7 mCi</td>
</tr>
</tbody>
</table>

Table 4. Dead time and SRC values at peak NEC for the different scanners.
IV. DISCUSSION AND CONCLUSIONS

All the scanners surveyed demonstrated significant mispositioning effects at peak NEC\textsubscript{NEMA}. As expected more substantial effects were found on the Anger camera based systems than on the block based systems. The CPET+ was more affected than the DUET, which may be explained by the fact that the DUET was operated with axial shields in place, whilst the CPET+ was fully 3D. The fact that the Discovery LS was more affected than the HR+ for a given amount of activity in the field of view is less easy to explain, since the Advance uses more detectors than the HR+ over a smaller field of view (336 over 15.2 cm compared with 288 over 15.6 cm). However, in this experiment the position of the point source with respect to the center of the nearest block detectors was not controlled, and it is quite possible that the mispositioning characteristics investigated here are dependent on block position, thus confounding the comparison somewhat.

The block-based systems showed only a small broadening of FWHM and FWTM at peak NEC\textsubscript{NEMA}. Both the DUET and CPET+ showed more noticeable broadening at FWTM but the CPET+ also showed significant broadening of FWHM, suggesting that at peak NEC\textsubscript{NEMA} a loss of image resolution should be expected as well as a loss of contrast.

If NEC* is accepted as an improved indicator of data quality over NEC\textsubscript{NEMA}, then for all scanners the data indicate that the optimum activity concentration for the acquisition modes investigated is lower than that predicted by NEC\textsubscript{NEMA}. In addition, the peak NEC* is substantially lower than peak NEC\textsubscript{NEMA} for the Anger camera based systems, particularly for the CPET+, where peak NEC* is less than half peak NEC\textsubscript{NEMA}. This suggests that there may be some benefit in introducing some kind of axial shielding for this design. However, firm conclusions cannot be drawn until further experiments are made to correlate NEC* with some more direct measure of image quality.

Newer camera designs incorporating further detector segmentation or faster scintillator crystals would be expected to suffer significantly less event mispositioning than their counterparts examined in this work. This may mean that performance improvements from such technology improvements may be greater than suggested by comparison of NEC\textsubscript{NEMA}. Again, this cannot be confirmed without further investigation of the relationship between NEC* and image quality.
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REFERENCES


