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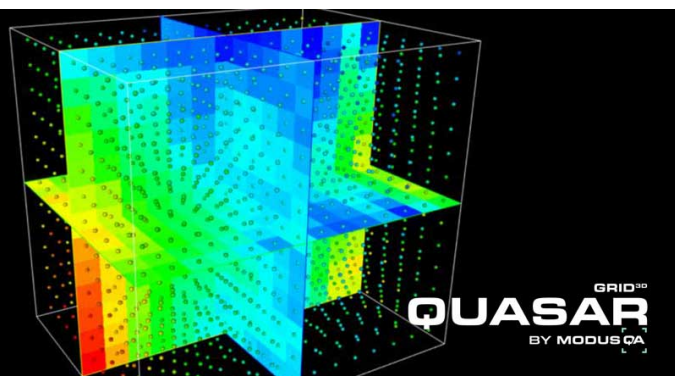
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Bipolar analog signal multiplexing for position-sensitive PET block detectors

Hyun Suk Yoon^{1,2} and Jae Sung Lee^{1,2,3}

¹ Department of Nuclear Medicine, Seoul National University College of Medicine, Korea

² Department of Biomedical Sciences, Seoul National University Graduate School, Korea

³ Institute of Radiation Medicine, Medical Research Center, Seoul National University College of Medicine, Korea

E-mail: jaes@snu.ac.kr

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Abstract

This paper describes a block detector multiplexing technique that simplifies the extension of axial length or ring radius without employing extra data acquisition channels. The proposed multiplexing circuit (bipolar multiplexing) multiplexes block detectors by encoding the position-related signal outputs with different combinations of polarity. Accordingly, it is possible to distinguish the detectors using a shared readout channel. This method was evaluated by assessing one to 16 block detectors using four data acquisition channels and one trigger input at different count rates. The experimental results showed that the multiplexing of block detectors did not significantly degrade timing, energy or spatial performance at low count rates, while reducing the required number of data acquisition channels and wire routing density. On the other hand, the degradation was seen as total count rates of all blocks increased.

Keywords: PET, multiplexing, scintillation detector

(Some figures may appear in colour only in the online journal)

1. Introduction

Positron emission tomography (PET) is the most advanced functional and molecular imaging device which is widely used for clinical and research purposes (Woo *et al* 2012, Im *et al* 2013, Jeong *et al* 2013). In PET, high scanner detection efficiency is required for assuring reliable image quality with a low radiation dose and a short scanning time. When the spatial resolution of a PET scanner is improved, the scanner's sensitivity also needs to be improved to maintain

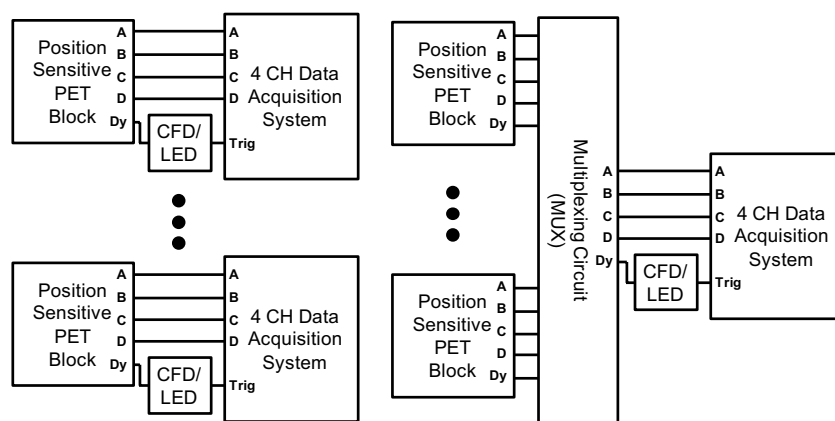


Figure 1. Block diagram of non-multiplexed (left) and multiplexed (right) detector configuration. A, B, C and D are position related signals obtained by applying Anger or charge division circuits and Dy is dynode/common signal from block detector.

the counting statistics and image quality (Green *et al* 2001, Pomper and Lee 2005). Temporal resolution of PET system, which is affected by the count rate related with the scanner's sensitivity, is important for measuring the dynamics of specific biological processes (Tai and Laforest 2005). In addition, better timing resolution of PET detectors assures the improvement of image quality by rejecting more random counts and incorporating time-of-flight information in PET reconstruction (Conti 2011, Lee and Kim 2014). Accordingly, there have been continuing efforts to develop better PET detectors with higher spatial resolution, timing resolution and detection efficiency (Lewellen 2008, Pichler *et al* 2008, Ito *et al* 2011). In many recent studies exploring the improvement of PET performance, high-density photo-sensors, such as the multi-anode photomultiplier tube (MA-PMT) and the array-type silicon photomultiplier (SiPM), are used to produce high spatial resolution and fast timing performance (Lewellen 2008). However, the use of such high-density photo-sensors leads to an increase in the number of output signal channels compared with conventional PET scanners that use head-on type single-channel PMTs.

Moreover, increasing the axial field-of-view (FOV) of the PET scanner by incorporating additional detector rings produces improvements in solid angle coverage and hence in overall sensitivity (Badawi *et al* 2000, Eriksson *et al* 2007). A potential way to approach the limit of PET sensitivity is to use a total body scanner with tunnel-like scanner geometry (Price *et al* 2014). However, the extension of axial PET FOV by adding more detector rings requires additional power, cost and space-consuming readout systems. One of the efficient ways to overcome this problem is to multiplex neighboring block detectors, which are not in coincidence, into several blocks before digitizing the output signals (figure 1).

Currently, the most used multiplexing methods can be categorized in two ways. Anger-like logic and resistive or capacitive charge division-based multiplexing methods reduce the multiple outputs of photo-sensors into four position-sensitive signals (Siegel *et al* 1996, Popov *et al* 2001, Olcott *et al* 2005, Popov *et al* 2006). Gain non-uniformity correction methods can be easily incorporated in these approaches (Popov *et al* 2006, Lee *et al* 2012). The other method is to allow the output signals from multiple detectors to share a readout channel and to distinguish between detectors using un-multiplexed trigger signals from the detectors (Lau *et al* 2010). However, the large-scale extension of the former type of multiplexing method has limitations: the increased number of input channels to the multiplexer leads to output pulse

dispersion based on an increased RC time constant, as well as the reduction of spatial dynamic range in the flood histogram map. The latter type of multiplexing method requires additional un-multiplexed trigger signals that need more input channels in subsequent data acquisition (DAQ) systems.

Therefore, in this study, we propose an alternative analog signal multiplexing method for position-sensitive PET block detectors that does not require additional input trigger channels to a DAQ system. The cost of multiplexing analog signal is the information loss and distortion and subsequent degradation of count rate performance mainly due to the higher pulse pile-up. Thus we evaluated the potential degradation of the block detector performance, such as crystal separation, energy resolution and timing resolution, at various multiplexing ratios and count rate conditions. Although this paper is focused on PET applications, the method, which uses a position-sensitive detector that gives out single-polarity pulses, is widely applicable elsewhere.

After our multiplexing method was developed, detailed investigation on the relationship between multiplexing ratio and detector performance was carried out, and initial manuscript was submitted, it was determined that a patent (Zhang *et al* 2009) exists that proposes similar idea of using different signal polarity of pulses. It seems that the patent is targeted to conventional PET block which is composed of four photo-sensors and their main goal is to build a large area block detector. On the other hand, we intended to utilize the polarity of output signals from the position-sensitive detector modules where the number of output signals was reduced by applying Anger or charge division circuits.

2. Materials and methods

2.1. Block detector and reference detector configuration

The block detectors used in this study consisted of a crystal array, a MA-PMT and readout electronics. The crystal array consisted of a 26×26 polished lutetium gadolinium oxyorthosilicate ($\text{Lu}_{1.9}\text{Gd}_{0.1}\text{SiO}_4\text{:Ce}$, LGSO; Hitachi Chemical, Japan) scintillation crystal with dimensions and pitch of $1.5 \times 1.5 \times 7 \text{ mm}^3$ and 1.65 mm, respectively. The crystal arrays were assembled using a reflector grid (Enhanced spectral reflector polymer, thickness 0.065 mm; 3M, USA) and optically coupled to a 64-channel MA-PMT (H8500; Hamamatsu Photonics, Japan) using optical grease (BC-630, index of refraction: 1.465; Saint-Gobain, France).

The readout electronics consisted of anode gain compensation circuits to compensate non-uniform anode gains from the MA-PMT (Lee *et al* 2012), a resistive charge division network (RCN) circuit to encode 64 signals into four position-related signals (A, B, C and D), (Kwon *et al* 2008) and an amplifier circuit to amplify four position-related signals and one dynode signal. A total of 16 block detectors were used in this study, and high voltage ranging from 980 to 1060 V was applied to the H8500 MA-PMTs to match the 511 keV peak position in the energy spectra.

The reference detector consisted of a $4 \times 4 \times 10 \text{ mm}^3$ LYSO scintillation crystal and a Hamamatsu R9800 PMT with single timing resolution of 199.9 ps (Ito *et al* 2013), which was also used for coincidence triggering and to resolve coincidence timing resolution with multiplexed block detectors.

2.2. Bipolar multiplexing circuit

Modern DAQ systems use analog–digital convertors (ADCs), which are capable of determining the polarity of pulse signals. The proposed multiplexing circuit (bipolar multiplexing) multiplexes block detectors by encoding the position-related signal outputs with different

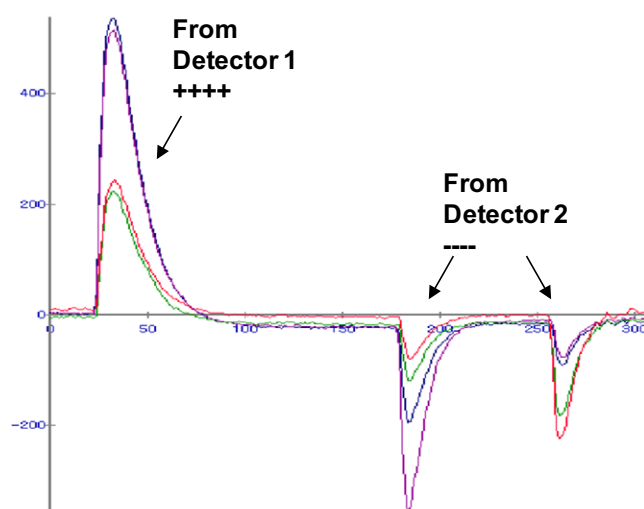


Figure 2. Sampled pulses of multiplexed position-related signals (A, B, C and D). Based on the polarity of pulses, it is possible to distinguish block detectors.

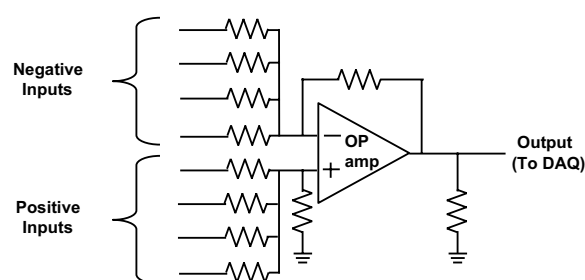


Figure 3. Circuit configuration for difference amplifier used in multiplexing. Position-related signals that need to be inverted are connected to the negative input, and the others are connected to the positive input.

combinations of polarity. Thus, it is possible to distinguish the detectors with a shared readout channel (figure 2).

The bipolar multiplexing circuit consists of four difference amplifiers and one summing amplifier. Four position-related signals (A, B, C and D) from the block detector are connected to the difference amplifiers with different combinations of positive or negative signal inputs. Dynode signals are connected to the summing amplifier (figures 3 and 4). Various multiplexing ratios of 1:1, 2:1, 4:1, 8:1 and 16:1 are supported with the proposed multiplexing circuit without additional components.

2.3. DAQ setup

Data were acquired using coincidence triggers from the multiplexed block detectors and the reference detector. Constant-fraction discriminators (CFDs, output width of 20 ns, threshold

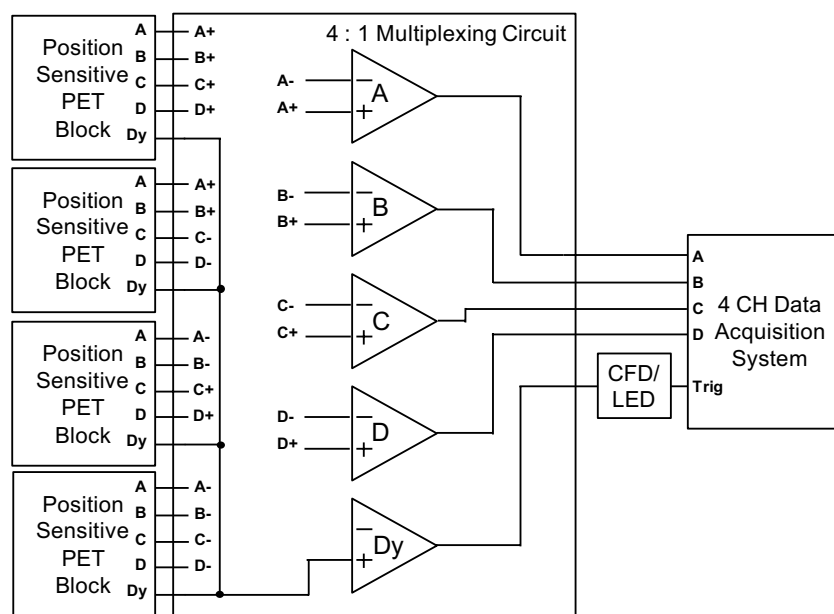


Figure 4. 4:1 multiplexing circuit consists of four difference amplifiers and a summing circuit. Various multiplexing ratios (1 to 16) are supported by adding a connection with a polarity combination.

of 10 mV; CAEN N842, Italy) were used to generate trigger signals from the dynode signals, and a coincidence trigger signal was generated using a logical AND unit (CAEN N455, Italy). Analog signals from the multiplexing circuit, four position-related signals and a dynode signal, and a dynode signal from the reference detector were sampled using a domino ring sampling 5GS/s digitizer (DT5742; CAEN S.p.A., Italy) (figure 5). The signals were acquired by the coincidence trigger, which was connected to the fast trigger port of the digitizer. For every coincidence trigger input, 1024 samples (total duration: 204.8 ns) of all signals were acquired and transferred to computer via USB. Count rates of multiplexed block detectors were measured with a NIM counter (CAEN N1145, Italy).

2.4. Generation of flood histogram

Five hundred out of 1024 samples (100 ns integration) of each position-related signal were integrated to obtain the energy, position and polarity information of the signals. The baseline was corrected by averaging 100 samples (20 ns) prior to the pulse. The block detectors were identified by the polarity of the position-related signal. The position (X , Y) and the energy (E) of each event was calculated with the following formulas.

$$\begin{aligned}
 X &= \frac{(|A| - |D|) + (|B| - |C|)}{|A| + |B| + |C| + |D|} \\
 Y &= \frac{(|A| - |B|) + (|D| - |C|)}{|A| + |B| + |C| + |D|} \\
 E &= |A| + |B| + |C| + |D|
 \end{aligned} \tag{1}$$

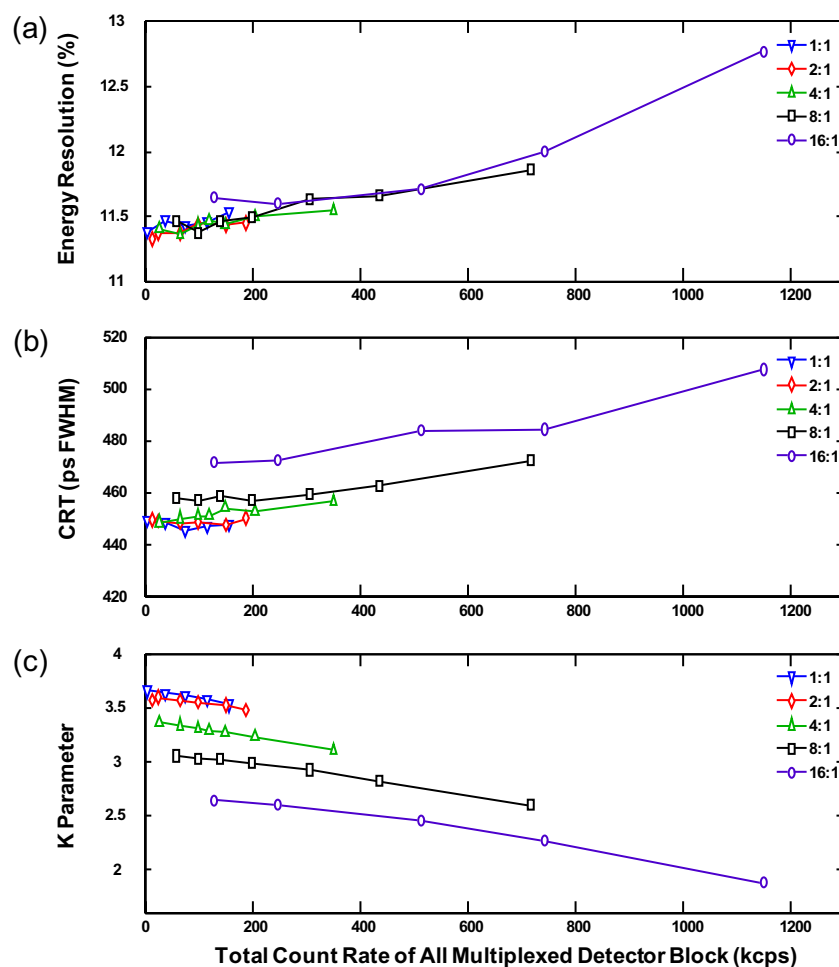


Figure 6. Changes in global average energy resolution (a), global average CRT (b) and flood histogram quality parameter k (c) in various multiplexing ratios and count rates of all multiplexed block detectors.

centroids of the flood histogram of the crystal at the (i, j) position. The parameter k corresponds to the average ratio of the width of the crystal measured in the flood histogram and the separation distance between neighboring crystal peaks in the x and y directions. Larger values of k correspond to a better-quality flood histogram, since the crystals are separated farther. The parameter k , higher than 1.00 and 2.00, corresponds to the separation of individual crystals with an error of 12% and 0.93%, respectively.

The energy resolution was calculated for all crystal positions, and the CRT was calculated using the time difference distribution between timestamps for coincidence events of 410–610 keV in the energy distribution. The average energy and CRT of all crystals were used for evaluations.

2.7. Experiments

Coincidence data were acquired using the coincidence of a multiplexed detector and a reference detector with a distance of 20 cm. A ^{22}Na point source with a nominal diameter of

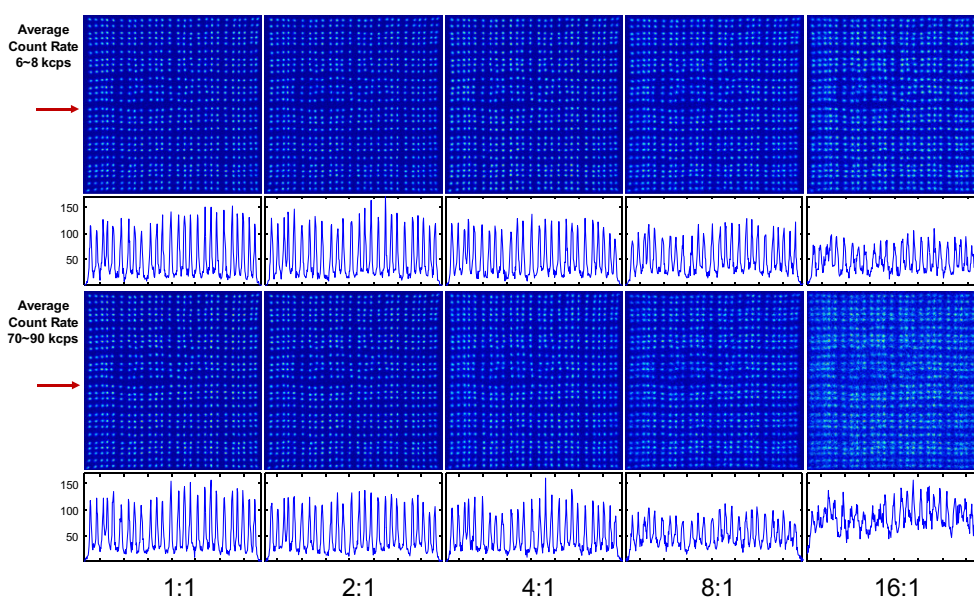


Figure 7. Flood histograms and line profile of a block detector for various multiplexing ratio at two different average count rates.

0.25 mm was placed on the center of the front surface of the reference detector (figure 5). We acquired 1.1 M valid events to explore the performance for all multiplexing ratios (1:1, 2:1, 4:1, 8:1 and 16:1) at different count rates and evaluated one of typical detectors. For the verification of peak separation on flood histograms in the 16:1 multiplexing condition, 16 block detectors were arranged in a circle and two ^{22}Na point sources were placed around the center of circle to evenly irradiate the block detectors. For every block detectors, 0.5 M events were acquired in single-acquisition mode at total count rate of 320 kcps from all block detectors.

3. Results

Figure 6 shows the experimental results obtained using the proposed multiplexing method with all multiplexing ratios (1:1, 2:1, 4:1, 8:1 and 16:1) at different count rates. Figure 6(a) shows the changes in energy resolution at different multiplexing ratios and count rates. There is no significant degradation in energy resolution due to multiplexing at low count rates, but the degradation is seen as total count rate of all blocks increases. This result demonstrates that signal multiplexing is not a main factor of energy resolution degradation.

The CRT (figure 6(b)) shows that degradation increases as the count rate of multiplexed block detector increased. This means that the CRT performance is determined by multiplexing ratio as well as by the count rate. Front-end circuit and photo-sensor noise are accumulated by multiplexing block detectors, causing the degradation in timing performance. The flood histogram parameter k (figure 6(c)) shows that degradation increases as the ratio of multiplexing and count rate increased.

Figure 7 shows the flood histograms of a block detector and the line profile of the 14th row at two average count rate ranges (6–8 and 70–90 kcps per block detector). As the multiplexing ratio is increased, the quality of the flood histogram and the line profile is degraded and the

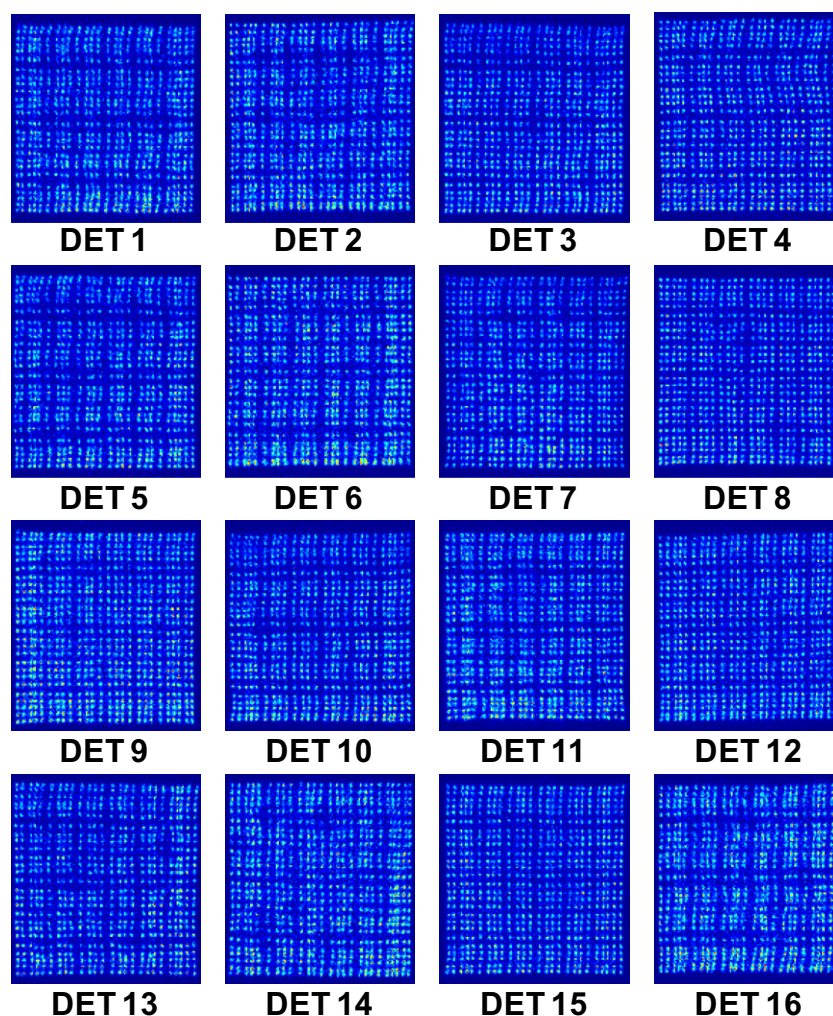


Figure 8. Flood histograms of 16 block detectors multiplexed with a 16:1 bipolar multiplexing circuit (500 000 single events per detector at 320 kcps count rate).

degradation is greater at higher count rate. All the flood histograms in the 16:1 multiplexing conditions were well de-multiplexed as shown in figure 8.

4. Discussion

4.1. Advantages of bipolar multiplexing

Multiplexing block detectors before digitization reduces the required number of readout channels by multiplexing ratio, decreasing system cost and power. Multiplexing techniques also reduce the number of signal transmission lines. Without multiplexing, each block detector requires five signal lines (four position sensitive + one common). This method produces an almost equivalent flood histogram to that produced by a non-multiplexed block detector. The

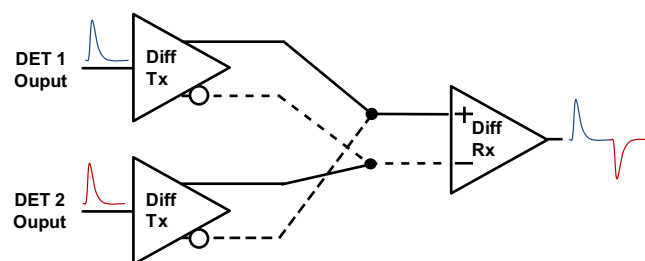


Figure 9. Multiplexing method with differential signaling. The polarity of the DET 2 output is inverted by reversing the polarity of transmitter output against receiver input.

flood histograms acquired by the multiplexing method did not require any changes in subsequent processing for crystal identification compared with the non-multiplexed ones.

When this multiplexing method is applied to systems using differential signal transmission for analog signal readout, the polarity of the signals can be inverted simply by reversing the polarity of transmitter output against receiver input (figure 9).

The proposed bipolar multiplexing method in this work has been applied to prototype MA-PMT based PET scanners under development in our group with different multiplexing ratios (2:1 and 4:1). With this multiplexing method, a 50–75% reduction in wire routing and readout channels was possible depending on multiplexing ratio. The bipolar multiplexing is not only useful for MA-PMT-based position-sensitive block detectors, but can also be used for all position-sensitive detectors that give out a single-polarity pulse. The bipolar multiplexing method has also been successfully applied to SiPM-based PET inserts for simultaneous PET/MR imaging with multiplexing ratios of 2:1 and 8:1 (Yoon *et al* 2012, Ko *et al* 2013).

4.2. Limitation of bipolar multiplexing

The number of block detectors that can be multiplexed (the ratio of multiplexing) is limited by the gain and noise of the system. The noise of the system increases as the number of multiplexed detectors increases, resulting in degradations of system performance such as flood histogram quality and timing resolution (figures 6(b) and (c)). The sources of noise are the intrinsic activity and after-pulse of the scintillation crystal, thermally induced noise from the photo-sensors (dark current for PMTs or dark count for SiPM), and electrical noise caused by front electronics such as preamplifiers. As the aforementioned noise sources are proportional to the area of the detector face, the maximum number of block detectors that can be multiplexed is mainly determined by the total area of multiplexed detectors. Additionally, with a photo-sensor that produces pulse-like noise such as SiPM (which produces dark counts), the signal-to-noise ratio (SNR) of flood images decreases as the area of photo-sensors increases. The multiplexing of block detectors that use such photo-sensors will decrease the SNR of flood images even more compared with the ones with less noisy photo-sensors such as PMT.

Another factor that limits the number of detectors that can be multiplexed is the required count rate performance for each block detector. As the multiplexed block detectors share readout channels, the required count rate performance for each channel is the sum of count rates for each block detector. Probability of pulse pile-up increases as multiplexing ratio increases at same count rate per block detector, causing performance degradation in energy resolution, CRT and flood histogram quality as shown in figure 6. Therefore, the ratio of multiplexing must be determined by the required count rate per block detector and the maximum count rate performance of the readout channel.

However, there are several methods to improve the count rate performance of the readout channel. One of them is to implement pulse pileup correction (Haselman *et al* 2012) in the DAQ system, which would recover overlapped pulses and increase count rate limits per channel. Another possible approach to improve the count rate performance of the multiplexed system would be to implement an analog filtering circuit to reduce the width of pulse (Gola *et al* 2013). As the probability of pulse pileup overlap is proportional to the count rate and pulse width, the reduction of pulse width will lead to a lower probability of pulse pileup, and therefore a higher count rate can be achieved.

5. Conclusions

A bipolar analog multiplexing method was developed for a position-sensitive block detector-based PET system that requires high sensitivity. It was verified through an experiment that the multiplexing of block detectors did not significantly degrade timing, energy or spatial performance at low count rates, while reducing the required number of data acquisition channels and wire routing density. On the other hand, the degradation was seen as total count rates of all blocks increased. The method described and tested in this study will be useful not only for PET systems, but also for other NM imaging systems (gamma cameras, SPECT) that use position-sensitive block detectors.

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