THE GE DIGITAL CSE™ DETECTOR

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GE Medical Systems

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INTRODUCTION

With the introduction of the Millennium Digital CSE detector, GE is bringing to market the fruit of several years of research. Our team was instructed to re-think every aspect of the detector design, taking nothing for granted from the outset.

The design objectives were:

1. Reliability
2. Uniformity
3. Stability
4. Resolution
5. Count rate

The reason for this order of priorities is simple:

1. Camera reliability is key for the smooth operation of a busy Nuclear Medicine Department.
2. Uniformity is essential for SPECT, and of crucial importance for optimal diagnostic value of the images.
3. Detector stability ensures low frequency of calibration, and little possibility of unscheduled downtime.
4. Energy and spatial resolution contribute significantly to clinical image quality.
5. Good quantitative accuracy at high count rates is vital for first pass studies and future high energy studies.

SQUARE PHOTOMULTIPLIERS

The first key difference with traditional gamma camera designs is the use of large square photomultipliers. The choice for this geometry was based on the realization that the majority of clinical customers now choose cameras with a rectangular field of view (FOV); the diagrams in fig. 1 make clear that square PMTs are better suited to this geometry, giving a truly rectangular FOV of 520 by 370 mm (20.5 x 14.5 in) with 48 PMTs.

There is a further complication of dead space around the edge of the detector which may be circumvented by the use of “half-hexagonal” PMTs - this does not, however, reduce the PMT count and the use of different types of PMT in the same detector could lead to reliability problems.

The Problem With Square PMTs

Although the use of square PMTs has the advantages outlined above, this comes at a price: using conventional Anger electronics, it is almost impossible to get a uniform image with square PMTs, and conventional non-linear signal processing on a per-PMT basis does not allow reasonable quality of uncorrected images. The reason for this is that the distance from the center of one PMT to the center of neighboring PMTs is no longer approximately the same in all directions: the four PMTs touching the sides of the center PMT are significantly closer than the four touching the corners only.

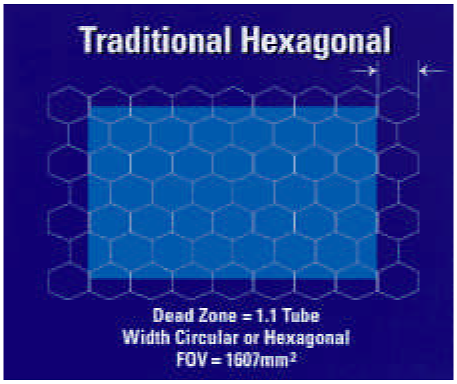


Figure 1a
Field of view with 60 hexagonal PMTs

As a consequence, if a point source is moved from one tube center to the next, the ratio of signal strengths from different PMTs changes by different amounts depending on whether the source is moving along the diagonal, or parallel to an edge of the PMT. These changing ratios in turn give rise to different distortions, which means that simple per-tube compensation cannot be used to obtain good uniformity.

Although modern correction techniques can be used to create a uniform image from even highly distorted images, the presence of rapidly changing distortions implies that even very small changes in PMT characteristics (such as gain) over time may result in corrections becoming invalid (see fig. 2), contravening our goal of uniformity and stability.

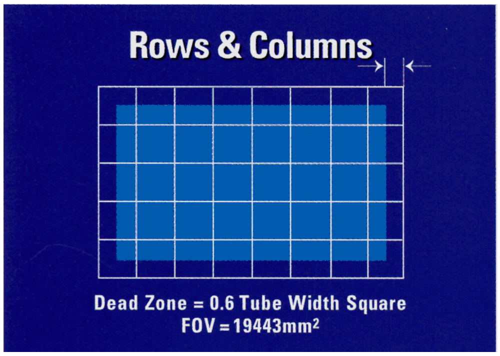


Figure 1b
Field of view with 48 square PMTs

CORRELATED SIGNAL ENHANCEMENT

Our design team realized early on that something had to be done to improve the situation outlined above, and came upon the idea of ***summing the rows and columns of PMT signals without prior signal processing.*** Consequently, the sums of every row and column could be treated as essentially one-dimensional, as the signal received on a column of PMTs would be largely independent of where the source was located along the length of the column (with some adjustment needed near the edge of the image).

This independence is only achieved with square PMTs: using hexagonal or round PMTs, the strength of signal along any row depends on the relationship of the source to the PMT centers (read: position along the row or column) and the method being described here does not apply.

In one dimension, the problem of achieving a uniform image through non-linear signal processing can be solved analytically. Indeed, it now became possible to derive the optimal processing required to achieve ***simultaneously good spatial resolution as well as uniform images***. From this analysis we arrived at the design of the processing electronics, and we were indeed soon able to obtain images with ***excellent linearity and uniformity, even without corrections applied***.

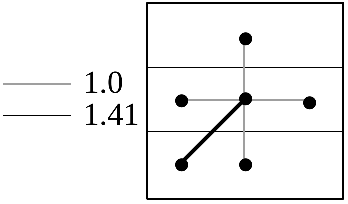


Figure 2:
Not all neighbors are the same distance away (relative distances shown)

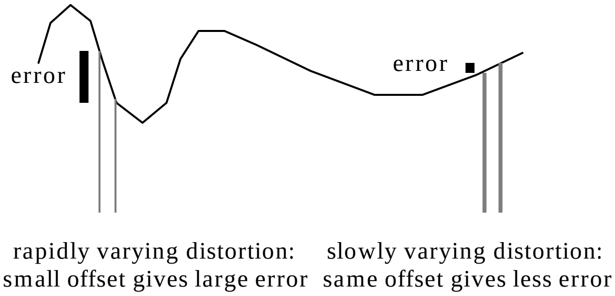


Figure 3
Plot of distortion (correction) against position, showing how a small offset on a rapidly changing correction causes a big error

As the problem was studied more closely, it was realized there was another, more fundamental, benefit to be gained from the summation of rows and columns of PMT signals, and this second benefit is what gave the method the name of Correlated Signal Enhancement.

Statistics and the need for photons

The number of secondary photons detected per event is small enough for the exact number to be influenced by statistics: if a process can produce on average N photons, the standard deviation of the distribution of photons will be $\sqrt{N}$. This means that the signal to noise ratio (SNR) will be $\frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}$ meaning that more photons (greater N) will give rise to better resolution. This is true both for spatial and energy resolution.

It is therefore important that in a gamma camera every effort is made to ensure that in determing position and energy of an event, ***all photons are used that contain useful information.*** In the next sections it will be explained how ***CSE technology excels in this respect***.

Thresholding and Anger electronics

When a scintillation occurs in a gamma camera, photons travel through the crystal to the PMTs. As the distance to the source increases, the number of photons detected by a PMT decreases. The curve that describes the number of photons detected by a PMT at a distance x from the event is typically called the fall-off curve, or FOC(x). Depending on the geometry of the PMT, there may also be an angular dependence, FOC(x,q). Because of multiple scatter in the crystal some photons will be detected far from the gamma interaction, giving rise to "tails" on the FOC.

Traditional Anger electronics uses the weighted mean of the signals from all PMTs for the position determination:

$$\hat{x} = \frac{S\ S_i x_i}{S\ S_i}$$

In this equation the Si are the signals from the ith PMT, with xi being the x position of that PMT. $\hat{x}$ is the estimated x position. The same expression can be used in the Y direction.

The problem with this approach lies in the tails of the FOC. Signals from PMTs far from the source - although small - will have a relatively large effect on the position determination because the signal size is multiplied by the distance; thus, a small signal at a large distance has the same effect as a large signal at a small distance. However, since the small signal has relatively poor signal to noise ratio (the number of photons N is small, so $\frac{1}{\sqrt{N}}$ is large), its contribution can degrade the position information and thus give rise to poor spatial resolution. It is therefore desirable to exclude those signals which have large position weight (far from the source location) and poor SNR.

In the case of Anger electronics, the only way to tell that a PMT is far from the source is to look at the magnitude of the signal; and by excluding all small signals, Anger electronics takes a first step towards improving the spatial resolution. This technique is called thresholding. Signals on each PMT are compared with a reference value (either fixed, or dependent on the energy of the event), and circuitry allows only those PMTs with signals exceeding the threshold to contribute to the position sum. No attempt is made to determine whether some small signals should be included while others should be excluded.

When square PMTs are used, this simple scheme of individual thresholding does not give optimal results, as there are many situations in which a large proportion of the useable photons are distributed among a number of PMTs each of which has a relatively small number of photons in it; and with individual thresholding, these signals and with individual thresholding, th would have would have been discarded.

A PRACTICAL EXAMPLE

The technique of Correlated Signal Enhancement is based on the realisation that not all small signals in a gamma camera are created equal.

Some small signals are a result of crystal phosphorescence, PMT dark current and “stray” photons, and thus contain no useful information regarding event location. Other signals - typically closer to the event location - do contain some information, and to ignore them would be to throw away information. The challenge is to distinguish between the two types with the simplest possible circuit.

Looking at the example (fig. 3), we show there the approximate average number of photons impacting each PMT in a 6 by 8 array of square PMTs when an event occurs over the center of a tube near the middle of the array. Apart from the four PMTs that touch the sides of the center tube, all PMTs contain “small signals” - that is, signals with magnitude approximately equal to the required threshold. In the case of an Anger camera, position determination would proceed as follows:

- Determine total signal sum
- Determine threshold (approx 2% of total)
- Subtract threshold from each signal
- Set any negative numbers to zero
- For each PMT, multiply the signal by the position
- Add the results, and divide by the sum of the signals to determine position.

Mathematically, the above can be expressed as:

$E = S\ S_i$ (the energy)

threshold = 0.02 * E

$T_i = (S_i - \text{threshold}) > 0$ (greater of the two)

$$\hat{x} = \frac{S\ T_i x_i}{S\ T_i}$$

It can be seen that the equation is the same as for the simple Anger matrix, except that the thresholded signal is used instead of the unmodified PMT output.

As the X position for each of the PMTs in a column is the same, it is mathematically equivalent to add the (thresholded) signals first along a column and then to perform the weighted mean. The line in the table marked “Threshold (100), then sum” exemplifies this: a threshold of 100 (approximately 2% of total) has been applied to individual PMT signals, after which they have been added together.

	1	2	5	8	5	2	1	1
	1	10	23	28	23	10	1	1
	2	23	120	450	120	23	2	1
	5	28	450	2500	450	28	5	1
	2	23	120	450	120	23	2	1
	1	10	23	28	23	10	1	1
sum	12	96	741	3464	741	96	12	6
Threshold (100), then sum	0	0	390	3100	390	0	0	0
sum, then threshold (200)	0	0	541	3264	541	0	0	0
% extra photons	0	0	28%	5%	28%	0	0	0

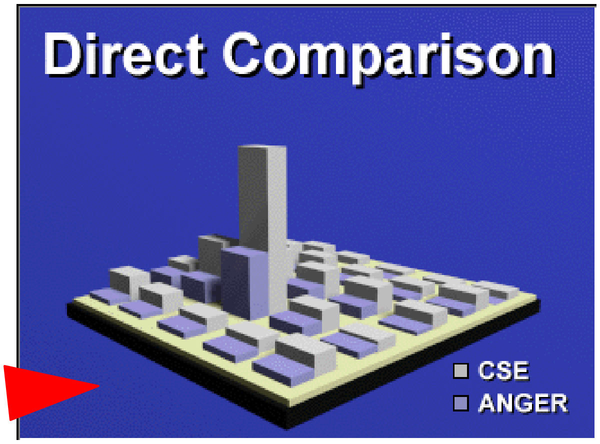
Figure 4:
Comparison of CSE and traditional tresholding

In the next line of the table the approach used in CSE is demonstrated: by first summing the signals along a column, and then applying a (greater) threshold, ***the total number of photons used to determine the position has increased significantly (increase of 28%, giving approximately 14% improvement in Signal to Noise Ratio)***. At a superficial level, this can be explained by saying that the CSE algorithm has allowed us to use a lower effective threshold.

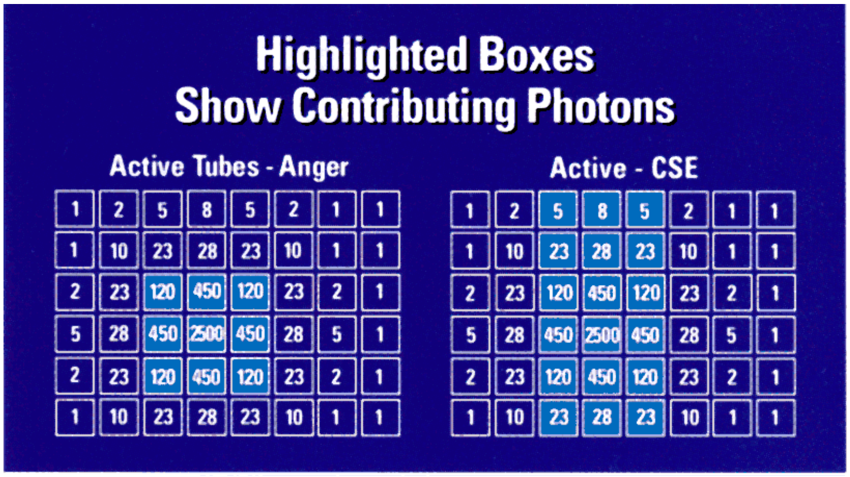
For simplicity, the table only illustrates the CSE method in one dimension ; in practice, a second set of identical circuitry processes signals in the other dimension to give the Y coordinate of the event.

Looking more closely at the numbers it can be seen that the algorithm essentially distinguished between small signals with relatively large position weight (far from the source in the X direction), and those that are closer; this comes about from the fact that along the rows adjacent to the center PMT there are some PMTs which will receive large signals; and these PMTs raise the signal level for that column above the threshold, so that all other PMTs in that row can contribute fully. Where no large signals are present in a column, the small signals do not amount to enough to raise the total signal size above the threshold, so all will be ignored.

Hence the name Correlated Signal Enhancement: small signals which are in the same column as (correlate with) larger signals are allowed to participate in the position determination (enhanced).



Direct Comparison



Highlighted Boxes
Show Contributing Photons

Active Tubes - Anger

1	2	5	8	5	2	1	1
1	10	23	28	23	10	1	1
2	23	120	450	120	23	2	1
5	28	450	2500	450	28	5	1
2	23	120	450	120	23	2	1
1	10	23	28	23	10	1	1

Active - CSE

1	2	5	8	5	2	1	1
1	10	23	28	23	10	1	1
2	23	120	450	120	23	2	1
5	28	450	2500	450	28	5	1
2	23	120	450	120	23	2	1
1	10	23	28	23	10	1	1

DIGITAL PROCESSING AND CONTROL

The Correlated Signal Enhancement, although an enabling technology which allowed the switch to larger square PMTs, is by no means the only important improvement in the new CSE detector - it just happens to be the one that lends its name to the detector. The previous generation of GE gamma cameras was built largely around digital technology, but ***with this new generation the use of digital technology has been driven right through to every aspect of the imaging chain.***

Event Detection

In order to perform well at high count rates, it is necessary to detect the start of each event accurately. This is especially important for pile-up separation: when two events occur within 1 ms of each other, the energy signal never returns to the baseline, and simple trigger schemes miss the start of the second event and thus cause mispositioning due to pileup. In the new CSE detector very high speed digitization of the energy signal is processed real-time to determine the exact timing of events, and this information is used to trigger event integration correctly at all countrates.

Event Integration

Accurate integration of events is performed with DSP technology: high speed (flash) digitisation of detector signals is followed by a digital integration stage. This gives full control over integration time, allowing shorter integration times at higher count rates to reduce dead time or increased integration time for better resolution at lower rates. As the integration time is changed dynamically, DSPs are used to correct for the apparent change in the integral, thus maintaining signal integrity.

Pileup Separation

When two events occur within a sufficiently short time interval, the apparent integral of the second signal will be increased as the signal rides on the tail of the previous signal. DSP technology is used to determine the error caused by this effect, and make adjustments. As with other aspects of the signal processing chain, the algorithm and lookup tables used are soft loaded, so that improvements in technology can be incorporated into existing detectors without costly hardware upgrades.

The great advantage of this technology is the fact that count rate performance of the detector is the same whether counts are evenly spread over the detector face (as is the case for the NEMA measurement), or whether they are concentrated in one area (as is the case in most clinically significant application of high count rates, e.g. first pass). ***Anyone considering count rate performance in the decision to purchase a new gamma camera should be aware of the method employed to achieve high countrate, and ensure that it is appropriate for their application.***

Signal Transfer Functions for every Row and Column

The explanation of Correlated Signal Enhancement given above was kept a little simplistic to aid understanding of the fundamental principle. In fact, processing at the row and column level involves more than just a threshold: a non-linear transfer function is needed which attenuates both very small and very large signals in order to optimize both resolution and uniformity. The signal transfer function has to be customized for every detector, in order to take into account small variations in crystal properties (light spread is a function of the grinding of the crystal surfaces, and consequently varies somewhat from one scintillator to the next). ***This process is done digitally, on the basis of measurements made on each detector as part of the manufacturing process.***

Normalization

The process that ensures good registration of images at different energy is called normalization. In the CSE detector this is a step which is performed by DSP, which ensures ***excellent multiple window spatial registration (MWSR)***

Offset adjustment

At every point in the circuit where analog to digital conversion takes place, circuitry is included which verifies continuously (up to 40 million times per second!) that zero volts input signal is correctly translated into a digital zero output - not one bit more, not one bit less. ***This ensures stability of the image geometry with time and environmental variations.***

PMT gain adjustment

Accurate adjustment of PMT gain is important for initial calibration of the detector, and also to be able to restore a camera to peak performance in the least possible time as part of preventative maintenance. ***12 bit DACs on each PMTs are used to set the gain with an accuracy better than 0.05% .***

PMT gain monitoring

The new Advanced AutoTune™ circuit stabilizes the PMTs in the presence of PMT aging, thermal fluctuations and magnetic fields. This circuit relies on a certain minimum gain in each PMT. Circuitry is included in the detector which allows the actual gain headroom of each PMT to be measured without disturbing normal operation of the camera. In this way it is possible for the detector to ***diagnose problems right at the PMT level*** long before they become an issue for the detector performance; and ***remote diagnostic monitoring*** permits access to PMT gain data to perform trend analysis and predict the need for preventative maintenance.

Data transmission from head to acquisition computer

All the digital processes described above take place within the enclosure of the imaging detector itself; the only signal link to leave the detector is a bidirectional high speed digital link, running at 100M baud. This provides for reliable data transfer to the acquisition computer, where dedicated hardware performs event correction and framing.

SELF-CALIBRATION CIRCUITRY

Advanced AutoTune™

As was mentioned in the introduction, stability of the detector was an important design consideration. The major contributor to instability (read: loss of uniformity) is the PMT, so the CSE design team decided to revisit the autotune circuit which has been employed successfully in GE cameras for approximately ten years, and make a good thing better.

The new circuit (Advanced AutoTune™) measures the gain of the PMT one hundred times per second, using a stabilised reference LED (one per PMT, built into the base for optimum alignment and geometry).

The true amplitude of the LED pulse is measured against the background, so that minimal peak shift is observed at higher count rates. Using switched pulse detection (lock-in amplifier technology) allows the use of lower frequency and lower intensity LED pulses than the original AutoTune circuit. This means that the LED generates less current through the PMT, which in turn contributes to better long term stability.

Special stabilisation of the dynode chain is also employed to ensure sudden changes in local count rate (as are experienced during first pass studies) do not affect PMT gain.

Offset adjustments

Every electronic circuit has some offset associated with it. These offsets, which may change with time and temperature, can cause degradation of detector performance: image shift, poor MWSR peak shift and image artifacts - to name but a few. At every point in the circuit where this could impact the performance of the detector, automatic offset sensing has been incorporated to minimize the over all detector drift.

Baseline Restoration

Most of the light output from Sodium Iodide scintillators is in the form of a brief pulse of secondary photons with a decay time of 230 ns. However, a fraction of the energy deposited in the crystal is trapped in states from which emission of photons takes place much more slowly, typically with a time constant of 0.15 s. At low count rates this is not noticeable, but as the countrate in the detector increases, the slow time constant gives rise to a shift in the energy baseline (extra photons are being emitted by the crystal all the time) and a a shift in the peak of the spectrum.

A circuit has been included in the CSE camera which detects the presence of this ‘slow phosphorescence’ component of the crystal output, and makes appropriate corrections for it. As a result, the peak remains accurate in all clinical imaging situations: for example, the peak of a Co-57 spectrum (normally at 122 keV) was measured at an incident count rate of 720 kc/s and found to be at 121.8 keV. In first pass acquisitions, this means that good quantitative accuracy will be maintained as the activity enters the field of view and is distributed.

SUMMARY

Every aspect of the new Digital CSE detector has been examined with clinically significant image quality in mind. The result is a detector that will give excellent diagnostic imaging with great reliability for many years to come. An investment in this detector is an investment for the future.

- Square PMTs optimally fill the rectangular FOV
- Low PMT and parts count for excellent reliability
- Digital self-calibration of gains and offsets for optimal stability and image uniformity
- Digital Correlated Signal Enhancement™ technology for optimized resolution
- Consistent high count rate performance with localized and distributed sources
- Digital normalization for excellent MWSR
- Digital interface from imaging head minimizes EMC susceptibility
- Remote diagnostics at the PM Tube level
- CE marking (EMC requirement)
- Advanced AutoTune™ for PMT gain stability
- Part of the GE continuum of products...designed optimally for present and future nuclear imaging requirements