Count-Rate Dependent Sensitivity in Position-Sensitive Photomultiplier Tubes

RA Mintzer, JN Aarsvold, KL Matthews II, CE Ordonez,
NJ Yasillo, J Chen, C-T Chen, RN Beck

Franklin McLean Memorial Research Institute, The University of Chicago
5841 S. Maryland Ave., MC-1037, Chicago, IL 60637

Abstract

A significant count-rate dependence of mean scintillation-pulse amplitude has been observed in prototype small gamma cameras employing NaI(Tl) crystals coupled to Hamamatsu R2487 and R3941 position-sensitive photomultiplier tubes (PSPMTs). The magnitude of the effect is position dependent. Within each camera's 56mm x 56mm field-of-view, as the scintillation rate is increased from 500 to 10,000 counts per second, the response to 140 keV gamma emissions from a collimated source of Tc-99m increases by approximately 2-8% in the R2487 and 1-6% in the R3941. The count-rate dependent sensitivities of both tubes were investigated by varying the rate and position of LED pulses directed at the face of the tubes with a 1mm diameter optical fiber. Within the specified effective area of the R2487, the increase in response from a 500 Hz rate to a 100 kHz rate varied from 1.5% in the center to 20% at one edge; corresponding increases in the R3941 were only 1% and 8%. In both cases, most of the response increase occurred between 500 Hz and 10 kHz. Similar LED tests on conventional photomultiplier tubes resulted in no more than 2% increases.

I. INTRODUCTION

Several research groups are pursuing the development of imaging devices that use Hamamatsu R2487 and R3941 position-sensitive photomultiplier tubes (PSPMTs) for nuclear medicine applications [1-14]. During our development of a small PSPMT/NaI(Tl) gamma-ray imager at The University of Chicago, we observed, in some areas of the device's field-of-view, a significant shift in the mean scintillation energy with varying count rate, i.e., a position-dependent "count-rate effect" [15-16]. The count-rate stability of photomultiplier tubes (PMTs) is considered a critical parameter for their use in gamma cameras because such stability is necessary for consistent energy windowing.

Here we report the results of measurements to assess this count-rate effect in both PSPMT variants. PSPMT-based gamma-ray imagers with single 73 mm x 73 mm x 8 mm NaI(Tl) crystals were tested using a Tc-99m source. Both tube variants were also tested without crystals by pulsing LED emissions directly onto the entrance window via optical fiber. Our results suggest that to fully utilize the field-of-view of these devices it will be necessary to improve the PSPMT count-rate characteristics or correct for these effects in system design.

II. METHODS

Figure 1 shows the experimental setup for measuring position and count-rate dependent response of PSPMTs and PSPMT-based small gamma cameras. The analog signal processing electronics consists of standard NIM spectroscopy amplifiers and a constant-fraction discriminator for event triggering; a simple circuit of retriggerable one-shots is used to satisfy the data-acquisition card's specific trigger-input requirements. An Apple Macintosh Quadra 800 and National Instruments NB-A2000 data acquisition card are used to acquire the four PSPMT position signals. These signals are summed and histogrammed in software to create the total energy pulse-height spectrum. The mean response is the location of the peak as determined by computing the centroid of the histogrammed data.
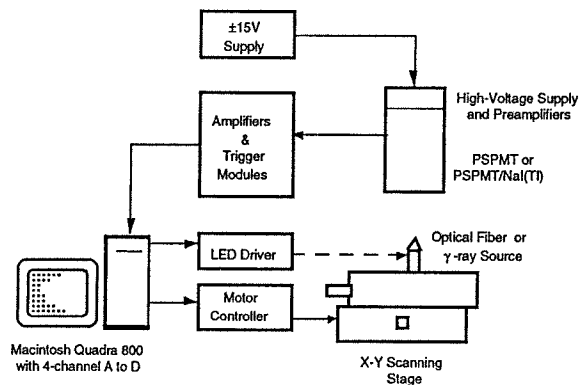

Figure 1. Diagram of experimental setup.

The PSPMT/NaI(Tl) gamma-ray imager is tested using a tungsten-shielded 1mm diameter collimated Tc-99m source (140 keV, 6.02 hr halflife). Data for various count rates are obtained by collecting periodically as the source decays. Testing of the PSPMT optical response is performed by directing pulses from a green LED (565 nm) at the face of the tube with a 1mm diameter plastic optical fiber. The frequency of these pulses is varied by triggering the LED driver with a programmable counter on the data-acquisition card. The photomultiplier and X-Y stage are placed in a light-tight enclosure for optical testing, and the LED driver is adjusted for pulses simulating the duration and intensity of NaI(Tl) scintillation pulses. A serial-port interfaced stepper-motor controller is used to position the optical fiber or gamma-ray source.

Both R2487- and R3941-based gamma-ray imagers were tested with the decaying Tc-99m source. Initial average count rate was approximately 11,000 cps. Twenty-eight hours

elapsed during scanning as the source decayed to less than 500 cps. Thirteen locations of a 5 x 5 array spanning an area 56 mm x 56 mm in size were scanned periodically (initially every five minutes; every ten minutes at the lowest count rates). The scintillation rate was computed from time data recorded with each scan-location acquisition sequence and the initial rate measured with a digital counter.

Both the R2487 and R3941 PSPMTs were tested optically as well. Frequencies from 500 Hz to 100 kHz were sequentially tested by completely scanning a 16 x 16 array of locations 56 mm x 56 mm in size.

In all PSPMT experiments, the tubes were operated at -1250 V and the total anode charge per pulse ranged from approximately 5 pC to 50 pC. Even at the highest average pulse rate employed (100 kHz), the average total anode current did not exceed 1% of the dynode voltage divider current.

Two conventional (not position sensitive) tubes were tested with the LED setup for comparison. A Hamamatsu R1635 (10mm diameter) operating at +1000 V and an RCA 4516 (0.75 in diameter) operating at +1400 V were tested with 5 kΩ load resistors. At these anode voltages, approximately 20 pC charge was output per LED pulse. Again, average anode current did not exceeded 1% of the dynode voltage divider current during the experiments.

III. RESULTS

Figures 2 and 3 show, respectively, a typical response of a PSPMT to LED pulses and a typical response of a PSPMT and scintillation crystal to Tc-99m gamma-ray scintillation pulses. We have found sensitivity variations as measured with an LED in two R2487 tubes and one R3941 ranging from 5:1 to 12:1 over a 56 mm x 56 mm area. We have found a 3:1 to 4:1 variation in response in these tubes over the same area for a gamma-ray imager.
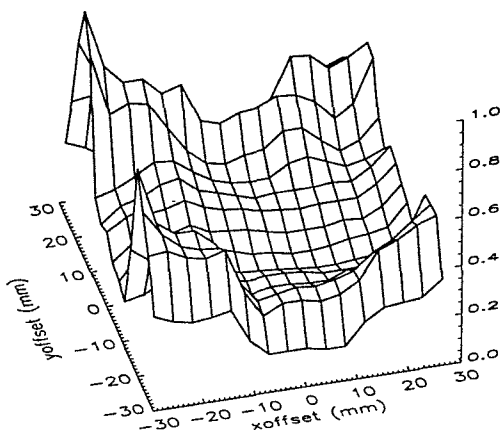

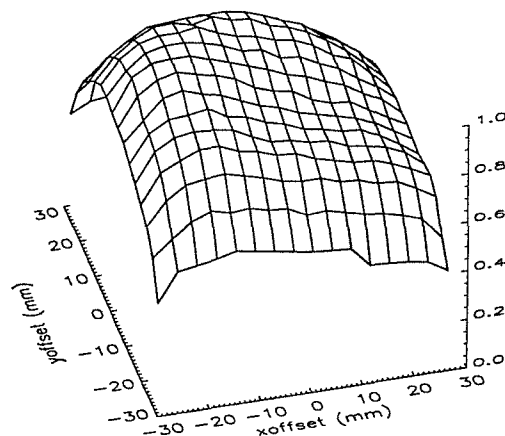Figure 2. Response of PSPMT to LED pulses.

Figure 3. Response of PSPMT/NaI(Tl) imager to Tc-99m gamma emissions.

Figures 4 and 5 show the results of Tc-99m decay experiments for the R2487 and the R3941, respectively. The fractional increase in response, at each location, relative to the response at that location when the rate had decayed to 500 cps, is plotted. For comparison with LED results the data are displayed as a function of computed count rate rather than decay time. In each, curves for three representative locations (from the center to one corner), out of the thirteen scanned, are shown. At 10 kHz, increases of approximately 2% in the center and 8% in one corner of the R2487 and 1% and 6%, respectively, in the R3941 are seen.

Figures 6 and 7 are plots showing, as a function of position, the fractional increase in total PSPMT response to LED pulses at the indicated pulse rates, for the R2487 and the R3941, respectively. The fractional increases are relative to the response at a 500 Hz pulse rate. The results for both tubes are plotted on the same scale for comparison. The position dependence is quite evident and is qualitatively similar for both. The edges with the greatest increases are those at the extremes of the "y-direction" as defined by the manufacturer, which is the smaller of the two dimensions of the specified effective area of the tubes.

Figures 8 and 9 are graphs of the maximum (■), average (◆), and minimum (▲) fractional increases in total PSPMT response to LED pulses derived from the complete sets of 16 x 16 scan data. The fractional increases are relative to the response at a 500 Hz pulse rate. The graph in Fig. 8 shows the R2487 results, while that in Fig. 9 shows the R3941 results; the data are plotted on the same scale for ease of comparison. For the R2487, the increase at 100 kHz varies from 1.5% in the center to 20% at one edge; corresponding increases for the R3941 were only 1% and 8%. Most of the response increase occurred before 10 kHz.

Increases in the conventional PMTs tested did not exceed 2% at rates up to 100 kHz; the data are not displayed.
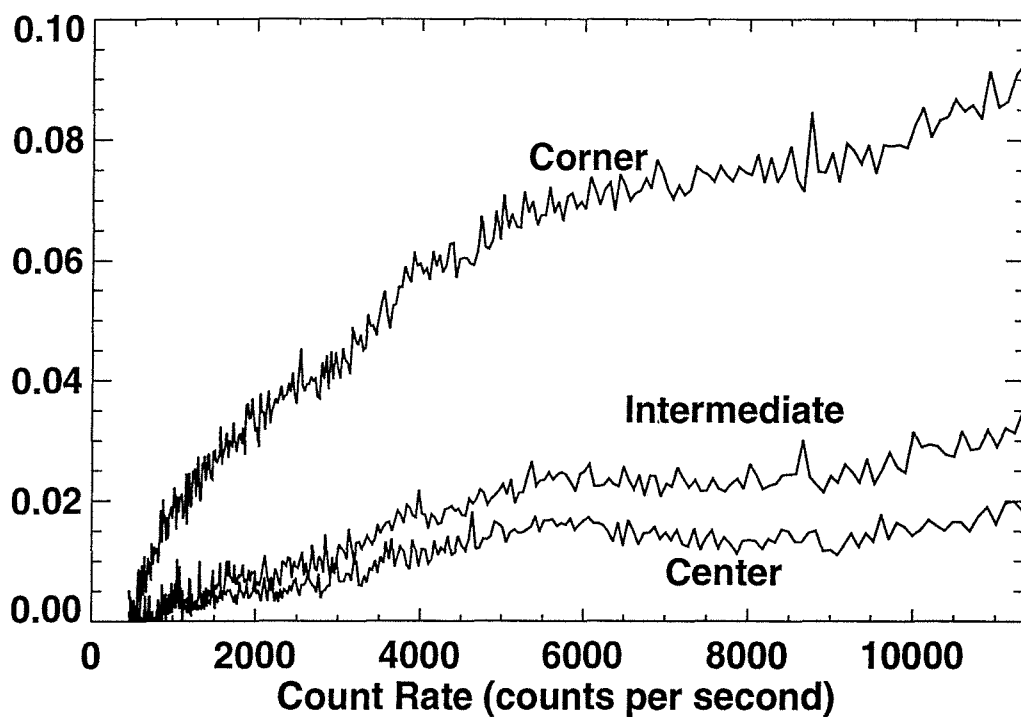
Figure 4. Tc-99m decay data for R2487. The fractional increase in response relative to the response at 500 cps is plotted as a function of average count rate for three representative locations.
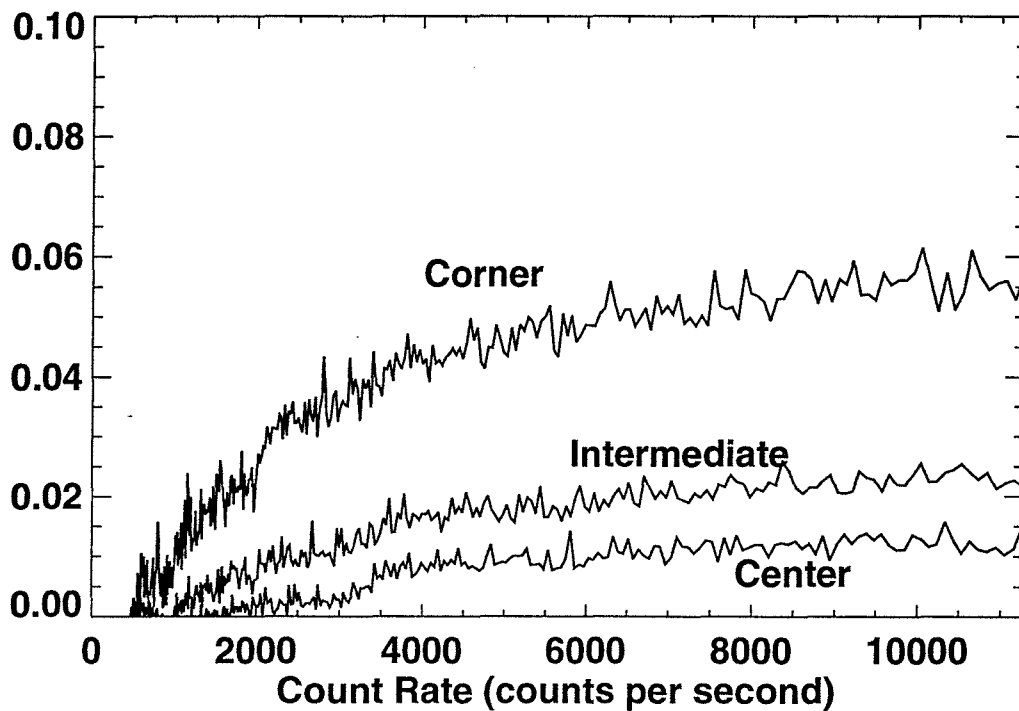

Figure 5. Tc-99m decay data for R3941. The fractional increase in response relative to the response at 500 cps is plotted as a function of average count rate for three representative locations.
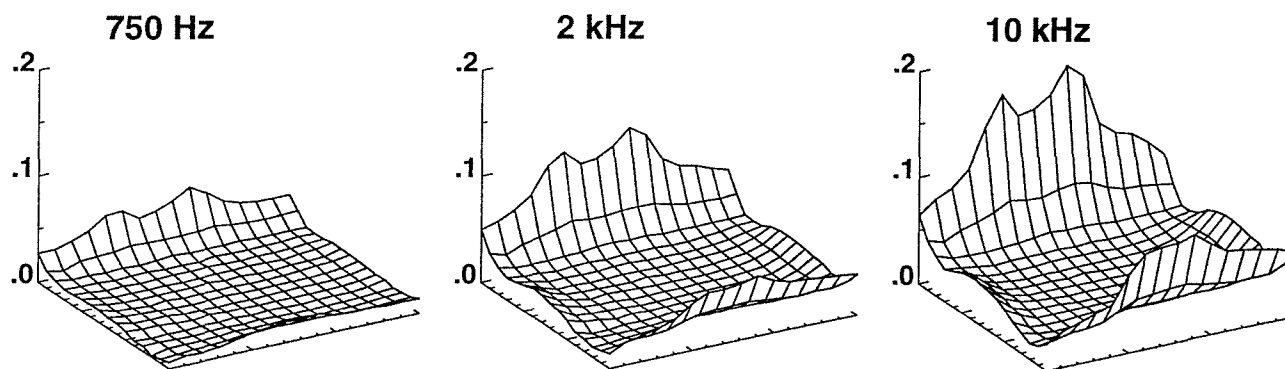
750 Hz   **2 kHz**   **10 kHz**

Figure 6. Partial LED test data for R2487. Surfaces show, as a function of position, fractional increases in response relative to the response at 500 Hz at indicated pulse rates.

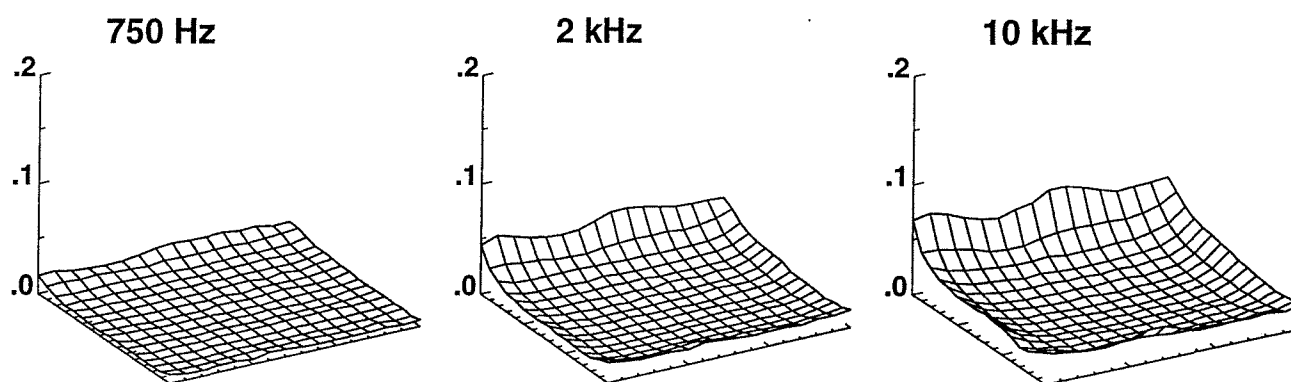**750 Hz**   **2 kHz**   **10 kHz**

Figure 7. Partial LED test data for R3941. Surfaces show, as a function of position, fractional increases in response relative to the response at 500 Hz at indicated pulse rates.
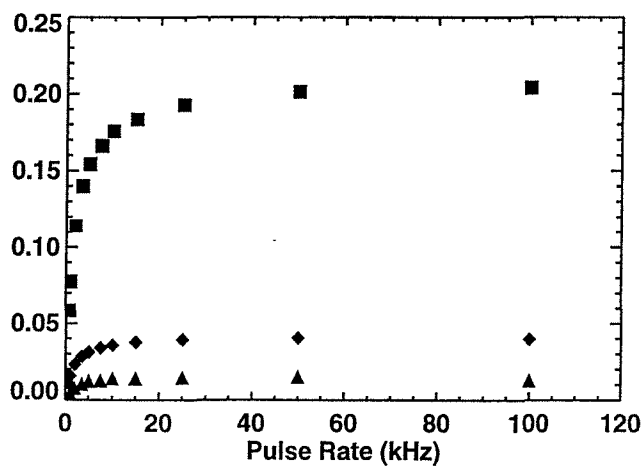
Figure 8. Graphs of the maximum (■), average (♦), and minimum (▲) fractional increases in total PSPMT response to LED pulses R2487.
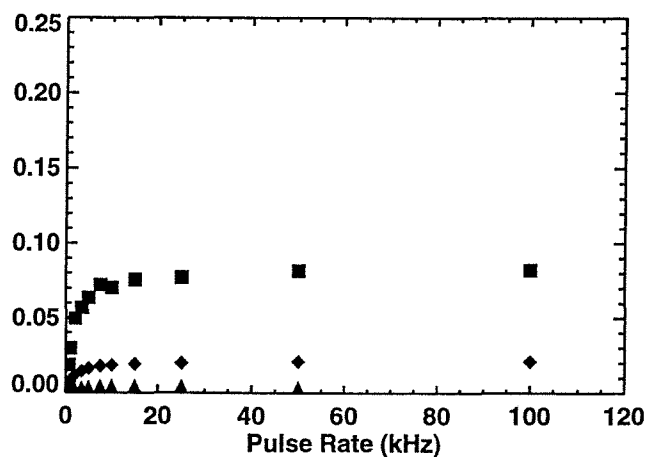
Figure 9. Graphs of the maximum (■), average (♦), and minimum (▲) fractional increases in total PSPMT response to LED pulses for the R3941.

IV. CONCLUSIONS

A significant count rate dependent sensitivity has been observed in Hamamatsu PSPMTs with both NaI(Tl) scintillations and with localized LED pulses. The effect is strongly position dependent. Whereas, in the center of the tube the count rate effect is of similar magnitude to that in conventional PMTs used for scintillation counting, within 10 mm of the edges of the specified effective area the effect is significantly greater. Although the effect is not as great in the R3941 as in the R2487, the effect is still of a magnitude as to have serious implications for the design of full field-of-view imaging devices for use in nuclear medicine--an application in which the range of count rates is typically large.

V. REFERENCES

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