THE INFLUENCE OF TRUE COUNTING RATE AND THE PHOTOPEAK FRACTION OF DETECTED EVENTS ON ANGER CAMERA DEADTIME

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As true counting rate (N) is increased, an increasing proportion of photopeak events go unrecorded by the Anger camera due to its pulse pair resolving time (T). With increasing radioactive source strength, the observed counting rate (R) is shown to reach a maximum (R_{max}) and then decrease. The resolving time (T) can be estimated by $T = (eR_{max})^{-1}$ and used in the equation $R = Ne^{-NT}$ to predict observed from true counting rate. T does not vary with counting rate until values of N well above those that would produce R_{max} are encountered. However, it is shown that variation in the window width setting or in the degree of scatter in and around the radioactive source will alter the value of T by altering the photopeak fraction (the fraction of detectable events which will fall within the window of the pulse-height analyzer.) Hence methods to correct quantitative data for loss of counts due to instrument deadtime should use correction factors appropriate for the photopeak fraction encountered during the study. Methods of achieving this are discussed.

Dynamic quantitative studies with radionuclides require the ability to record very high counting rates so that the counts recorded over short time periods in selected regions of interest will be statistically adequate. At these high counting rates, a large proportion of photopeak events in the crystal of the Anger camera go unrecorded because of its finite resolving time. The proportion of unrecorded events increases greatly as the true counting rate increases above 10,000 counts per sec (cps). Correction for this loss of counts should be made to any quantitative data and the correction factor will vary with the true counting rate and with the resolving time of the instrument.

Anger camera resolving time has also been reported to vary with the true counting rate (*1*). The present article presents data to show that the Anger camera behaves as a paralyzable instrument and that its resolving time does not vary with changes in counting rate up to and somewhat beyond the maximum observable counting rate if the known relation between true and observed counting rates for an ideal paralyzable instrument (*2*) is used. However, it is demonstrated that variation in either the spectrometer window width setting or in the degree of scatter in and around the radioactive source will change the deadtime of the Anger camera.

METHODS

Two Nuclear-Chicago cameras were studied at Michael Reese Hospital. One was 7 years old and had been upgraded from Pho/Gamma II to Pho/Gamma III 3 years ago; the second was an HP camera newly installed in October 1973. The high-sensitivity 15,000 parallel-hole collimator was used throughout.

The relationship between true and observed counting rate was determined as follows. A number of ^{99m}Tc sources each of 10-ml volume but of progressively greater activity were prepared and placed in separate but similar lead containers with removable lead tops. These were then placed about 4 ft below the face of the Anger camera. By uncovering various sources, either alone or in combination with others, the camera was exposed to varying activities of radioisotope while the counting geometry of each source remained constant throughout the study. By prior choice of graded source activities, the lower activity sources alone gave low counting rates insufficient to require deadtime correction. The observed counting rate with several low activity sources was then plotted against the true rate computed from the

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sum of the individual counting rates. From this plot the true counting rate of slightly higher activity single sources was determined and the process repeated until high counting rates were achieved.

The influence of the window setting and of the presence of scattering material on the maximum recordable counting rate was shown as follows. Progressively increased ^{99m}Tc activity was placed in front of the Anger camera with high-sensitivity collimator in place, and 10 sec counts recorded after each increase until the observed counting rate reached a maximum and began to decrease. This was done for different window settings at each level of activity and repeated for the three conditions of scatter described below and designated "slight", "mild", and "severe" scatter.

Initially the source was pertechnetate solution 1 cm deep in a 9.5 cm diam cylindrical plastic container, the base of which was separated from the collimator face by 1 in. of polystyrene foam (slight scatter). Beginning with only background activity, small volumes of pertechnetate (approximately 2.5 mCi/ml) were added until the maximum counting rate on each window setting had been exceeded. This was then repeated with 1-in. thickness of Lucite separating the source from the collimator (mild scatter). Finally, the procedure was repeated with 10 cm of water in the source container which remained sitting on the Lucite block but was surrounded by a water bath 10 cm deep as additional scattering material (severe scatter).

RESULTS AND DISCUSSION

The results of experiments to relate observed to true counting rates are shown in Table 1 and Fig. 1. These show that as true counting rate is increased the observed counting rate increases to a maximum at which point the true counting rate is almost three times as great; thereafter the observed counting rate falls with increasing source activity. For the Pho/Gamma HP, two spectrometer window widths have been shown, the commonly used 20% window symmetric about the photopeak and an asymmetric 30% window obtained by centering a 20% window in the photopeak and then expanding the window to 30% to include more of the upper portion of the photopeak to improve system sensitivity while still excluding the lower photopeak-scattered radiation. It can be seen that this increases the maximum counting rate obtainable.

The resolving time of counting instruments limits the observed counting rate at high true counting rates. Following one event no further events can be registered until a time equal to or greater than the pulse pair resolving time of the instrument has elapsed. At high counting rates successive events are more likely

TABLE 1. OBSERVED (R) AND TRUE (N) COUNTING RATES FOR INCREASING SOURCE RADIOACTIVITY

Pho/Gamma III			Pho/Gamma HP				
	20% window			20% window		30% asymm. window	
Source	R(cps)	N(cps)	Source	R(cps)	N(cps)	R(cps)	N(cps)
BKG	8	8	BKG	10	10	12	12
A	2,348	2,348	A	1,268	1,268	1,337	1,337
A¹	2,387	2,287	A¹	1,422	1,422	1,496	1,496
AA¹	4,550	4,627	AA¹	2,654	2,680	2,806	2,821
B	3,560	3,590	B	2,725	2,750	2,909	2,925
AA¹B	7,950	8,210	AA¹B	5,251	5,420	5,575	5,734
C	8,573	8,880	C	5,639	5,815	5,932	6,112
AA¹BC	16,032	17,082	AA¹BC	10,510	11,225	11,088	11,834
D	18,206	19,706	D	9,650	10,250	10,253	10,863
BCD	28,000	32,160	D¹	11,158	11,940	11,759	12,600
E	28,980	33,020	DD¹	19,446	22,180	20,494	23,450
E¹	25,380	28,430	E	18,848	21,360	19,850	22,650
EE¹	47,100	61,445	DD¹E	33,207	43,530	35,180	46,090
F	45,200	58,000	F	36,037	48,500	38,080	52,000
EE¹F	70,300	119,440	DD¹EF	53,184	92,000	56,300	98,080
G	71,560	123,700	G	51,262	86,000	54,440	93,000
FG	81,800	181,700	G¹	52,940	91,500	56,320	98,100
H	77,000	146,000	GG¹	64,880*	177,500	69,420*	191,100
GH	82,800	269,700	H	64,460	166,000	69,130	185,000
I	82,350	280,000	GG¹H	51,700	343,500	58,260	376,100
HI	73,540	426,000	FG	61,600	134,500	66,000	145,000
JKL	62,960	549,700	FGG¹	63,000	226,000	67,500	243,100
E¹FK	84,900*	232,400	GH	61,000	252,000	66,050	278,000

* Maximum observed counting rate (R_{max}).

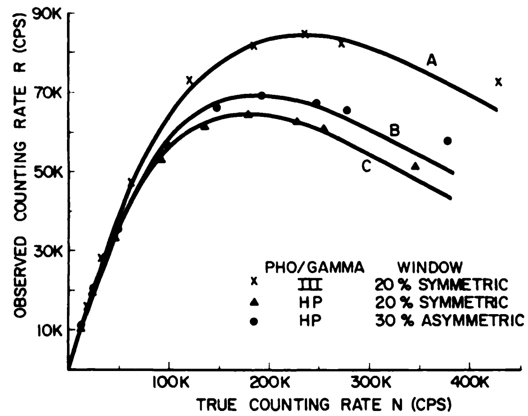

FIG. 1. True counting rate vs observed counting rate (from Table 1) and predicted observed counting rate from $R = Ne^{-NT}$ where $T = (e\,R_{max})^{-1}$. Curve A: $R_{max} = 84{,}900$ cps, $T = 4.333$ μsec. Curve B: $R_{max} = 69{,}420$ cps, $T = 5.3$ μsec. Curve C: $R_{max} = 64{,}880$ cps, $T = 5.67$ μsec.

to occur at intervals less than the resolving time so that the second event will not be recorded.

Two idealized counter types have been described (*2*). In Type I, the paralyzable model, a second event will not be recorded unless it is preceded by an event-free time interval at least equal to the resolving time (T) of the instrument. If during time T following an event a second event occurs, then the deadtime is further extended for an additional time T. For this type of instrument the observed counting rate (R) of a random process such as radionuclide decay is predicted from the Poisson distribution (*2*) by the equation

$$R = Ne^{-NT} \qquad (1)$$

where N is the average number of true events per unit time and T is the resolving time. By differentiation of this equation with respect to N, it can be shown that the observed counting rate passes through a maximum (R_{max}) when NT equals 1 and that

$$R_{max} = (eT)^{-1} \qquad (2)$$

Type II, the nonparalyzable model, is not influenced by events which occur during its recovery time (T) so that the apparatus is dead for a fixed time T after each recorded event. The fraction of the true number of events which are recorded (R/N) will equal 1 − RT so that

$$N = \frac{R}{1 - RT} \qquad (3)$$

The observed counting rate of this type of instrument will continue to increase with increases in the true counting rate, approaching asymptotically a maximum of value of R_{max} equal to 1/T when N is infinitely great (*2*).

The observed data for Nuclear-Chicago Pho/Gamma III and HP cameras as shown in Fig. 1 show a definite maximum in observed counting rate as the true counting rate increases. These cameras therefore resemble the paralyzable instrument model described before. To check if this model fits the data, the resolving time T of the cameras was calculated from the observed maximum counting rate using Eq. 2 and the predicted observed counting rate for various true counting rates was then calculated from Eq. 1. The predicted relationships have been graphed in Fig. 1. This shows a good fit to the actual observed relationship between R and N even for values of R slightly above the maximum. At very high true counting rates, too few observed counts are predicted but this is not important in practice as this portion of the curve would never be used.

These findings would suggest that the true counting rate could be predicted from the observed counting rate of an Anger camera by measuring the system resolving time by Eq. 2 from the maximum observable counting rate and then determining N from R using Eq. 1. If the paralyzable instrument model is used, the resolving time does not appear to vary with counting rate. If the resolving time is calculated assuming the camera is a nonparalyzable instrument by using Eq. 3, then the resolving time so obtained will vary with the counting rate (*1*). This method seems unnecessarily cumbersome and would also be prone to error if the calculated deadtime at low counting rates was used to correct the observed counting rate at high counting rates. Use of the paralyzable instrument model and Eqs. 1 and 2 obviates the dependence of Anger camera deadtime on counting rate.

The data in Table 2, however, show that even using the paralyzable model, the camera resolving time (as measured by maximum observable counting rate) varies with the spectrometer window chosen and also with the degree of scatter in and around the radionuclide source. Whereas the window setting can be fixed, we have no control over the degree of scatter which will vary with patient size and shape and with the type of study performed.

Changes in the spectrometer window setting or in the degree of scatter of the photons before they reach the detector will alter the fraction of total events occurring in the crystal which will fall within the window setting of the pulse-height analyzer, i.e., the photopeak fraction. The ideal paralyzable instrument model described previously did not take the photopeak fraction into account—all events occurring in the detector were recordable if they occurred after the immediately preceding event at a time interval equal to or greater than the resolving time. In the

TABLE 2. EFFECT OF WINDOW WIDTH SETTING AND SCATTERING MATERIAL ON SCINTILLATION CAMERA COUNTING RATE PARAMETERS

	Pho/Gamma III			Pho/Gamma HP		
Window setting	15%	20%	30% asymmetric	15%	20%	30% asymmetric
Slight scatter*						
R_{max} (cps)	73,350	86,900	103,000	48,000	59,500	64,800
$(e\,R_{max})^{-1}$ (μsec)	5.01	4.23	3.57	7.66	6.18	5.68
Mild scatter*	5.25	4.45	3.86			
R_{max} (cps)				39,550	50,450	55,300
$(e\,R_{max})^{-1}$ (μsec)	70,100	82,750	95,400	9.3	7.29	6.65
Severe scatter*						
R_{max} (cps)	57,800	69,500	82,700	29,400	38,300	44,550
$(e\,R_{max})^{-1}$ (μsec)	6.36	5.29	4.45	12.51	9.60	8.26

* Radioactive source: $^{99m}TcO_4$ solution in 9.5 cm diam cylinder.
Slight scatter: source 1 cm deep.
Mild scatter: source 1 cm deep; 2.5-cm Lucite between source and collimator face.
Severe scatter: source 10 cm deep; 2.5-cm Lucite as before; water 10 cm deep surrounding sides of source container.

Anger camera, a nonphotopeak event will be processed by the pulse-height analyzer before its rejection and during this time the instrument will be unresponsive to a second event. Instrument deadtime may be shorter following a nonphotopeak event than a photopeak event which after acceptance by the pulse-height analyzer must be processed for positional information. If D is the resolving time of a nonphotopeak event, P the resolving time of a photopeak event, and F the fraction of total events which are photopeak events, then the observed counting rate R of a paralyzable instrument could be predicted from the true counting rate N by the equation (see Appendix):

$$R = FNe^{-NP/F} + (1 - F)Ne^{-ND/F} \qquad (4)$$

If the resolving time of a nonphotopeak event is the same as that of a photopeak event and this resolving time is designated by K, then Eq. 4 simplifies to

$$R = Ne^{-NK/F} \qquad (5)$$

The term (K/F) in Eq. 5 is equivalent to T in Eq. 1 and this explains why T will vary with F. Measurements of the photopeak fraction F under several different conditions of scatter and window width setting have shown that Eq. 5, where photopeak and nonphotopeak resolving times are assumed equal, gives a reasonable prediction of the variation of observed from true counting rate with variation in the fraction of photopeak events.

In clinical practice, however, the photopeak fraction is not readily measured. To circumvent this problem, quantitative data collected at high counting rates should be corrected for instrument deadtime measured under identical scatter conditions. This is most readily performed by placing a small radioactive source shielded from the patient in the field of view of the detector but away from the area of patient interest. Then any fall in counting rate in the region of the small source can be determined throughout a dynamic radionuclide study and used to calculate the correction factor necessary to determine true from observed counting rate (*3*). This method has another advantage: it will give a true representation of deadtime counting losses even if the system does not approximate either a truly paralyzable or nonparalyzable instrument. For quantitative data analysis, analog-to-digital conversion and storage of data is necessary and methods of doing this may appreciably increase the system deadtime (*4*) and could change the system characteristics to more closely resemble a nonparalyzable system. Ideally, however, the time necessary to digitize and store the pulses should be less than the resolving time of the camera (*5*). The inclusion of derandomization buffers (*6*) in a data recording system to prevent loss of counts due to the longer deadtime introduced could also cause deviation in response from that of an ideal paralyzable detector. The method of monitoring a single source of radioactivity described above would remain a valid means of determining deadtime loss of counts.

Of the two Anger camera models studied, the Pho/Gamma III showed an appreciably shorter resolving time than the Pho/Gamma HP. This has been noted previously (*7*). Cameras of several other manufacturers also exhibit a maximum observable counting rate followed by a decline as true counting rate is increased (*8*) and hence it is likely they also behave as paralyzable instruments.

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APPENDIX

Derivation of formula to predict observed counting rate of a paralyzable detector:

- $G =$ total number of events in crystal per unit time.
- $N =$ number of photopeak events in crystal per unit time.
- $F =$ fraction of all events which are photopeak events.
- $R =$ recorded photopeak events per unit time.
- $D =$ resolving time following a nonphotopeak event.
- $P =$ resolving time following a photopeak event.

F and $(1 - F)$ represent the fraction of total events preceded by photopeak or nonphotopeak events respectively. Events in these fractions will be processed only if they occur at intervals greater than P or D respectively. From the Poisson distribution, the total number of random events which occur at intervals greater than P will be Ge^{-GP} and the number occurring at intervals greater than D will equal Ge^{-GD}.

Therefore, the total number of events processed by the system will be $FGe^{-GP} + (1 - F)\,Ge^{-GD}$ and of these, F will be the fraction that are photopeak events and so are recorded. Therefore,

$$R = F\,[FGe^{-GP} + (1 - F)\,Ge^{-GD}]$$

Since $N = FG$ the above equation can be rewritten

$$R = FNe^{-NP/F} + (1 - F)\,Ne^{-ND/F}$$