PHYSICAL SPECIFICATION OF A GAMMA CAMERA

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Since the gamma camera was first described by Anger (*1*), a number of papers describing both the physical characteristics of the instrument and its applications have been published (*2–12*). However, the performance of the gamma camera has usually been discussed in terms of the parameters fundamental to a conventional scanner, and insufficient emphasis has been placed on characteristics that are unique to the camera. It is, of course, necessary to compare the camera with the scanner to assess its value, and consequently there has been much investigation into the sensitivity and limits of resolution of the camera.

However, the uniformity of response over the crystal area is an equally limiting factor in the camera's ability to represent accurately the differences in distribution of an isotope within a volume. Furthermore, linearity, which is a measure of the image distortion of the spatial distribution of an isotope, is also a factor in camera performance. Except for line stagger or scalloping, linearity presents no problem in mechanically moving scanners.

In practice, resolution, uniformity, linearity and sensitivity are interdependent, and because optimum operating conditions for one may not be optimum for the other parameters, some compromise based on the relative importance of each parameter must be arrived at. It is also important to keep in mind the fact that these parameters will vary over the sensitive area of the crystal and that these variations should be included in the specification of camera performance. All of these factors have practical significance because it is important for the performance of such an instrument to be readily measurable and for optimum operating conditions to be checked with the minimum time spent in routine adjustments.

We will discuss the performance of a Nuclear-Chicago gamma camera using a 28-cm-diameter, 1.27-cm-thick sodium iodide crystal in terms of the basic parameters mentioned above. We hope that the definitions described below for these parameters will simplify the assessment of the performance of gamma cameras.

DEFINITIONS

Resolution. The resolution of a radioisotope imaging device is a measure of the accuracy with which it can delineate regions with different isotope concentrations. Brownell (*13*) has proposed a definition for resolution as the distance apart of two point sources which gives "touching image circles on the detecting crystal." However, this value is difficult to measure. A more practical definition put forward by Mallard and Myers (*8*) equates resolution with the distance apart of two point sources which gives touching image circles on the display. This approach includes any distortions introduced by the analog circuitry forming the display and relies on a subjective assessment.

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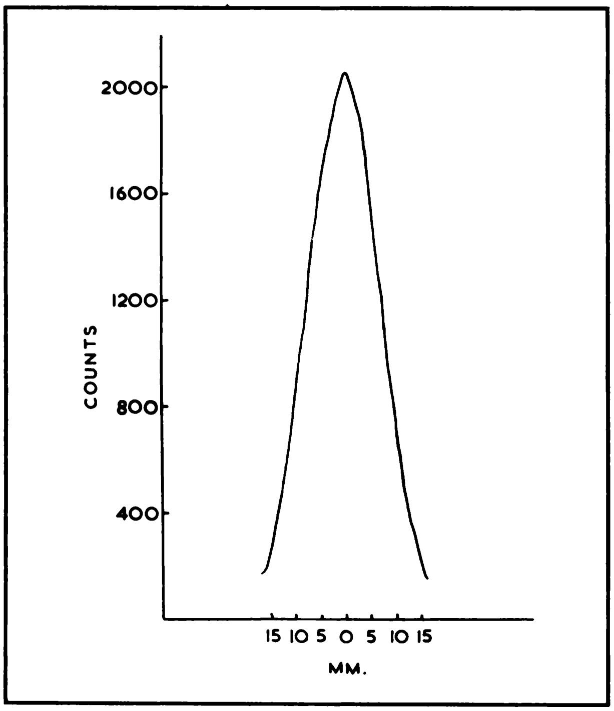

FIG. 1. Line-source distribution function for ^{203}Hg. Source was located 10 cm from 3-in. collimator during measurement.

Because the aim of this paper is to discuss the performance of the camera in terms of parameters that are measured easily, the following definition of resolution will be used. Resolution is the full width at half height (FWHH) of the camera response to full photopeak radiation from a line source placed with its longitudinal axis along a major axis of the crystal. This value is commonly used to describe scanning collimators, and although it is not the only parameter for describing resolution (see below), it is useful for showing variations in performance with varying gamma-ray energies, source-collimator distances and variation over the face of the crystal.

If the distribution of counting rate were truly Gaussian, the FWHH would represent the distance apart at which two point sources can just be resolved. If this is not the case, a full description can only be provided by the curve showing the point or line-source distribution function (Fig. 1). For convenience, however, we list in Table 1 the widths of the line-source distribution function at 50% and 75% of full height; we include the former figure for the reasons given above and the latter because it has been found in practice to give the distance at which two point sources can just be resolved.

TABLE 1. WIDTHS OF LINE-SOURCE DISTRIBUTION RESPONSE*

Isotope	FW50%H (mm)	FW75%H (mm)
^{18}F	30.8	16.9
^{131}I	19.3	12.0
^{203}Hg	18.4	10.3
^{197}Hg	23.0	15.1

* Values, given at 50% and 75% height, refer to full photopeak of isotope, 10 cm from 3-in. collimator.

The time required to obtain the counts in the channel corresponding to the maximum of the resolution curve puts a practical limitation on the number of counts that can be accepted. The usual procedure we use is to accept a total of 2,048 counts in the maximum channel, which results in a 5% maximum error in the estimate of the resolution width.

Uniformity. The uniformity of the gamma camera refers to its ability to produce a true representation of the radioactivity distribution within a region. This parameter is most easily assessed in cameras by uniformly irradiating the crystal with a point source at a distance. Variations in the output signals corresponding to different areas of the crystal then reflect the lack of uniformity of the camera system. Using the usual photographic output, it is difficult to assess this quantitatively, and therefore comparisons between different cameras or variations in uniformity of a single camera over a period of time are difficult to estimate.

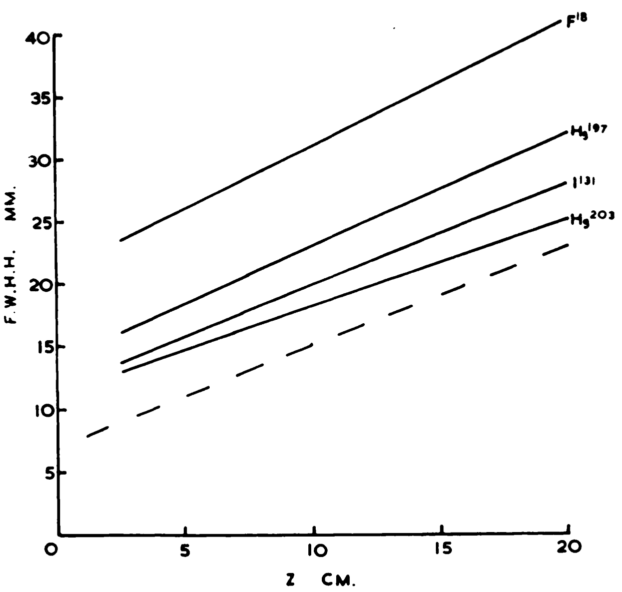

FIG. 2. Full width at half height (FWHH) of response to line sources of ^{197}Hg, ^{203}Hg, ^{131}I and ^{18}F in air plotted as a function of source-collimator distance (Z) for 3-in. deep collimator. Calculated resolution (7) is shown as interrupted line.

One definition of uniformity is the variation in the size of the summed voltage pulses, corresponding to the photoelectric peak, which appear at the output of the photomultiplier tubes as the point of interaction of the gamma ray in the crystal changes. This is a fundamental "detector-head" definition because it only involves the crystal, the light guide and the photomultiplier tubes.

Uniformity can also be defined as the variation in the number of position pulses that occur between any arbitrary pulse-height limits when the crystal is uniformly irradiated. This definition is in terms of the camera electrical output and consequently is not only more easily measured but is more objective than the final analog output. In practice, pulse-height limits can be selected that correspond to a crystal area of about 2 x 2 cm (see below), and we have arbitrarily selected this unit area. The selection of this area size was governed in our case by the measuring equipment available (a 16 x 32 measuring matrix). The 28-cm crystal face cannot easily be divided into units much smaller than 2 cm. The size of the area is also controlled by the need for obtaining a good statistical estimate of the number of counts in each area. In our case a total count of 10^6 counts resulted in a standard error of 2% in each area because the count in each area was about 2,500. This was considered a satisfactory degree of accuracy.

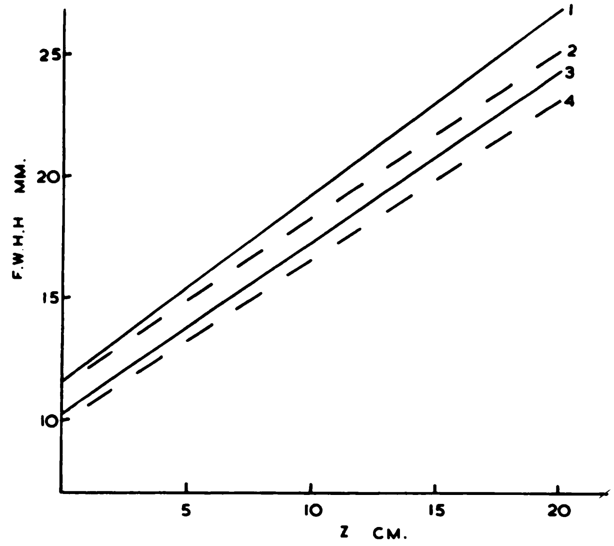

FIG. 3. Full width at half height (FWHH) of response to ^{203}Hg line source: (1) in water, full photopeak; (2) in water, 10% analyser window; (3) in air, full peak; and (4) in air, 10% analyser window plotted against source-collimator distance (Z).

Linearity. Linearity is the property of the gamma camera that determines its ability to reproduce the spatial distribution of an isotope. The property is most easily illustrated by Fig. 8 which is the image of a number of collimated point sources in a rectangular array. It can be seen that straight lines are distorted by the camera and that the degree of distortion varies over the crystal area. Pictures such as this are easy to produce and have been published (*5*), but objective comparisons of camera performance are difficult from such a test.

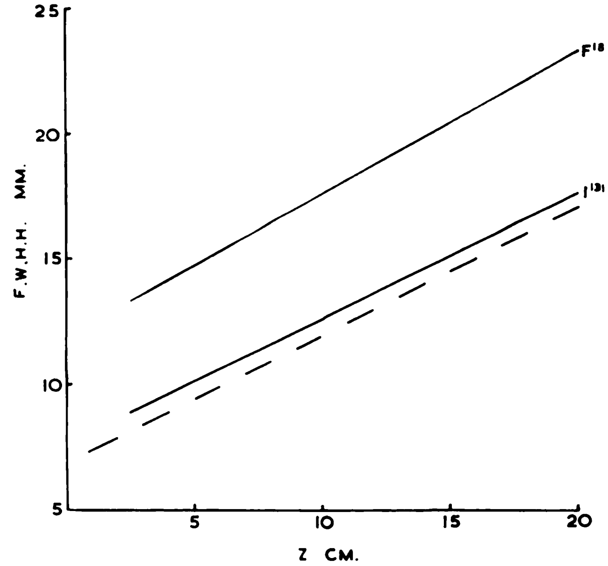

FIG. 4. Full width at half height (FWHH) of response to line sources of ^{131}I and ^{18}F in air plotted against source-collimator distance (Z) for a 4.5-in. collimator. Calculated resolution (7) is shown as interrupted line in figure.

We propose that the linearity of the camera be defined as the ratio of the distance between the center of the crystal and the point of interaction of the gamma ray to the amplitude of the resultant of the positioning pulses along each axis. The distance from the center of the crystal within which this ratio is being measured must be specified. In our case the linearity refers to the area within a circle 23 cm in diameter.

To obtain a meaningful estimate of the linearity, measurements must be made from an array of equally distributed points throughout the region of interest. Positional points 2.5-cm apart in a square array yield about 50 points on which an estimate of linearity can be made. In practice, it is the maximum value, not the average value, of this quantity which is of interest.

Sensitivity. At first sight it may seem more realistic to assess sensitivity using a large extended source because both cameras and scanners normally examine large areas, and comparisons between them can be readily made by comparing the total number of counts accumulated from the entire area of interest in a given time per microcurie. In practice, however, there is an edge effect in the case of the camera which results in a reduced total count/microcurie from an extended source compared with a point source. The shape of an extended source used for a practical comparison is also of some importance. A circular source with a diameter less than that of the collimator is appropriate for the camera, while a rectangular source is more suited to the scanner. However, to compare the performance of cameras with each other, a simple, meaningful measurement can be made using a point source on the central axis at a fixed distance. As will be seen later, point and extended source results differed by only 10–15% for the camera.

Sensitivity is defined as the number of counts per minute per microcurie within the full photopeak obtained from a point source of radioactive material placed along the central axis of the detector head 12.7 cm from the collimator face. Because this sensitivity figure will depend on the isotope used and the collimator, these must also be specified if any figure for sensitivity is to be meaningful. We selected 12.7 cm as the maximum distance that is likely to be of practical interest.

Results of point source measurements and of extended-area sensitivity measurements are presented here. An extended source slightly smaller than the useful area of the camera should be chosen; e.g. a 20-cm-diameter source if a camera-scanner comparison is to be made.

METHODS

Resolution. As an indication of the limiting resolution of the crystal-photomultiplier-electronics-display without the collimator a rapid method of checking long-term stability has been obtained using an array of lead blocks mounted between perspex sheets and fixed directly above the crystal which is then irradiated by a point source at a distance. The dimensions of the lead blocks and their separations are identical to the array of tungsten blocks previously described by Anger (*5*).

We investigated the resolution of the collimators —a very different parameter—using a radioactive line source of polythene tubing 1 mm in diameter and about 3 cm long. The length is greater than the FWHH values measured with the exception of that for ^{18}F (Fig. 2).

We investigated two collimators, both with holes 0.237 in. in diameter and septa 0.075 in. thick. The collimator lengths are 3 in. and 1.5 in., and they can be used together to make a length of 4.5 in. The line source was placed in front of the collimator, parallel to one of the major axes, and the positioning pulses in the other axis were fed into a 512-channel pulse-height analyser. Calibration of the positioning pulse amplitudes in terms of millimetres at the point of measurement was made with two finely collimated sources placed at a known distance apart. Source-to-collimator distances from 2.5 to 20 cm in both air and water were investigated with gamma-ray energies varying from 80 to 511 kev. In each case measurements were carried out at several points over the crystal area.

Uniformity. Uniformity measurements on the gamma camera were carried out by irradiating the crystal with a point source of activity placed not less than 2 meters from the camera. The x- and y-position pulses were analysed in a 16 x 32 matrix using the 512-channel analyser in its bi-dimensional mode. Because the position signals are both positive and negative, we had to add a positive pulse of constant amplitude to each signal so that the signals would be accepted by the analyser. Photographic records of the output were made concurrently with the bi-dimensional analysis.

Linearity. The linearity of the camera was measured directly in terms of the proposed definition. A collimated point source was placed over the crystal in a series of positions to form a rectangular array covering the crystal area. The position pulses from each point for the linearity measurement were then analysed, one dimension at a time, using a multichannel analyser. Because the distance of each point on the array to the crystal center was known, the positioning pulse heights in millivolts were used directly to provide a ratio of signal to actual distance. The variations in this ratio for points within specified distances of the crystal center were then calculated.

RESULTS

Resolution. Irradiating the crystal and lead-block array with ^{131}I radiation shows that at the crystal center, lead blocks 5 mm wide and separated by the same distance can be visually resolved at the output if a total of 10^6 counts is obtained. However, towards the edge of the crystal the minimum separation to be resolved is about 7 mm.

Figure 2 shows the FWHH plotted against source-to-collimator distance for four different gamma-ray energies using the 3-in. deep collimator. The FWHH distance is greater than the distance at which two point sources can be visually resolved, as was discussed earlier. For example, two ^{131}I point sources 12 mm apart can be resolved with this collimator when $Z = 19$ cm although the corresponding FWHH is 19.3 mm (see Table 1). These results are for a source in air and at the crystal center; the full photopeak of the isotope is accepted in each case. The "geometrical resolution" (*7*) of the collimator is also shown in Fig. 2.

Decreasing the window width of the single-channel analyser reduces the FWHH by up to 10% while decreasing the sensitivity to about one third. FWHH is a minimum at the center of the crystal and increases by up to 20%, reaching a maximum at a radius of about 18 cm and then remaining fairly constant up to 23 cm.

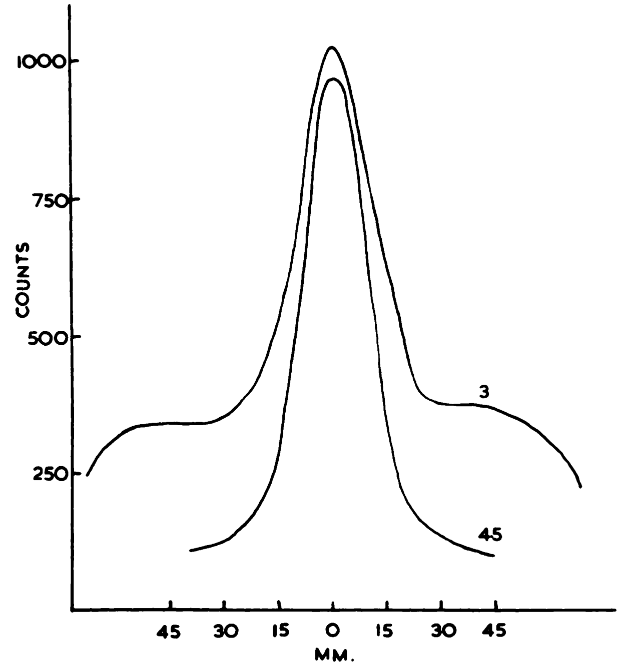

FIG. 5. Response to line source of ^{18}F in air using 3- and 4.5-in. deep collimators. Source-collimator distance was 10 cm.

Figure 3 shows how the FWHH depends on source-to-collimator distance and the analyser gate width for a line source of ^{203}Hg in air and in water.

The characteristics of the 4.5-in. collimator are indicated in Fig. 4 for ^{18}F and ^{131}I, together with its geometrical resolution. The difference in the shape of the response to 511-kev radiation for the 3-in. and 4.5-in. collimators is shown in Fig. 5, and a considerable improvement in resolution is achieved by using the 4.5-in. collimator. However, the sensitivity is reduced from 192 to 59 cpm/μc for ^{131}I (Table 2).

TABLE 2. SENSITIVITIES FOR POINT SOURCES*

Isotope	Sensitivities (cpm/μc)		
	1.5" collimator	3" collimator	4.5" collimator
^{197}Hg	1,368	—	—
^{203}Hg	882	174	66
^{131}I	—	192	59
^{18}F	—	—	190

* Point sources 12.5 cm from collimator.

Uniformity. Figure 6 shows a series of profiles of counts per unit area across the face of the crystal which had been uniformly irradiated by 1,000,000 counts. The corresponding Polaroid photograph of the output is shown in Fig. 7. Each address in the 16 x 32 matrix represents a crystal area of about 1 in.^{2} so that the number of counts per unit area was about 2,500 and the standard deviation of counts per address in the example shown is about 2%. To insure accuracy for specification purposes this error should not exceed 2%.

The bright rim around the display reflects a dot density of approximately twice that in the central area. This is due to light reflection at the edge of the crystal, and it significantly reduces the usable diameter of the crystal from 28 cm to about 23 cm. The uniformity shown may be specified in terms of the second definition given above as having a maximum deviation from the average number of counts per address of + 17% and — 14% within a 23-cm diameter of the crystal area.

A and B in Fig. 6 shows the extremes of the 23-cm diameter, and both are 10% above the average number of counts. The curve at C lies 11% below the average. However, it can be seen that in general changes in the profile are gradual rather than abrupt, with the large positive deviations invariably lying in close relation to the bright rim.

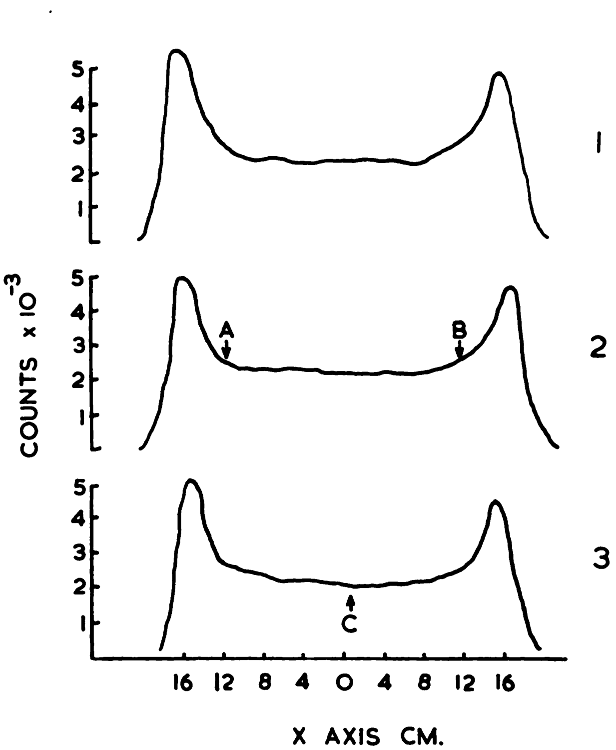

FIG. 6. Profiles of counts as function of crystal radius at three positions across uniformly irradiated crystal. A and B represent limits of usable diameter and are 10% higher than average counts within useful area. At C, profile is 11% below average.

Linearity. The ratio of the x- and y-pulse amplitudes to the amplitude corresponding to the distance between the source and crystal center was calculated for a total of 42 points in a rectangular array covering a circle of diameter 23 cm (Fig. 6).

The maximum deviation from the mean within the stated area was ±5% parallel to the x-axis and ±8% parallel to the y-axis. The deviation increased from the center to the edge, as Fig. 8 shows.

Sensitivity. Sensitivity, as defined earlier, is indicated for ^{197}Hg, ^{203}Hg, ^{131}I and ^{18}F with three collimators in Table 2. The single-channel analyser was set to accept the entire photopeak in each case. The isotope spectrum and the accepted counts were simultaneously displayed on a multichannel analyser to insure correct settings. These results should be considered in association with the resolutions indicated in Figs. 2 and 4. The sensitivity for a point and an extended source are also shown (Table 3).

TABLE 3. SENSITIVITIES FOR POINT AND EXTENDED SOURCES*

Isotope and collimator	Sensitivities (cpm/μc)	
	Point	Extended
^{18}F (4.5" coll.)	190	170
^{131}I (3" coll.)	192	162

* Extended source has 21-cm dia. Both are 12.5 cm from collimator.

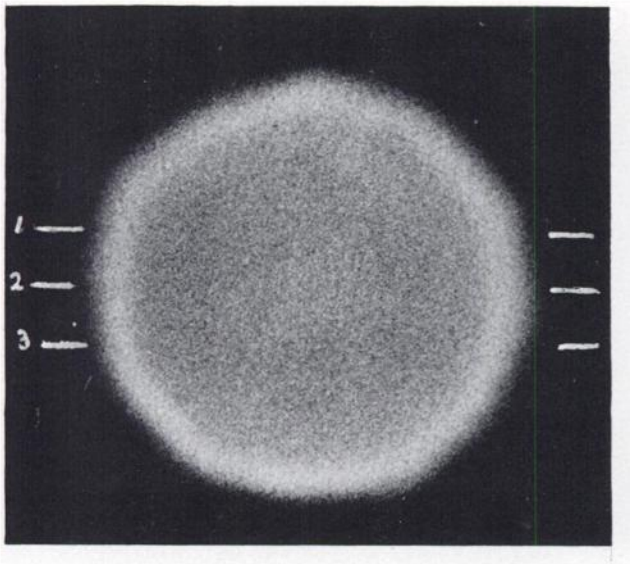

FIG. 7. Polaroid of output display from uniformly irradiated crysts corresponding to Fig. 6 (1, 2 and 3 show profile positions).

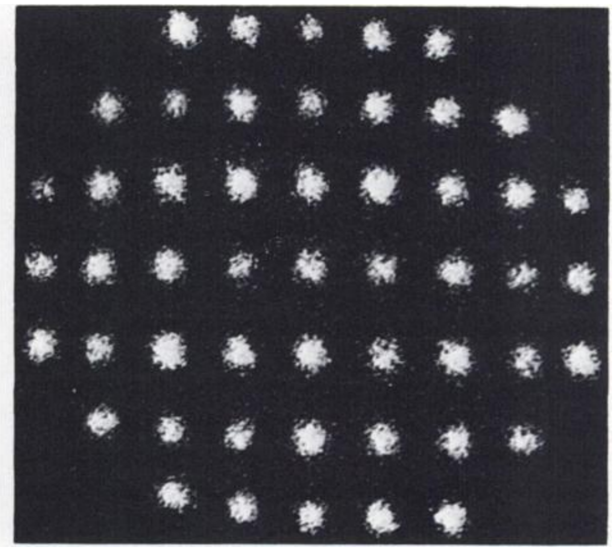

FIG. 8. Polaroid photograph of rectangular array of collimated point sources recorded with scintillation camera.

DISCUSSION

While the visual separation of the shadows of lead blocks placed directly against the crystal does not provide an accurate value for inherent resolution, it does indicate a value for comparison with the results obtained with the collimators. The factors involved in the inherent resolution of a gamma camera, such as the Compton scattering within the crystal, the light spread within the crystal and the statistical fluctuations in the number of photoelectrons resulting from a single event, have been discussed in detail by Brownell (*14*). It is these factors which limit the resolution of the camera for low-energy gamma rays and which cause the appreciable variation in resolution across the surface of the crystal. In general, however, the inherent resolution is superior to that obtained with the collimator, so that the limitations in this respect are due to the collimator and not to the camera system. It can be seen from the results that quite good FWHH values can be obtained with 511-kev radiation if a 4.5-in. collimator is used. Improved collimator designs can therefore improve the resolution of the instrument at the expense of sensitivity.

The uniformity results show the importance of this parameter in considering camera performance. Marked variations in response over the usable area of the crystal can result in misleading clinical interpretations of the image photograph. We find that camera readjustment to improve uniformity can easily degrade the resolution beyond usable limits; therefore it is essential that both parameters be included in the performance specification. The values shown above represent one compromise which gives useful clinical pictures.

Variations in the linearity of the camera are seen to produce "barrel distortion" which is more marked towards the periphery of the crystal. From the results quoted, it has been calculated that the displacement of a point in three dimensions due to camera nonlinearity is less than 7 mm. However, this property also depends on the same factors as resolution and uniformity and must be included in the consideration of over-all performance of the instrument.

The importance of being able to specify the performance of the instrument does not need to be stressed, and it is surprising that this has not been provided so far by camera manufacturers nor demanded by purchasers. The results presented in this paper are an attempt to provide this information in one form. These results also indicate some of the factors that affect the parameters necessary to specify the performance.

CONCLUSIONS

Working definitions are proposed for sensitivity, resolution, uniformity and linearity which let one uniquely specify the performance of a gamma camera. Values for these parameters measured on a Nuclear-Chicago 11-in. gamma camera are as follows:

Sensitivity: (Point source of ^{131}I, 3-in.-long collimator, 0.237-in.-hole diameter, 0.075-in. septal thickness, at a distance of 12.5 cm from collimator face)
= 192 counts/min/μc max. value in air

Uniformity: (Within 23-cm diameter)
$= +17\%, -14\%$
Resolution: (Within 23-cm diameter, point source 5 in. from the collimator face for ^{131}I on central axis)
= 22 mm FWHH
Linearity: (Maximum variation within 23-cm diameter)
$= \pm 8\%$

The variation of resolution and sensitivity with radiation energy and distance from the collimator and other factors such as photopeak channel width are discussed.

SUMMARY

The performance of a gamma camera is specified quantitatively in terms of practical definitions of sensitivity, resolution, uniformity and linearity. The effect of various relevant parameters such as radiation energy on these quantities is presented.

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