COLLIMATOR CHARACTERISTICS FOR RADIOISOTOPE SCANNING

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For scintigraphic instruments such as scanners and scintillation cameras, collimators with greatly different characteristics have become available during recent years. In general little information is given concerning the performance of focused collimators to the physician or physicist who has to select the proper collimator for a particular application.† Only the number of holes, the focal length and the spatial resolution of the collimator at the focal plane are provided by most manufacturers.

The present paper describes briefly the fundamental parameters of collimator-detector systems and their significance. The characteristics of collimators for some commercial scanners are given and corresponding data for other makes of scanners as well as for scintillation cameras should become available shortly.

EVALUATION OF COLLIMATOR PERFORMANCE

A simple method for determining the performance of collimators has been established recently (*1–3*). However, even without measurements the geometrical response of a collimator can be derived from its design and dimensions. Examples are given on top of Figs. 1 and 2 where a cross section through the axis of each collimator is given together with its geometrical field of view. In particular, the radius of the field of view, R, at the focal distance is a measure of the best resolution of that particular collimator. The 12.7-cm (5-in.)-dia collimator of Fig. 1 is designed for the medium-energy gamma rays of ^{131}I; the 7.6-cm (3-in.)-dia collimator of Fig. 2 is for low-energy gamma rays such as those of ^{99m}Tc. The essential dimensions of each collimator are given in the table at the right upper corner of each figure.

The response of a collimator to gamma rays of different energies can be derived from its geometrical specifications with the aid of computers (*2,4*). However, only an experimental investigation can encompass the physical properties of the collimator as well as those of the radiation detection system (*5–8*).

In this study the collimator response has been derived from multiple scans of a line source in air at various distances from the face of the collimator. The line source was moved in a plane perpendicular to the axis of the collimator (*3*). The variation in count-rate, expressed as a percentage of the maximum count-rate at the experimental focal distance, is plotted as a function of the displacement of the source from the axis of the collimator (Figs. 1 and 2, bottom). The experimental focal distance, where the observed count-rate along the axis of the collimator is greatest, must not coincide with one of the source-to-collimator distances chosen at 2.5-cm intervals.

At the lower right corner of each figure, additional specifications are given such as the make of the collimator, the number of holes, the dimensions of the crystal, the radioisotope source employed, the window width of the pulse-height analyzer and the collimator sensitivity. To minimize the detection of degraded radiation without excessive loss of primary radiation, the lower discriminator is set at about 90% of the gamma-ray energy (*9*). For the measurements of the collimator response to low-energy gamma rays, the long-lived radionuclide ^{141}Ce (145 keV) is used as a substitute for ^{99m}Tc, although the experimental data are referred to the latter radionuclide.

RESULTS

Collimator spatial resolution. The first parameter that must be determined for each collimator is its spatial resolution perpendicular to the axis of the collimator. For the detection of variations in radioisotope concentration within a narrow region, the spatial resolution of the collimator should be comparable with the dimensions of this region. In gen-

† For references see: Myhill, J. and Hine, G. J.: Multihole collimators for scanning. In *Instrumentation in Nuclear Medicine*, vol. 1, Hine, G. J., ed., Academic Press, N.Y., 1967, p. 429.

Received March 4, 1969; revision accepted Sept. 15, 1969.

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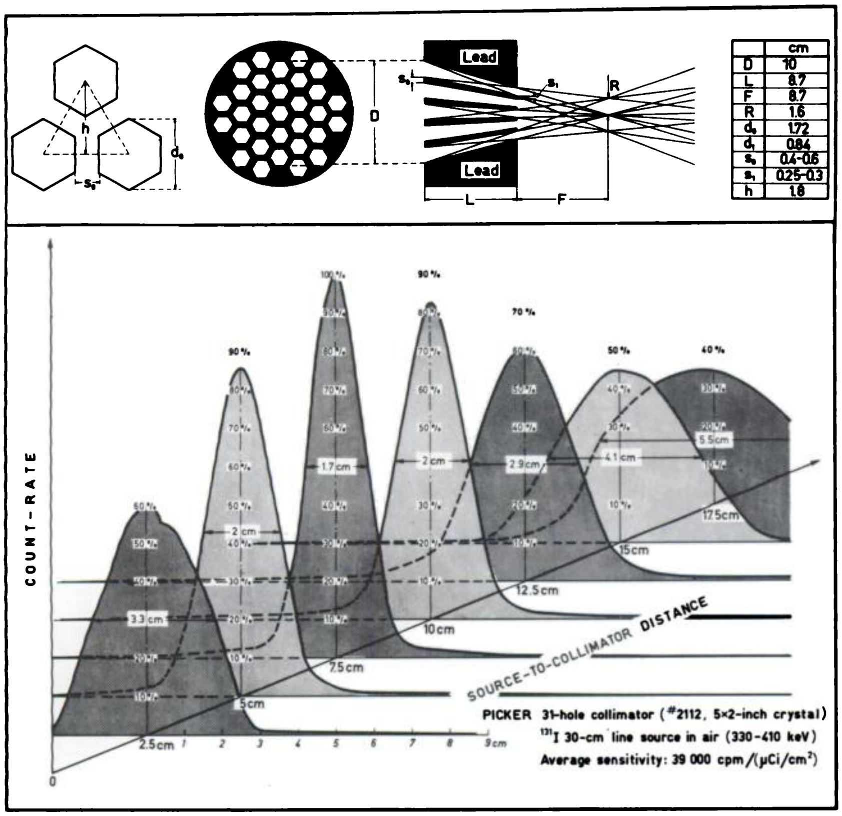

FIG. 1. Geometrical specifications of Picker #2112 collimator (top), and ^{131}I line-source response at 2.5-cm intervals from face of collimator (bottom).

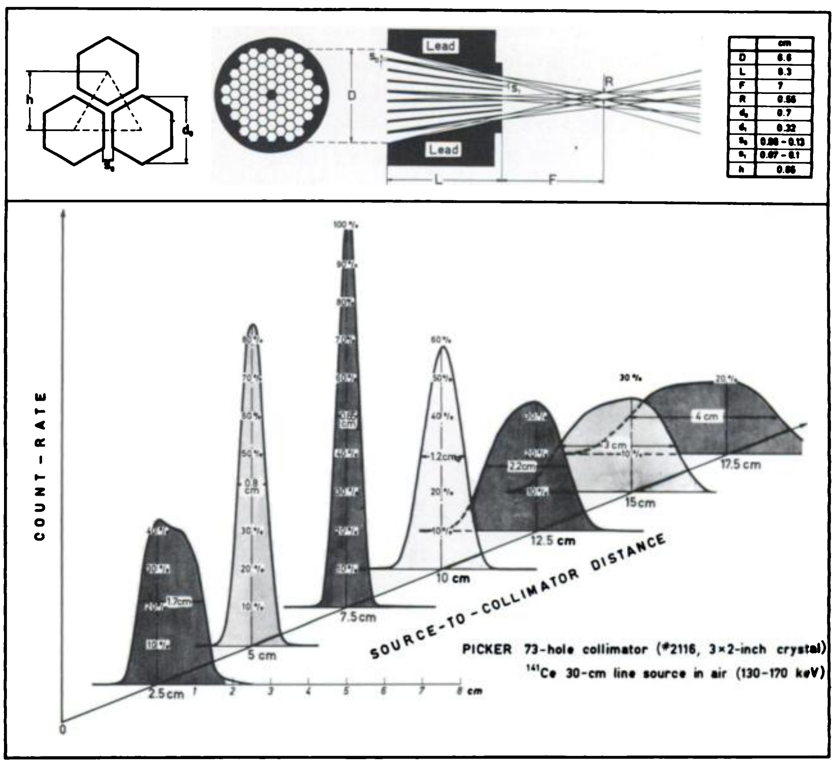

FIG. 2. Geometrical specifications of Picker #2116 collimator (top) and ^{141}Ce line-source response at 2.5-cm intervals from face of collimator (bottom).

eral, so-called "fine-focus" collimators are used for thyroid scanning and "broad-focus" collimators for nearly all other scintigraphic applications. The best resolution of the first is less than 1 cm and that of the latter about 2 cm.

Many suggestions have been made concerning the definition of collimator resolution (*1,2*). Since the line-source response curves of a collimator (Figs. 1 and 2) can be approximated by a Gaussian distribution (*3*), the full width at half maximum

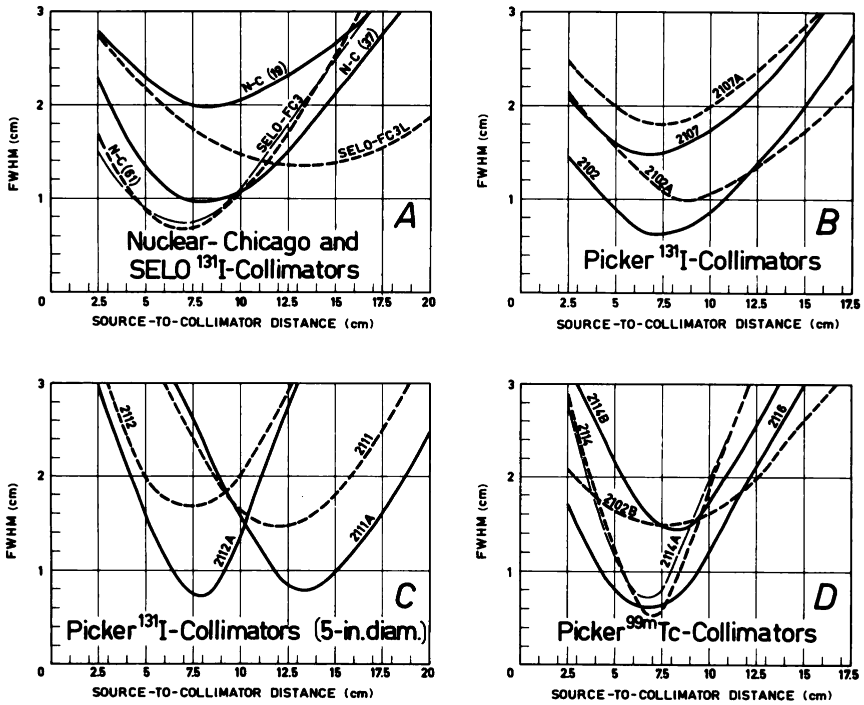

FIG. 3. Spatial resolution (FWHM) of 18 commercial collimators for various distances of source from face of collimator. A: Nuclear-Chicago and SELO 7.6-cm (3-in.)-dia ^{131}I-collimators; B: Picker 7.6-cm (3-in.)-dia ^{131}I-collimators; C: Picker 12.7-cm (5-in.)-dia ^{131}I-collimators; D: Picker 7.6-cm (3-in.) and 12.7-cm (5-in.)-dia ^{99m}Tc-collimators.

(FWHM) of the line-source response curve is directly related to the spatial resolution of the collimator in the absence of significant septum penetration. The resolution at various distances from the face of the collimator can thus be determined from the corresponding response curves. At distances close to the collimator face the response curve is distorted when rows of holes lie parallel to the axis of the line source; at some distances beyond the focal plane, the line-source response curves also appear distorted, probably caused by collimator imperfections.

Because the spatial resolution of the collimator varies along its axis, it is not sufficient to specify the resolution at the focal distance only. Furthermore, with increasing energy of the gamma rays the resolution of the collimator may be affected depending on the thickness of the septa. Therefore, the resolution must be stated for various distances from the face of the collimator and for a certain gamma-ray energy.

In Fig. 3 the FWHM is given for 18 different collimators* as a function of source-to-collimator distance measured from the face of the collimator along its axis. For collimators of equal focal distance, the variation of collimator resolution with depth becomes more pronounced as the diameter of the collimator increases. Of the different collimators investigated, the 7.6-cm (3-in.)-dia SELO #FC3L (Societa Elettronica Lombarda, Milano, Italy) long-focus collimator has the least variation of resolution with depth.

Curves as shown in Fig. 3 are essential for the selection and use of a collimator in a given application. The distance between the face of the collimator and the patient should be chosen so that all sections of the organ to be scanned are as close as possible to the region of best resolution of the collimator. The resulting "average" resolution of the collimator depends on the radioisotope distribution along the axis of the collimator for various sections of the organ. For example, in thyroid scanning it is important to choose a collimator with an average resolution of about 0.8 cm in a depth interval sufficiently large to include the entire thyroid gland. In the case of large organs, especially the liver, the variation of the collimator resolution with depth can present a severe problem (*5*). An average resolution of about 1.5 cm appears desirable for most major organs although useful information may still be obtained with somewhat larger FWHM values. All information, however, is lost if the FWHM reaches about twice the diameter of the region with the abnormal radioisotope concentration (*10*).

Collimator plane-source sensitivity. As is well known, a penalty has to be paid for good spatial resolution of a collimator. For a certain collimator

* The data for the Nuclear-Chicago collimators have kindly been provided by A. Dias-Neto, Centro de Medicina Nuclear, São Paulo, Brazil.

diameter and focal distance, the geometrical efficiency of the collimator is proportional to the square of its FWHM at the focal distance (*2*). The plane-source sensitivity of a collimator-detector system is a parameter which combines the geometrical efficiency of the collimator and the detection efficiency of the detector system for gamma rays of given energy. It states the count-rate from a large plane source in air perpendicular to the collimator axis for a given concentration of a gamma-ray-emitting radionuclide and a selected pulse-height interval.

The plane-source sensitivity is obtained by integrating the count-rate of a line-source response, as shown in Figs. 1 and 2. For a particular collimator it is found to be nearly the same for all distances from the face of the collimator (*1,3,5*). For the 18 collimators included in Fig. 3, the relative plane-source sensitivity is given in Table 1 together with the FWHM at the experimental focal distance. The plane-source sensitivity of the Picker #2107 19-hole, 7.6-cm-dia collimator-detector system is taken as 100% for both radioisotopes.

By the use of calibrated sources the plane-source sensitivity can be determined in absolute units of activity. For ^{131}I gamma rays, the absolute plane-source sensitivity of the Picker #2107 collimator-detector system is found to be 10,000 cpm/(μCi/cm^2). With this value the relative sensitivities of other ^{131}I-collimator systems listed in Table 1 can be converted into absolute units. Conversely, if the plane-source sensitivity of another system for ^{131}I gamma rays is determined in absolute units, its relative sensitivities can also be compared with those of the collimator systems listed in Table 1.

The plane-source sensitivities of the collimator systems given in Table 1 vary by as much as a factor of 60. This obviously affects greatly the count-rate to be expected from a given activity. Recent trends have given preference to high-sensitivity systems, especially those incorporating 12.7-cm-dia crystals. Since data on the variation of the collimator resolution as a function of depth, as shown in Fig. 3, are generally not available, high-sensitivity collimator systems may be employed even when their resolution is insufficient for the scintigraphic problem on hand. More correctly, that system which combines the highest sensitivity with the required spatial resolution over the desired depth interval should be selected (*5,11*).

Collimator septum penetration. As indicated in Table 1, most available collimators have been designed either for the 364-keV gamma rays of ^{131}I

TABLE 1. COLLIMATOR PARAMETERS

Collimator	Number of holes	Hole dia, d_0 (cm)	Collimator length, L (cm)	Experimental focal distance (cm)	FWHM at focal distance (cm)	Sensitivity rel. to #2107 (%)	Septum penetration fraction (%)
				collimators for 7.6-cm (3-in.)-dia crystals designed for ^{131}I			
Picker #2102	31	0.8	10.0	7.4	0.6_5	12	10
2102A	31	0.8	7.6	8.7	1.1	36	18
2107	19	1.2	7.8	6.9	1.5	100	20
2107A	19	1.4	7.7	7.5	1.8	154	50
SELO #FC3	37	0.9_5	10.0	7.0	0.7_5	35	55
FC3L	37	0.9	10.0	13.6	1.3_5	52	33
Nuclear-Chicago							
#596	19	1.2_5	7.8	8.3	2.0	150	58
593	37	0.8	7.8	8.0	0.9_5	33	19
597	61	0.7	7.8	7.0	0.7	20	43
				designed for ^{99m}Tc			
Picker #2102B	31	1.1_5	6.2	7.4	1.5	210	—
2116	73	0.7	8.3	6.8	0.6	30	—
				collimators for 12.7-cm (5-in.)-dia crystals designed for ^{131}I			
Picker #2111	85	0.9_5	8.7	12.0	1.4_5	150	9
2111A	265	0.5	8.7	13.3	0.8	43	12
2112	31	1.7	8.7	7.4	1.7	390	20
2112A	163	0.7	8.7	7.9	0.7_5	65	20
				designed for ^{99m}Tc			
Picker #2114	271	0.6_5	8.7	7.1	0.5	85	—
2114A	271	0.6_5	7.4	6.7	0.7	120	—
2114B	55	1.5_5	8.4	8.3	1.4_5	560	—

TABLE 2. FWHM (CM) FOR PICKER #2102A COLLIMATOR AT 7.5-CM SOURCE-TO-COLLIMATOR DISTANCE IN AIR AND WATER FOR GAMMA RAYS OF THREE ENERGIES EMPLOYING TWO ANALYZER WINDOW WIDTHS FOR EACH

Radioisotope (gamma-ray energy)	^{141}Ce (145 keV)				^{131}I (364 keV)				^{198}Au (412 keV)			
Analyzer window	130–170 keV		115–170 keV		330–410 keV		312–410 keV		370–460 keV		350–460 keV	
Medium	Air	Water	Air	Water	Air	Water	Air	Water	Air	Water	Air	Water
FWHM (cm)	1.01	1.05	1.00	1.06	1.09	1.12	1.08	1.13	1.10	1.13	1.11	1.14

or for the 140-keV gamma rays of ^{99m}Tc. Such collimators differ in the thickness of their septa between the holes (*5*). In collimators for low-energy gamma rays the minimum septum thickness is dictated by mechanical difficulties of casting or assembling thin lead foils (Fig. 2). For the gamma rays of ^{131}I the minimum thickness is about 1.5–4 mm (Fig. 1). However, independent of septum thickness there always will be some gamma-ray penetration of the edges of the septa, although for low-energy gamma rays the amount of edge-penetration is negligible (*4*).

The increase in collimator sensitivity caused by septum penetration is "unwanted" since it results from a widening of the field of view of the collimator beyond its geometrical response. This is well illustrated in Fig. 1 where the gamma rays of ^{131}I reaching the detector from points outside the geometrical response of the collimator produce the long tails of the response curves. For low-energy gamma rays, however, septum penetration is negligible even if the septa are very thin (Fig. 2).

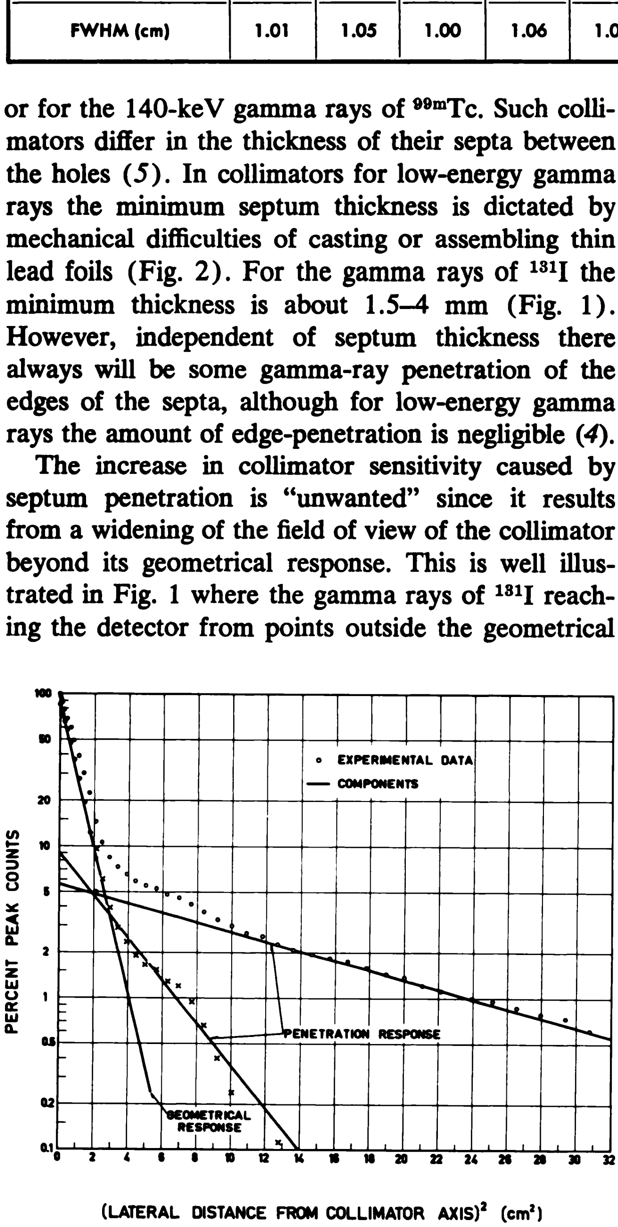

FIG. 4. ^{131}I line-source response of Picker #2107A collimator at 7.5 cm. Logarithmic plot of count-rate vs. linear plot of square of source distance from collimator axis. Experimental data can be analyzed into three straight-line components. Crosses represent data after subtraction of one component of penetration response; solid dots are data remaining after subtraction of both penetration response components.

The resolution of a collimator defined as FWHM may be affected only a little by septum penetration (Table 2), even though septum penetration is significant. Therefore, for a complete description of the collimator properties, a third collimator parameter, that is the septum penetration fraction, must be specified for a stated gamma-ray energy.

The septum penetration fraction, f_p, is defined as the ratio of the detected gamma rays crossing the septa and side shielding to the gamma rays passing through the holes of the collimator (*1,4*):

$$f_p = \frac{\text{count-rate due to septum penetration}}{\text{count-rate due to collimated primary radiation}}.$$

Although several methods (*7*) have been suggested for the experimental determination of f_p, none of these can be applied successfully to widely differing collimators. Therefore a graphical method for the evaluation of f_p is introduced. For the line-source response close to the focal distance of a collimator, the count-rate is plotted on a logarithmic scale against the square of the displacement of the line source from the axis of the collimator on a linear scale (Fig. 4). In this kind of presentation a Gaussian curve appears as a straight line. From the example of Fig. 4 it is apparent that the ^{131}I line-source response is not a straight line and therefore not a single Gaussian curve (*3*). However, as shown, the data can be analyzed into three straight-line components. The sum of the two low-intensity components may be regarded as caused by penetrating radiation while the remaining main component (solid dots) represents the geometrical response of the collimator. The latter is in good agreement with the response of the collimator to low-energy gamma rays. The penetration fraction, f_p, can then be determined as the ratio of the areas of the two low-intensity components to that of the main component.

The septum penetration fractions obtained by this method for the gamma rays of ^{131}I are given in Table 1 for all ^{131}I-collimators. The well-designed collimators have a penetration fraction of 20% or less, in good agreement with the values calculated by Rotenberg and Johns (*4*) for edge penetration. However, some of the collimators show a considerably larger septum penetration fraction up to 50–60%, meaning that for 100 gamma rays from a large source passing through the holes, an additional 50–60 gamma rays are registered from areas outside the geometrical response of those collimators. This obviously has a significant effect on the quality of the resulting scans by decreasing their contrast. Therefore, collimators with a high septum penetration fraction should be avoided or at least used with care, or used only for lower-energy gamma rays.

DISCUSSION

In clinical scintigraphy, the radioactivity of an organ is distributed within an absorbing and scattering medium. The methods used for determining the collimator parameters described above involve only measurements in air, under conditions in which gamma-ray absorption and scattering are minimal. Therefore the question arises whether the collimator parameters determined in this way are applicable to clinical situations.

For sources in an absorbing medium, gamma-ray attenuation obviously affects the number of gamma rays reaching the collimator. The energy of the gamma rays as well as the fraction of scattered radiation included in the photopeak determine their actual attenuation. Under scanning conditions, about 7 cm of tissue decrease the number of gamma rays from ^{131}I by one-half. The attenuation of the gamma rays of ^{99m}Tc appears to be nearly the same since at lower energies more of the scattered gamma rays are detected (*5*).

Only for plane sources in air, the plane-source sensitivity of a collimator-detector system, as defined above, is nearly independent of their distance from the collimator. Since gamma-ray attenuation reduces the observed count-rates of all collimator-detector systems about equally, it need not be taken into account for the selection of a particular collimator. In the interpretation of scintigraphic data, however, it must be kept in mind that a reduced count-rate within a certain area may be caused by increased gamma-ray attenuation if the tissues in this area are located at greater depth than those of other areas in the same scan. The use of two collimator-detectors facing each other from opposite sides of a body section will minimize the effect of gamma-ray attenuation (*5,12,13*).

Closely connected with gamma-ray absorption is the problem of detection of radiation scattered within the body. If the scattered radiation originates outside the geometrical response of the collimator, it may have a similar effect on the response of the collimator-detector system as radiation penetrating the septa of the collimator. The variation of the FWHM of a collimator for line sources in air and water, as given in Table 2, does not fully reflect the contribution of scattered radiation. However, the data in Table 2 for gamma rays of three energies and two lower discriminator settings each, at 90% of the gamma-ray energy and at the valley on the low-energy side of the photopeak, clearly show the trend caused by the various experimental conditions on the resolution of the collimator.

Pulse-height spectra for a particular gamma-ray emitter recorded with different collimators have shown that for a particular gamma-ray energy the detection of scattered radiation does not depend on the design and dimensions of the collimator. Therefore the scatter fraction is not regarded as a collimator parameter although it varies with the size of the source and its position within an absorbing medium (*9*).

SUMMARY

The physical properties of a collimator-detector system for rectilinear scanning are described by its spatial resolution, its plane-source sensitivity and its septum penetration. These three parameters depend on the design and dimensions of the collimator, the energy of the gamma rays employed and the properties of the detection system.

For a particular gamma-ray emitter, the three collimator parameters can be determined from scans of a line source in air. A knowledge of these parameters is indispensable for the selection and best use of a collimator for a particular scanning application. Special attention must be given to the variation of collimator resolution with distance from the face of the collimator. Values for the three parameters have been determined for 18 collimators from three manufacturers.

ACKNOWLEDGMENT

The authors wish to express their appreciation to the Picker Nuclear and SELO Companies for making their equipment available to the IAEA laboratory. They would like to thank Mrs. L. Schindl for her help in evaluating the data and for preparing the graphs.

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