# METHOD FOR REDUCING THE ENERGY DEPENDENCE OF THE RESOLUTION OF FOCUSED COLLIMATORS

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Where the septa of focused collimators are thick enough to ensure that septal penetration is much less than edge penetration, as is the common practice (*1,2*), the marked deterioration in collimator resolution with increasing incident photon energy is attributable almost entirely to increasing edge penetration. In this paper a method of substantially reducing this dependence is described and assessed. The method involves incorporating mid-penumbral shielding in focused collimators, a procedure which has been suggested previously (*3*) but which has not been evaluated. The inclusion of mid-penumbral shielding involves essentially the use of collimator holes of nonuniform taper. This contrasts with all other approaches to the design of focused collimators where invariably holes of uniform taper have been used (*1,2,4–8*).

In the present study the performance of a collimator with modified taper is compared with that of a corresponding collimator of conventional but optimum design. For the sake of simplicity the collimator with modified taper will be referred to as the modified collimator.

## MID-PENUMBRAL SHIELDING

Mid-penumbral shielding describes a certain arrangement of additional shielding applied at the inlet and outlet pupils of the holes of a collimator (*3*). It is illustrated in Fig. 1 for the case of a single-hole collimator.

The purposes of mid-penumbral shielding are (A) to attenuate photons which would otherwise penetrate the edges of the unmodified apertures, and thereby to reduce edge penetration and (B) to attenuate photons from sources in positions significantly off-axis and by selectively reducing the response to low-response regions improve the shape of the point or line-spread function. In effect the addition of mid-penumbral shielding steepens the slopes of the limbs of the associated line-spread functions below the 50% response levels without significantly affecting the shapes of the functions within the 50% response levels.

## DESIGN OF COLLIMATORS

The procedure introduced by Rotenberg and Johns (*1*) and developed further by Husak and Perinova (*8*) was adopted for the design of the conventional lead collimator. It was decided that holes of circular cross section would be used. The required focal length (127 mm) and geometric resolution index (approximately 11 mm) of the collimator were specified and the septa thickness calculated using the criterion that $ul = 4$ where u is the linear absorption coefficient of lead at the photon energy (500 keV) for which the collimator was designed and l is the minimum path length through a septum for single-septum penetration. The plane source sensitivity (assuming zero penetration) was then calculated as a function of collimator thickness, and the optimum thickness, which occurs when the plane sensitivity is a maximum, was found. This specifies the dimensions of the optimum collimator of conventional design which is shown in Fig. 2A.

Subsequent studies by us which will be published have shown that for focused collimators with holes of circular cross section optimal overall performance is achieved when the septa thickness is calculated using the criterion that $ul = 2.8$, where u and l have the same meanings as above. On this basis a collimator designed for 500-keV photons using the criterion that $ul = 4$ is in fact optimum for 660-keV photons.

Holes of circular rather than hexagonal cross section were used because we believe that the advantages

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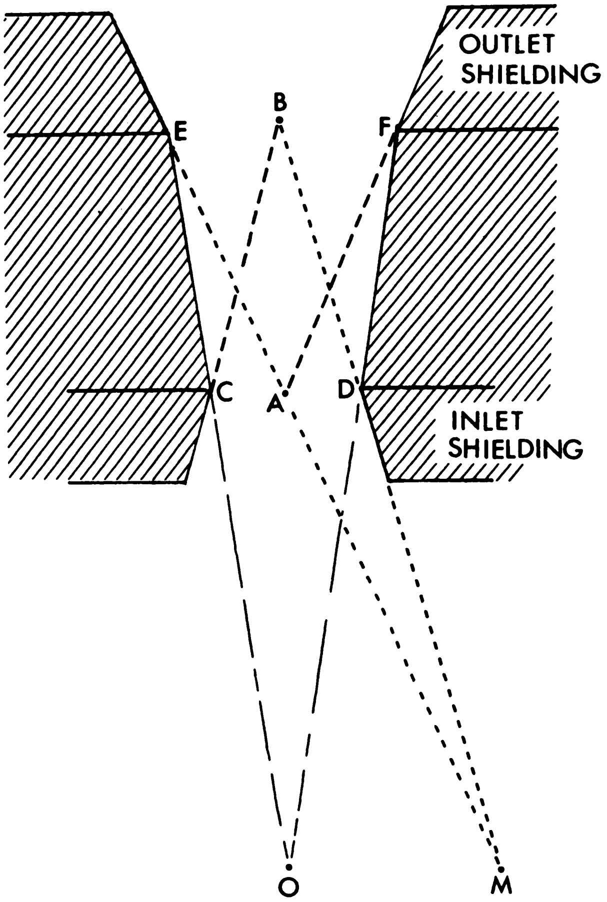


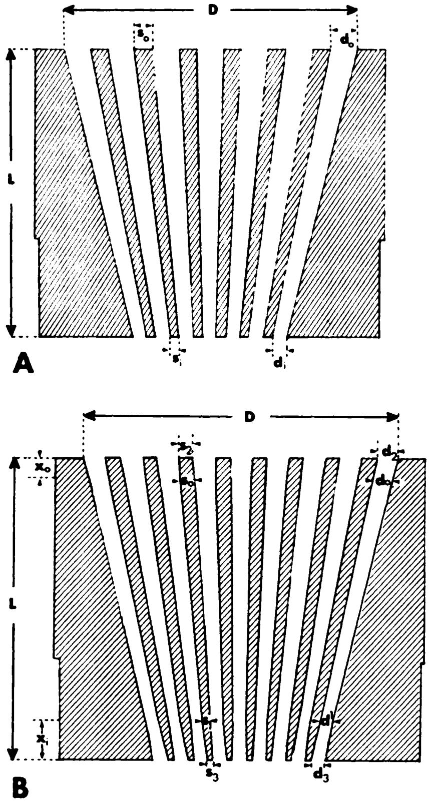
**FIG. 1.** Shows addition of mid-penumbral shielding to single tapered-hole collimator with axis OAB. AF and AE are produced to align outlet shielding and BC and BD to align inlet shielding.

of holes of hexagonal cross section in collimators for high-energy photons are not significant enough to justify the additional constructional problems, as will be shown in a later publication.

The design of the corresponding collimator which also had holes of circular cross section but incorporated mid-penumbral shielding was harder to specify. It should be stressed that by corresponding is meant that the collimator should be designed for the same source frequency as the conventional collimator and should be as similar in other respects as possible. However, neither the experimental data available nor the theoretical techniques at hand were adequate for the purpose. It was decided that the modified collimator should have the same total length as the conventional collimator to obviate objections that the improvements in penetration characteristics were simply the result of using more lead shielding. Since the overall length of the modified collimator included mid-penumbral shielding, it was clear that the fundamental length which we define to be the length excluding mid-penumbral shielding had to be less than that of the conventional collimator. This in turn meant that for the resolution indices of the two collimators to be the same, the diameters of the holes of the modified collimator also had to be less than those of the conventional one. The reduced diameters of the holes allowed more holes to be accommodated. The focal length of the modified collimator, defined as the distance from the inlet face to the focus of the holes, was the same as that of the conventional collimator.

The proportion of the total length of the collimator allocated to mid-penumbral shielding is a matter that may ultimately be amenable to optimization. However, as was indicated, insufficient data were available. It was clear that had mid-penumbral shielding occupied a very large proportion of the overall length, the reduction in the fundamental length of the collimator together with an increase in the focal length of this part (that is the distance from the inlet face of the fundamental part of the collimator to the focus) would have seriously reduced the plane sensitivity. On the other hand had it occupied a very small proportion of the overall length it would have been ineffective.

It was decided [having some regard to previous studies with a single-hole collimator (*3*)] to allocate



Conventional Collimator

| | cm |
|---|---|
| D | 12·0 |
| L | 11·4 |
| $d_0$ | 1·08 |
| $d_1$ | 0·57 |
| $s_0$ | 0·70 |
| $s_1$ | 0·37 |

Modified Collimator

| | mm | | cm |
|---|---|---|---|
| $d_0$ | 7·88 | D | 12·0 |
| $d_1$ | 4·85 | L | 11·4 |
| $d_2$ | 8·78 | $x_0$ | 1·02 |
| $d_3$ | 5·68 | $x_i$ | 1·52 |
| $s_0$ | 5·40 | | |
| $s_1$ | 3·30 | | |
| $s_2$ | 5·06 | | |
| $s_3$ | 1·60 | | |

**FIG. 2.** A shows collimator of conventional design (37 hole). B is modified collimator (61 hole).

a length of the collimator equal to twice that necessary to attenuate by a factor of ten photons of the energy for which the collimator was designed. Since 12.5 mm of lead attenuates 500-keV photons by a factor of ten, 25 mm of the total length of 114 mm was allocated to mid-penumbral shielding.

Calculation showed that in the absence of mid-penumbral shielding 70% of the edge penetration would have occurred at the inlet face of the collimator and the remaining 30% at the outlet face. In order to make edge penetration the same at both faces, 15 mm of mid-penumbral shielding was added at the inlet face and 10 mm at the outlet face.

The septum thickness was determined again using the criterion that ul = 4 where u is the linear absorption coefficient in lead of 500-keV photons. Detailed dimensions of the modified collimator are shown in Fig. 2B.

## EVALUATION OF THE COLLIMATOR PERFORMANCES

All that is required to completely describe the performance of a collimator to sources of photons of given energy on the focal plane is the appropriate line-spread function. To assess the two collimators, line sources comprising 250-mm lengths of capillary tubing filled with solutions containing $^{125}$I (27-keV photons), $^{7}$Be (480-keV photons), and $^{137}$Cs (660-keV photons) were used.

From the line-spread function l(x) it is possible to calculate (*10*)

1. the plane sensitivity E from:

$$E = \int_{-\infty}^{\infty} l(x)dx, \qquad (1)$$

2. the modulation transfer function MTF(λ) from:

$$MTF(\lambda) = \frac{1}{E}\int_{-\infty}^{+\infty} l(x)\cos\left(\frac{2\pi x}{\lambda}\right)dx, \qquad (2)$$

3. the point-spread function p(r) from:

$$p(r) = \frac{1}{\pi}\frac{d}{dr}\int_{r}^{\infty} \frac{l(x)r}{(x^2 - r^2)^{1/2}}dx, \qquad (3)$$

4. the figure of merit Q(λ) of Beck from:

$$Q(\lambda) = E[MTF(\lambda)]^2. \qquad (4)$$

It has been shown (*11*) that the concept of the comparative optimum response wavelength $\lambda_{opt}$, where $\lambda_{opt}$ is the source wavelength at which the function MTF(λ)/λ passes through a maximum, is a very important and meaningful one for evaluating the performance of a collimator. Consequently the function MTF(λ)/λ was calculated for each MTF(λ).

## RESULTS

Normalized point-spread functions for both collimators are shown in Fig. 3. For $^{125}$I, where penetration effects are negligible, the spread functions are virtually identical between the 100% response levels and the 50% response levels. Below the 50% response level the spread function for the modified collimator decreases more rapidly with increasing displacement from the axis than that of the modified collimator owing to the influence of mid-penumbral shielding.

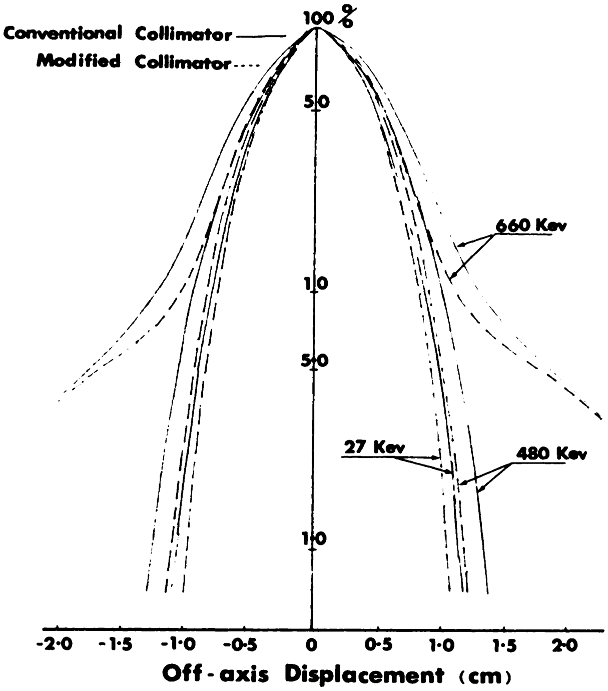


**FIG. 3.** Normalized point-source response functions for conventional and modified collimators at 27 keV, 480 keV, and 660 keV.

With 500-keV photons which, according to the criterion of Rotenberg and Johns, are those for which the collimators were designed, and with which septal penetration is still very small, the point-spread function of the modified collimator is significantly narrower than that of the conventional collimator. The difference in regions of high response is even more marked with 660-keV photons. However, in this case for displacements x greater than approximately 20 mm, which corresponds to response levels of less than 5%, the functions are virtually identical. This is not surprising since the response in these regions is dominated by septal penetration.

The plane sensitivity of the modified collimator is less than that of the conventional collimator for all photon energies studied, as is shown in Table 1. The fractional difference is greatest for 480-keV photons owing to the significant difference in edge penetration. With 660-keV photons, septal penetration, which effects both collimators to approximately the same extent, predominates and this reduces the fractional difference in plane sensitivity.

**TABLE 1. RATIO OF PLANE SENSITIVITY OF CONVENTIONAL COLLIMATOR TO THAT OF MODIFIED COLLIMATOR AT 27 keV, 480 keV, AND 660 keV**

| Energy (kev) | $E_c/E_m$ |
|---|---|
| 27 | 1.09 |
| 480 | 1.26 |
| 660 | 1.18 |

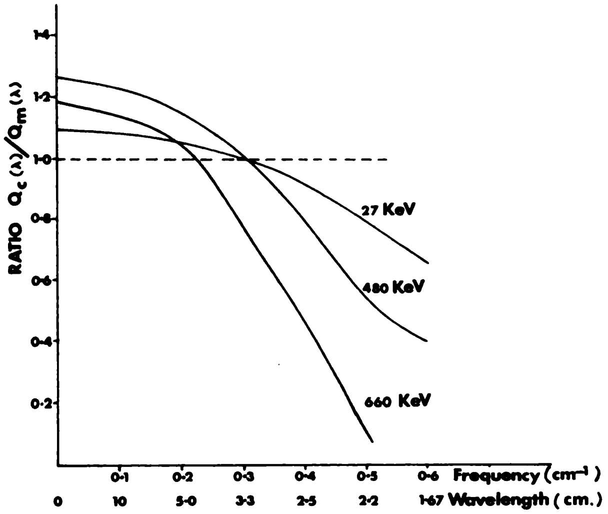


**FIG. 4.** Ratio of $Q_c(\lambda)$ to $Q_m(\lambda)$ (the figures of merit of conventional and modified collimators, respectively, at wavelength $\lambda$) as function of frequency and wavelength at 27 keV, 480 keV, and 660 keV.

The ratios of the Beck figures of merit (Eq. 4) as functions of $\lambda$ are shown in Fig. 4. These show that for all source wavelengths less than 45 mm at 660 keV and 32 mm at both 27 keV and 480 keV, the modified collimator has a better overall performance than the conventional collimator. In effect the superior resolving power of the modified collimator below these source wavelengths more than compensates for its reduced sensitivity. At higher source wavelengths this is not the case, and the performance of the modified collimator is poorer than that of the conventional collimator. In circumstances of this nature it is important to have an objective method of deciding which of the two collimators is basically of better design. This can be done by comparing the performances of the two collimators at their comparative optimum response wavelengths and normalizing performances to the same comparative optimum response wavelength, as described by Wyper and Gillespie (*11*). Briefly, if the comparative optimum response wavelength of the conventional and modified collimators are $\lambda_c$ and $\lambda_m$, respectively, then $\lambda_m{}^2Q_c(\lambda_c)$ and $\lambda_c{}^2Q_m(\lambda_m)$ give a measure of the basic respective overall performances of the two designs of collimator. By collimators of the same design as a particular collimator is meant here that the collimators have the same length and total diameter and that the hole-septa pattern is a magnified or minified version of that of the particular collimator. The results following normalization show that the overall performance of collimators of the design of the modified one is better than that of the conventional one by 8.4% at 27 keV, 8.1% at 480 keV, and 2% at 660 keV.

Since the two collimators were designed to have approximately the same resolution index, it is not surprising that corresponding comparative optimum response wavelengths are not very dissimilar. When this is the case, it is not unreasonable to use the simpler method of comparing the Beck figures of merit at a wavelength midway between the two corresponding comparative optimum response wavelengths. When this was done in the present case, the modified collimator was found to have figures of merit greater than the conventional collimator by 8%, 8%, and 2% for 27 keV, 480 keV, and 660 keV photons, respectively—in good agreement with the results of the more rigorous approach.

The most significant results of the present study appear in Fig. 5A, which shows the variations of comparative optimum response wavelength with photon energy. This shows the greatly reduced energy dependence of the modified collimator. The increase over a range of 660 keV is only 15% compared with 50% with the conventional collimator. The resolution index (Fig. 5B), although an arbitrary parameter which ignores low-level response regions, shows a similar trend. Again it should be stressed that this is achieved without sacrificing overall performance. In fact, as has been shown, overall performance is increased.

## DISCUSSION

It is important to note that although only one pair of corresponding collimators was evaluated, the results of the comparison are not confined to this pair alone. It has been shown (*11*) that if the conventional collimator is considered to belong to a set of collimators, all with identical focal lengths and overall thicknesses and with hole-septa patterns magnified or minified versions of those of the conventional collimator, then the line-spread functions of all the collimators in the set have basically the same shape. One restriction is that the number of holes of any collimator in the set is not less than about 20. More specifically the line-spread function $l_m(mx)$ of the collimator in the set with hole-septa pattern related to that of the conventional collimator by scale factor (or magnification factor) m is given by

$$l_m(mx) = ml(x), \qquad (5)$$

where l(x) is the line-spread function of the actual collimator. The situation is similar for the set of collimators of modified design. Consequently the results of the comparison between corresponding collimators in the two sets, i.e. collimators having the same scale factor m, would be the same as those obtained with the actual modified and conventional collimators.

The conventional and modified collimators were built by a firm specializing in lead fabrication at costs of $210 and $340, respectively. These costs are certainly much lower than would be charged by a medical nucleonic firm for which overheads are much higher. We were assured that the costs of additional collimators of the two types would not be so unequal, the difference in the costs of the two prototypes being attributable to the difference in the number of holes and consequently in the amount of machining of the pins. The pins of the modified collimator were of uniform taper and were of lengths equal to the overall thickness of the collimator. The mid-penumbral shielding was achieved by reaming the apertures of the moulded collimator.

The weights of the modified and conventional collimators are the same. Consequently there are no additional loading or handling problems associated with the use of the modified collimator.

There is clearly an advantage in eliminating or virtually eliminating one of the variables (incident photon energy) in the specification of a focused collimator. However, collimators with resolution independent of photon energy may be of most value in quantitative scanning studies involving the simultaneous use of more than one isotope. This, a largely unexplored field, is likely to grow in importance as data processing facilities associated with scanning systems become more sophisticated and their use more widespread.

## SUMMARY

It is shown that the addition of mid-penumbral shielding at the inlet and outlet faces of a focused collimator considerably reduces the deterioration in resolution with increasing incident photon energy. In particular, it is shown that the comparative optimum response wavelength of a collimator incorporating mid-penumbral shielding increases from 2.3 cm for 27-keV photons, to 2.9 cm for 48-keV photons, and to 3.1 cm for 660-keV photons, whereas for an equivalent collimator of current conventional design, the corresponding comparative optimum response wavelengths are 2.6 cm, 3.7 cm, and 5.4 cm. The improvements in resolution characteristics are not achieved at the expense of overall performance, as defined using the figure of merit. In fact, in the case considered overall performance is improved.

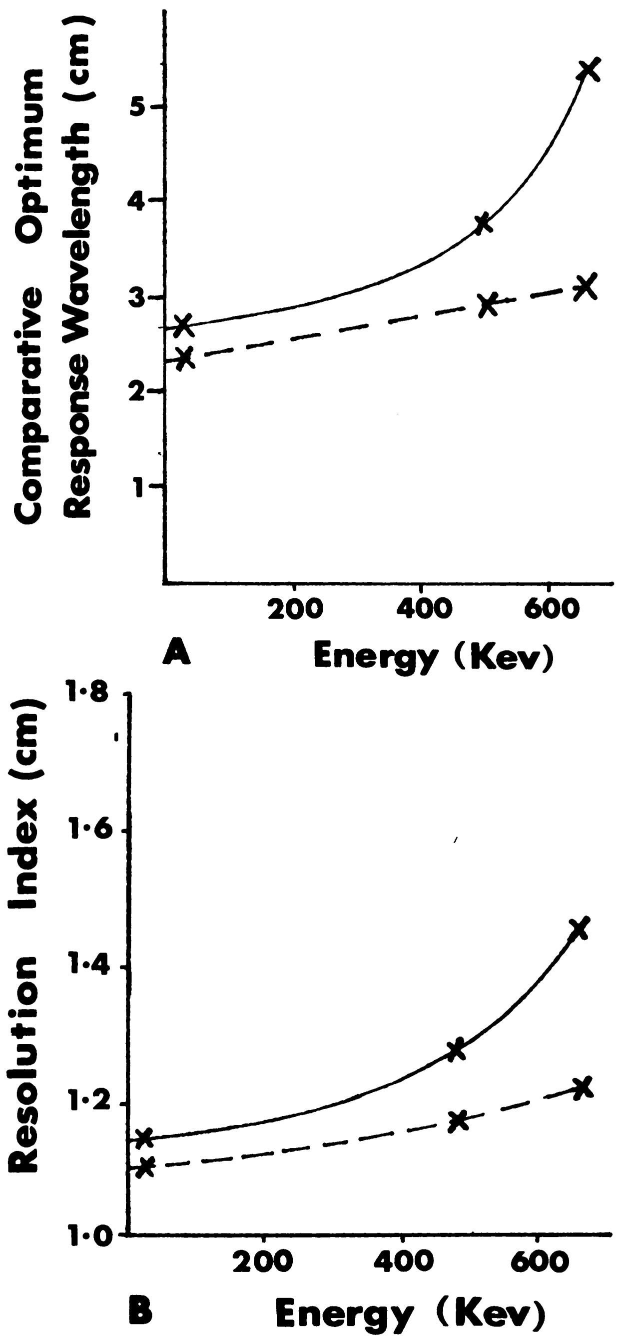


**FIG. 5.** A shows comparative optimum response wavelength as function of energy for conventional (continuous line) and modified (broken line) collimators. B shows resolution index as function of energy for conventional (continuous line) and modified (broken line) collimators.

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