ASSESSING THE PERFORMANCE OF RADIOISOTOPE SCANNERS: DATA ACQUISITION

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For the past several years attempts have been made by a number of users of radioisotope scanning devices to arrive at an acceptable method of assessing the performance of scanners. This is reflected by the report presented by Hine (*1*) at the 13th Annual Meeting of the Society of Nuclear Medicine; also the need for a common method of intercomparison has been emphasized by Mallard (*2,3*).

The most important parameter for which definitions have been made is spatial resolution. This has been defined by some as the distance between two point sources which are just distinguishable on the display. The dependence of this definition on the method of display makes it unsatisfactory. The more commonly accepted definition is the width of the 50% isoresponse volume at the level of the geometric focal plane. Although this parameter is easier to determine than that which depends on the separation of two point sources, it still does not give a complete description of the characteristics of the collimator. Harris *et al* (*4*) have pointed out that even when the 50% isoresponse volume is very small, the lower-percentage isoresponse volumes may contribute a significant amount of the output signal and thereby degrade the spatial resolution. This latter condition can be of particular importance when medium or low-energy collimators are used in conjunction with high-energy radionuclides. The result is a loss of resolution due to septal penetration.

It is the purpose of this paper to describe a simple, yet effective technique for measuring the performance of the data-acquisition system of a radioisotope scanning device up to the output of the pulse-height analyzer. The method involves the measurement of a simple line-source response function which is then used to calculate the modulation transfer function of the system. It must be emphasized that this assessment does not include the data-handling or display systems, but involves only the information available for data-processing and display. It is felt that the data-handling and display methods form an equally important but separate topic which is best dealt with as such. However, it should also be observed that the methods involving the use of the modulation transfer function are equally applicable to all sections of the scanning device from the collimator to the observer's eye (*5*).

MODULATION TRANSFER FUNCTION

In 1964, Beck (*6,7*) proposed the adoption of the modulation transfer function (or MTF) as a method of assessing the spatial resolution of a collimator. The modulation transfer function is that function which relates the modulation of the image signal to that of a sinusoidally varying object signal. The frequency of the output signal (in this case, a spatial frequency) is the same as the frequency of the input signal. In most situations a response function that is symmetrically shaped about the central axis will be involved, and under these conditions, there will not be a phase difference between input and output signals. For the concept of MTF to hold true, it is necessary for a linear relationship to exist between input and output. That is, the proportionality between input and output should depend only upon the frequency and not the contrast of the input signal.

For a sinusoidally varying input function as depicted by Fig. 1A, the modulation is

$$m_i = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}. \qquad (1).$$

Similarly, the modulation of the output function (Fig. 1B) will be given by

$$m_o = \frac{I'_{max} - I'_{min}}{I'_{max} + I'_{min}}. \qquad (2)$$

Thus the modulation transfer function M will be given by the ratio of the output to input modulations $M = m_o/m_i$.

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If the modulation of the input or object source is unity—that is, if the intensity varies between zero and a certain defined maximum (i.e. $I_{min} = 0$)—then the modulation of the image is a direct measure of the modulation transfer function.

The modulation transfer function varies with the spatial line frequency of the source. It usually has a value of 1 or 100% at zero line frequency and falls toward zero as the line frequency is increased. A value of zero for the modulation transfer function implies that the line structure of the object can no longer be observed in the image under any conditions. A negative modulation transfer function implies that the line structure will be imaged 180 degrees out of phase with the object—a condition known as spurious resolution. This has been demonstrated by Beck (*6*).

The fact that the modulation transfer function varies in a continuous fashion over a range of spatial line frequencies automatically implies that there is a gradual rather than a sharp cut-off in the ability with which increasing line frequencies can be distinguished. This method of expressing resolution is an improvement over the two point-source definition because the latter implies that there is one distance at which the sources can be distinguished and another distance, differing only slightly from the first, at which the sources are indistinguishable. Experience indicates that this is not the case.

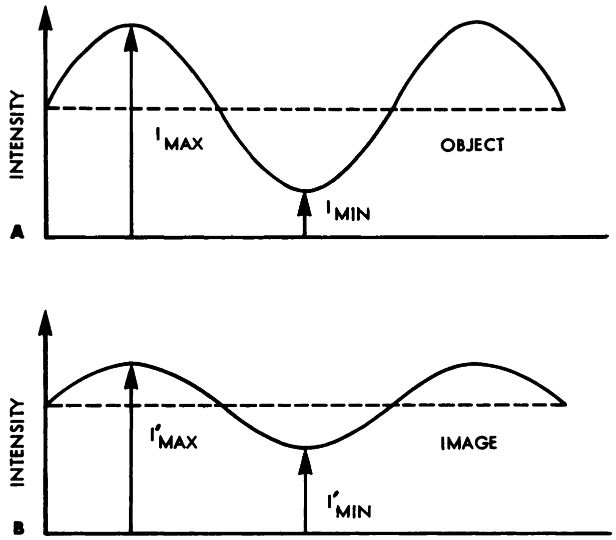

FIG. 1. A: Representation of modulation of sinusoidally varying object. B: Representation of modulation of image resulting from A.

METHODS OF MEASURING MODULATION TRANSFER FUNCTION

Beck (*6*) originally suggested the use of a wedge-shaped phantom analogous to the Sieman's star phantom used in optics. A photograph of such a phantom is shown in Fig. 2A from which it can be seen that the activity varies in a crenelate or square-wave fashion at any one radius. A crenelate object of this type can be manufactured fairly simply and is easy to use if one adopts the technique described by Beck (*6*). However, it does suffer from the disadvantage that it gives rise to enhanced modulation-transfer-function values at frequencies greater than zero. This enhancement of the modulation transfer function due to the square-wave nature of the object is shown in Fig. 3 in which the modulation transfer function for a crenelate phantom is compared to that for a phantom with a sinusoidally varying intensity pattern.

In addition to this disadvantage, the resolution volume of the detector, although centered on one radius or spatial frequency, will in fact include a range of spatial frequencies.

Although it gives a more accurate modulation transfer function, the sinusoidal phantom (Fig. 2B) also suffers from the latter problem. Furthermore, it is difficult to manufacture. Indeed, it may not be possible to manufacture it unless one enjoys the services of a well-equipped machine shop.

Because the modulation transfer function is, in fact, the Fourier transform of the line-source response function, it seems reasonable to use the latter as a means of arriving at the modulation transfer function. Such a technique has been applied to radiographic systems by Rossman (*8*). If F(x) is the line-source response function, then the modulation

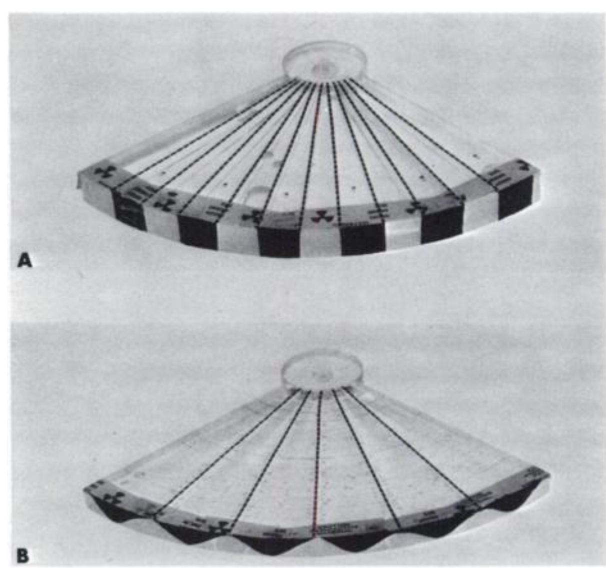

FIG. 2. A: Siemen's star phantom of crenelate type. Black masks indicate wedge portions containing radioactive material. B: Siemen's star phantom with sinusoidally varying cavities. Black masks show portions containing radioactive material.

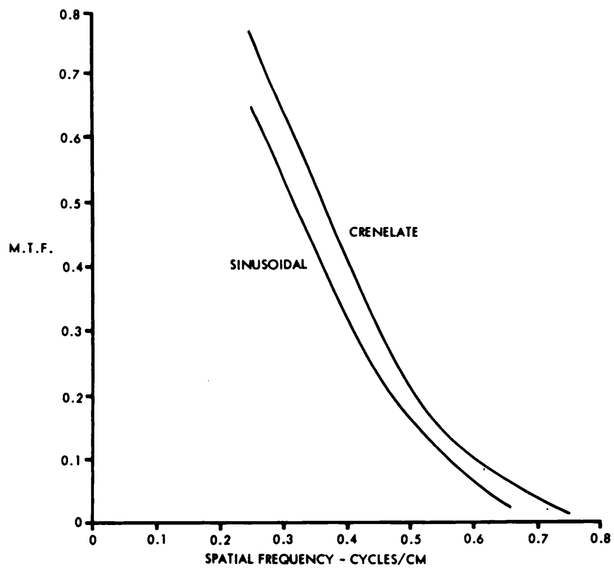

FIG. 3. Modulation transfer functions resulting from two phantoms shown in Fig. 2. Crenelate phantom gives enhanced MTF.

transfer function $F(\nu)$ is expressed mathematically by the equation

$$F(\nu) = \frac{\int_{-\infty}^{\infty} F(x) \cos 2\pi\nu x \, dx}{\int_{-\infty}^{\infty} F(x) \, dx} \qquad (4)$$

where the integral of the line-spread function in the denominator acts as a normalizing function.

This equation applies to the cosine transform only, and since the spread functions encountered in practice are usually symmetrical, it may be considered the only term involved. Transformations involving a symmetrical spread function and a sine transform are zero for all frequencies because the negative terms exactly cancel the positive ones. In cases when slight asymmetry is involved, the contribution of the sine term may be considered negligible to a first-order approximation. If, however, the asymmetry becomes excessive, then the sine term must be included in the transform.

The practical way of evaluating the transform expressed by Eq. 4 is illustrated by Fig. 4 for one particular frequency. The abscissa is divided into small uniform increments of the whole range of the spread function at $x_{-m}, \ldots x_1, x_2, \ldots x_i, \ldots x_n$ as shown; the corresponding value of the function $\cos 2\pi\nu x_i$ is multiplied by the value of the spread function at each point, and finally the resulting products are summed over the whole range of the spread function. The equation corresponding to Eq. 4 which expresses this step-by-step summation process is

$$F(\nu) = \frac{\sum_{i=-m,n} F(x_i) \cos 2\pi\nu x_i}{\sum_{i=-m,n} F(x_i)} \qquad (5)$$

where i ranges from the point corresponding to the smallest measurable value of the spread function at —m on one side to the point corresponding to the smallest measurable value at n on the other side. When symmetry exists, —m should equal —n.

The summation described above gives the numerator at the selected frequency, and the denominator is the same summation without the cosine term as a multiplying factor; it is the integral of the response function. The process is repeated for successively higher frequencies (except that the denominator must be computed only once) until a frequency is reached beyond which the numerator becomes negligible. The ratio gives the modulation transfer function as a function of spatial frequency.

Such a procedure can be carried out on a desk calculator. This, however, is tedious, and a computer program has been written to perform the same task. This program in Fortran IV is available on request.

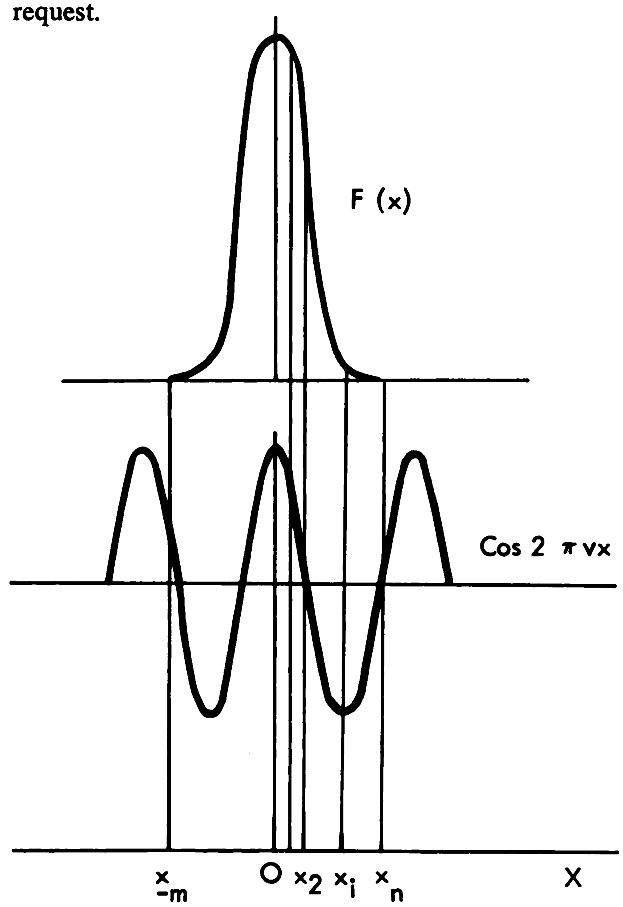

FIG. 4. Diagram illustrates method used to calculate value of MTF of line-source spread function F(x) at frequency ν.

This technique using a line-source response function has been applied to scanning devices of both the moving and stationary-detector types (Cradduck, Fedoruk and Reid *9,10*). When stationary-detector devices or scintillation cameras are involved, this technique is easier to apply than one which involves the use of a phantom. If a phantom is used, then a dual-parameter analyzer must be used to analyze the position signals. Even then, this technique is difficult to perform although Gottschalk (*11*) has reported on such a method. When analysis of the position signals in only one direction (perpendicular to the line source) is required, a single-channel analyzer and multichannel analyzer in coincidence or even two single-channel analyzers in coincidence are sufficient.

RESULTS

In the present investigation modulation transfer functions have been obtained for the data-acquisition system of a Picker Magnascanner with three collimators. These are numbers 2102, 2107 and 2102B, respectively designated as: fine focus (¼ in., medium energy, 100–400 kev), medium focus (½ in., medium energy, 100–400 kev) and coarse focus (½ in., low energy, 150 kev).

The results obtained can be used to compare the three collimators because the same amplifier and analyzer were used throughout and were set at the standard settings for the radionuclides studied. Under normal circumstances these latter components of the data-acquisition system will have little or no effect upon the over-all modulation transfer function of the system.

The modulation transfer functions have been measured using line sources of ^{125}I (27 kev), ^{99m}Tc (140 kev) and ^{131}I (364 kev) placed at the geometrical focal plane of the collimators and at positions both closer to and further from the face of the collimator.

Let us first consider the variation in modulation transfer function with energy. The 2102 collimator is a medium-energy collimator which might be expected to have a reasonably good modulation transfer function for all three radionuclides or energies considered. This is confirmed by the results shown in Fig. 5 in which the modulation transfer functions for all three radionuclides are comparable. The slight improvement of the low-energy radionuclides over ^{131}I is due to less septal penetration although this effect is shown to be minimal. The 2107 collimator exhibits similar characteristics although in this case the modulation transfer functions are all poorer than for the 2102 because it is a medium rather than a fine-focus collimator.

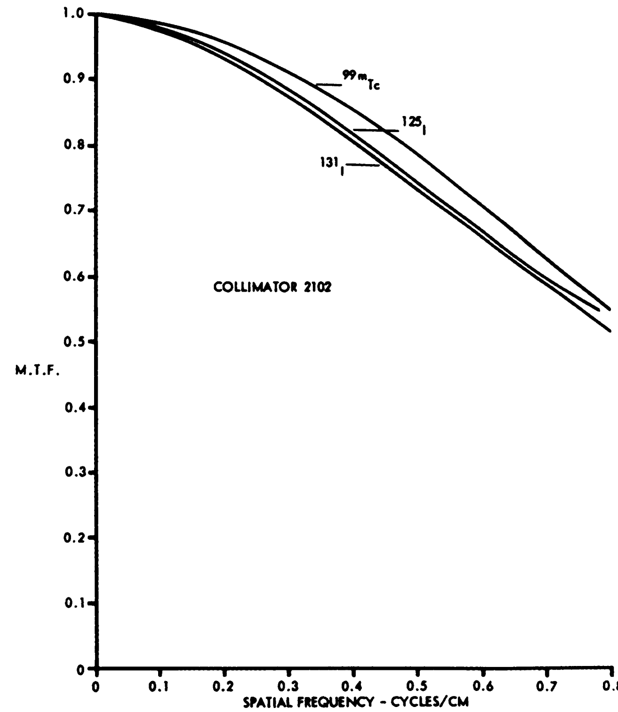

FIG. 5. MTF's for data-acquisition system at different energies using collimator 2102.

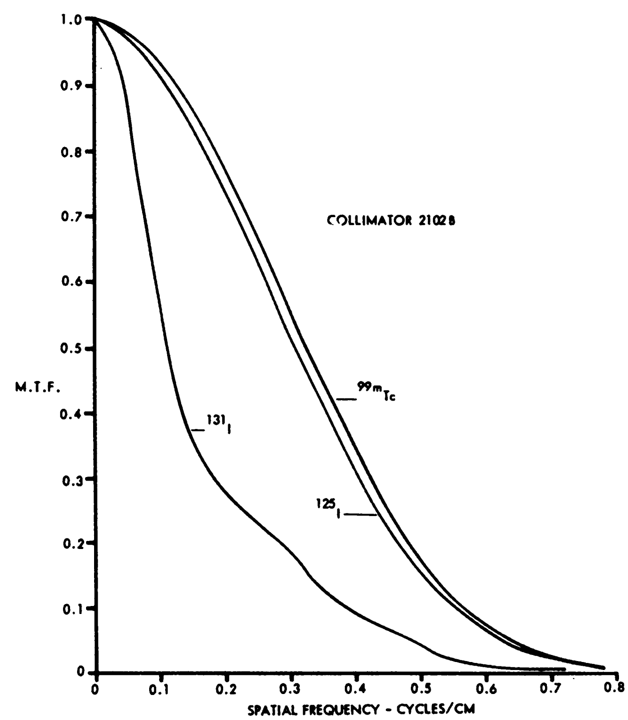

FIG. 6. MTF's for data-acquisition system at different energies using collimator 2102B.

Although the response to ^{99m}Tc and ^{125}I is much the same as for the 2107 collimator, with the low-energy collimator (2102B) the response to ^{131}I is considerably degraded (Fig. 6). This result

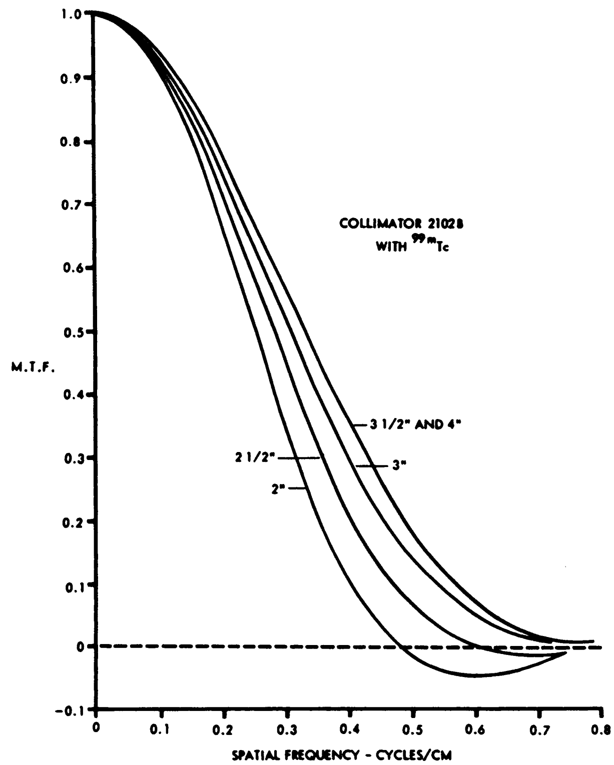

FIG. 7. MTF's at different distances from face of collimator for ^{99m}Tc and collimator 2102B.

demonstrates very conclusively the poor results that are to be expected when a low-energy collimator is used in conjunction with medium or high-energy radionuclides.

It is of interest to note that at the level of finest resolution of the 2102B collimator the full widths at half maximum of the line-source response functions are ½ in. for ^{99m}Tc and ⅝ in. for ^{131}I. These values are in reasonable agreement with one another. It is the wide base of the line-source response function which has such a deleterious effect upon the resolving capability of the collimator. The "breakaway" point of the response function for ^{131}I occurs at about 30% whereas it is not visible in the curves for ^{99m}Tc.

Thus, if full-width-at-half-maximum values for the 2102B collimator were to be quoted at ^{99m}Tc and ^{131}I energies, little information would be available. On the other hand, the modulation transfer functions for the same collimator at these two energies demonstrate every clearly the poor response to the higher energy.

As far as variations with distance from the collimator face are concerned, Fig. 7 shows the variation in modulation transfer function for the 2102B collimator with ^{99m}Tc. Between 2½ in. and 4 in. from the collimator face, the variation in modulation transfer function is slight. The same was true for ^{125}I with the 2102B collimator and for ^{131}I with the 2102 collimator. The 2107 collimator exhibited a very uniform response over a depth of 2 in. centered on the focal plane.

SENSITIVITY

The second criterion of performance is that of sensitivity. The sensitivity and spatial resolution of radioisotope scanning devices are two closely related parameters. The sensitivity depends largely upon the total solid angle subtended by the detector at the source. If this solid angle is made as large as possible, then the spatial resolution is likely to be poor.

The sensitivities of both moving-detector and stationary-detector scanners have in the past been defined in terms of the counting-rate response to a point source of radiation. Such figures are certainly useful for comparison between instruments of the same type, but when comparison is required between scanners of different types, this method fails to give useful information. Referring to Fig. 8, it can be seen that the former looks at the area of interest element by element on a sequential basis whereas the latter views the whole area of interest simultaneously (which might be considered as being composed of the same number of elements as before).

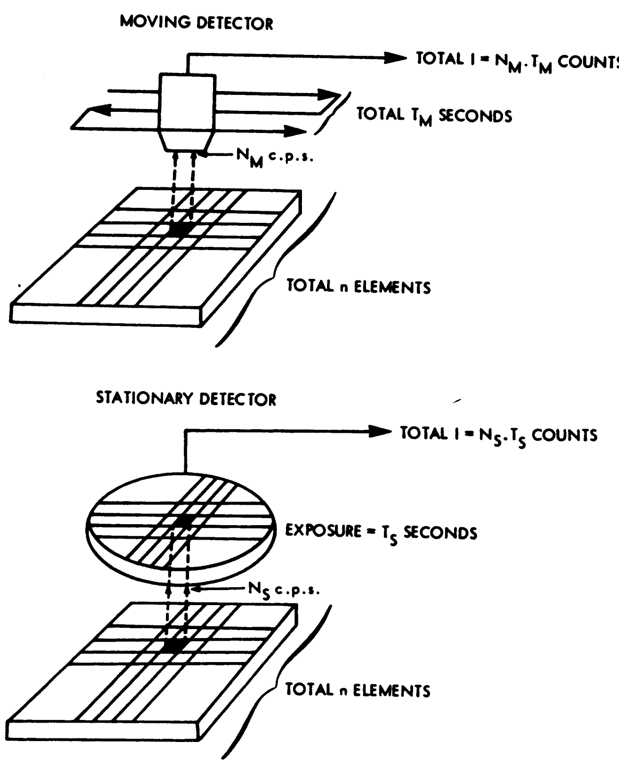

FIG. 8. Diagram to illustrate basic difference between moving detector scanners (upper) and stationary detector scanners (lower) from point of view of sensitivity.

Regarded in this manner, it seems more logical to express the sensitivity of a scanning device in terms of the counting-rate response to a sheet source of activity extending over the whole field of view. Thus a moving-detector scanner may take T_M seconds to scan n elements, each of which gives rise to N_M counts per second, in order to achieve a final image content of I counts. On the other hand, the stationary detector scanner will be required to be exposed to T_S seconds in order to collect the same number of counts I from the same number of elements, n, where in this case each of the elements is giving rise to N_S counts per second.

Thus it is suggested that the sensitivity of a radioisotope scanning device should be expressed in terms of the counting rate recorded from a distributed sheet source of activity covering the whole field of view of the detector.

This can be accomplished in one of two ways. The first method is to integrate the total number of counts under the line-source response function. This method requires an accurate measure of the activity per unit length of the line source which will give the activity per unit area because it is moved across the field of view of the detector; thus, the sensitivity can be expressed as counts per second from a sheet source of activity 1 $\mu c/cm^2$.

The second method is to make up a slab source 1 cm thick containing a known activity per cm^3. Providing this source covers the whole field of view of the detector, the result will also be a measure of activity in terms of counts per second from a sheet source of activity 1 $\mu c/cm^2$.

Both these methods are equivalent and may be used with moving, stationary and multicrystal or hybrid (*12*) scanners. The second method was chosen for the measurements described here because it is simpler to assay the source used in a slab phantom than to determine the activity per unit length of the line source. Table 1 shows the sensitivities for the various collimators with the radionuclides used. These sensitivities are expressed in counts per second per number of gamma rays emitted per second from one square centimeter of the slab source.

Table 2 shows the relative sensitivities with respect to the 2107 collimator at the various energies and as expected from theoretical considerations. The low-energy 2102B collimator gives considerably greater sensitivity (about 3 times) than is to be expected. The measurements have been checked and are confirmed by the measurements of Hine (*13*) made independently using the integral of the line-source spread function. The difference between the measured values and theory remain unexplained.

TABLE 1. SENSITIVITY

	Sensitivities ($\times 10^{-3}$)*		
Collimator	^{125}I (1.43 gamma/disn.)	^{99m}Tc (0.9 gamma/disn.)	^{131}I (0.82 gamma/disn.)
2107	4.85	6.36	11.65
2102	0.588	0.572	1.37
2102B	12.35	16.95	46.9

* cps/gamma-ray emitted/sec/cm^2.

TABLE 2. RELATIVE SENSITIVITIES

	Relative sensitivities			
Collimator	^{125}I	^{99m}Tc	^{131}I	Theory
2107	1.00	1.00	1.00	1.00
2102	0.121	0.09	0.118	0.11
2102B	2.53	2.67	4.02	0.65

FIGURE OF COMPARISON

Resolution (modulation transfer function) and sensitivity (counts per second from the sheet source) are of little value when expressed as separate entities. If one reverts to the concept of the 50% isoresponse diameter as a measure of resolution, then the sensitivity expressed as the response to a sheet source is directly proportional to the square of the resolution ($S \propto R^2$ where S is the sensitivity and R is the 50% isoresponse diameter). Because spatial resolution and sensitivity are so closely related, we may introduce a "figure of comparison" C which is the product of the modulation transfer function and sheet-source sensitivity at each spatial frequency. Beck (*6*) has already introduced a "figure of merit" Q which is a fairly complex function of resolution and sensitivity and is applicable to moving-detector scanners. However, it cannot be determined for stationary-detector scanners because it embodies the counting rate arising from activity in the "resolution volume." No such volume exists for a scintillation camera because it views the whole area of interest at one time. For this reason it is rejected because, to be useful, a figure of comparison should allow comparison between instruments of different types as well as between instruments of the same type.*

* Since this paper was originally submitted for publication it has been established that Beck's "figure of merit" Q, is identical to the product of the plane-source sensitivity and the square of the MTF. The "figure of comparison" C described above is therefore a first approximation to the "figure of merit," and although it provides a measure of system performance, it might best be replaced by Q in all systems both moving and stationary.

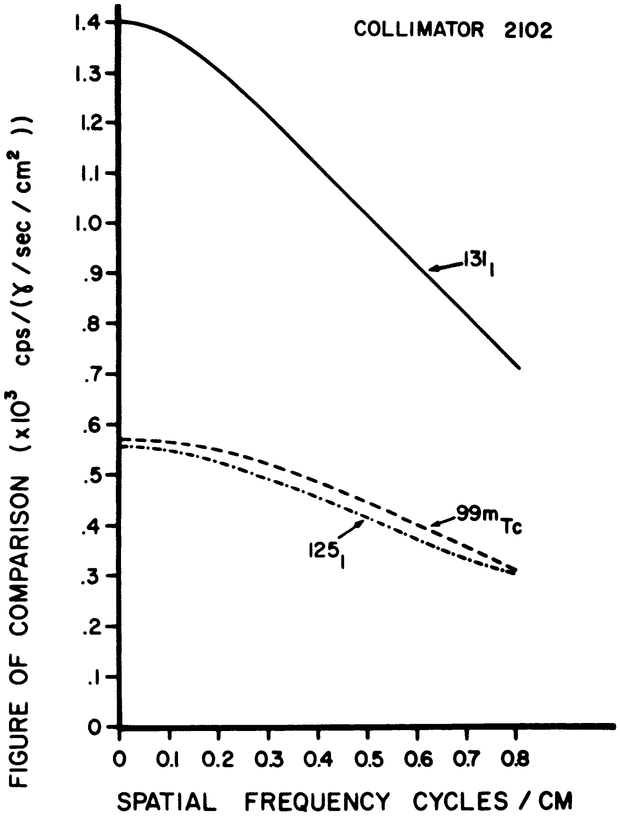

FIG. 9. Plots of figure of comparison for collimator 2102.

Figures 9 and 10 are comparable to Figs. 5 and 6, respectively, and it will be observed that the figure of comparison for ^{131}I is the largest in both cases at the spatial frequency of 0 cycles/cm. However, in the case of the low-energy collimator 2102B, the response to ^{131}I falls off very rapidly with increasing spatial frequency, indicating the degree to which septal penetration degrades the collimator response.

CONCLUSION

The intention here is not to demonstrate the capabilities of a particular scanner but to set down a standardized and comparatively simple method for measuring the performance characteristics of the data-acquisition system of any scanner. The full width at half maximum of a point-source response function does not describe the spatial resolution of a scanner because it fails to describe the other characteristics of the point-source response function. Also, the point-source response function is difficult to obtain by measurement whereas the line-source response function is somewhat easier to determine. Furthermore, although the sensitivity of two different systems to a point source at the focal plane may be identical, the respective sensitivities to a plane source may differ considerably, and it is this response that is of practical value.

Finally, it must be emphasized that the work described in this paper has dealt only with the information available for data manipulation and display. The modulation transfer function has not been applied to the data-handling and display systems although this could be done. It is the fact that the modulation-transfer-function type of analysis can be applied to each part of the system and then embodied into an over-all modulation transfer function for the whole system which makes it such a useful characterization of performance.

SUMMARY

A method of assessing the performance of both moving and stationary-detector scanners is described. This method uses the line-source response function to calculate the modulation transfer function of the system. The modulation transfer function is the method which is being used increasingly to describe the performance of optical and radiographic systems.

In addition to the modulation transfer function, a method of defining the sensitivity to a sheet source of activity is described. This sensitivity is then combined with the modulation transfer function to give a "figure of comparison."

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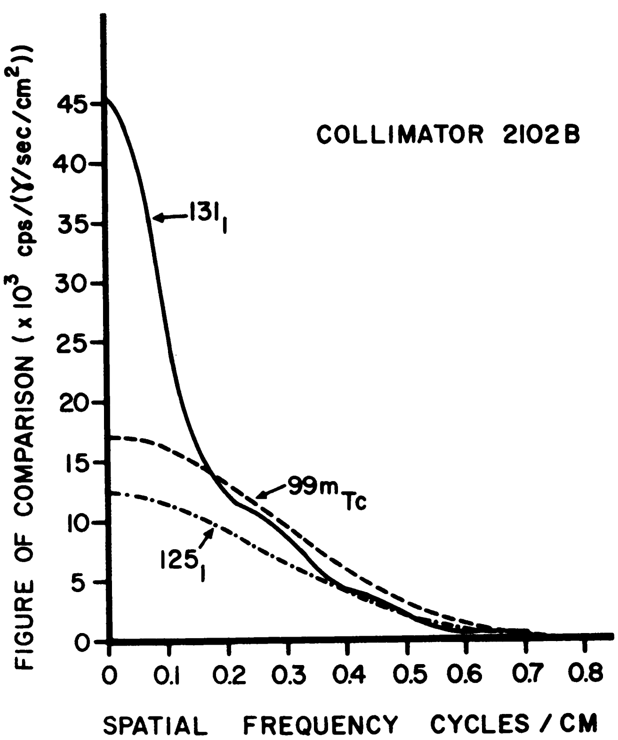

FIG. 10. Plots of figure of comparison for collimator 2102B.

assistance has been in the form of critical discussions at each stage of the work and provision of computational facilities at the University of Saskatchewan (Saskatoon Campus) Computation Centre. Mrs. P. Klotz made many of the measurements from which the line-source response functions were drawn.

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APPENDIX

The following computer program was written in Fortran suitable for the University of Saskatchewan's I.B.M. 7090.

```
C       PROGRAM CALCULATES MTF VS
        FREQUENCY IN CYCLES/CM
C       GIVEN THE LINE SOURCE
        RESPONSE FUNCTION (LSRF) AT
        SET INTERVALS
C       INITIALIZE
        DIMENSION A(200)
C       FORMATS
    1   FORMAT (2I3,IF4.1,1F6.2,I2)
    2   FORMAT (20F4.1)
    3   FORMAT (I10,2F10.3)
    4   FORMAT (8X,2HNO,3X,4HFREQ,9X,
        4HMTFC)
C       PROGRAM
  100   READ 1, NDIM,LIM,FINC,HINC,
        NEND
C       NDIM MUST BE DIVISIBLE BY 2,
        NEND MUST BE -1, 0, OR +1
  101   READ 2,(A(I), I=1, NDIM)
        WRITE (6,4)
        DENOM=0.
        J=NDIM-1
        DO 10 I=1,J
   10   DENOM=DENOM+A(I)
   13   DO 11 N=1, LIM
C       THIS EXTENDS MTF OUT TO
        ((LIM-1)*1/FINC) C/CM IN
        FREQUENCY
        DIVI=O.
        XN=N
        FREQ=(XN-1.)/FINC
C       FINC IMPLIES INCREMENTS OF
        1/FINC C/CM IN FREQUENCY
        DO 12 I=1,J
        LINC=NDIM/2
        ETA=(I-LINC)
        ETA=ETA/HINC
C       HINC IMPLIES INCREMENTS OF
        1/HINC IN LSRF
        ANGLE=6.28*FREQ*ETA
   12   DIVI=A(I)*COS(ANGLE)+DIVI
        SWR1=DIVI/DENOM
   11   WRITE (6,3) N,FREQ,SWR1
        IF (NEND) 100,8,101
    8   STOP
        END
```

DESCRIPTION

This program is a modification of the previous MTF programs and is more generalized. A choice is given concerning the increments in the line-source response function and the frequency to which the MTF calculations are extended. A maximum of 200 values in the line-source response function is allowed. All other values and limits are open. It is possible to change the increments and limits between read-in operations of input data.

Input Data:

Card #1 Program initialization. Five values must be provided by this card. They are:

NDIM Cols. 1–3	a 3-integer number giving the total number of line-source-response-function values that will be read in. NDIM must be an even number.
LIM Cols. 4–6	a 3-integer number giving the limit in frequency to which the MTF is to be calculated. This end limit will have the value ((LIM−1)*1/FINC) cycles/cm.
FINC Cols. 7–10	a F4.1 number giving the increments in frequency at which the MTF will be calculated. These increments are given by 1/FINC. Thus 0.025 cycle/cm intervals implies a FINC value of 40.0.
HINC Cols. 11–14	a F6.2 number giving the increments in centimeters at which values of the line-source response function are sampled. These intervals are given by 1/HINC so that 2.5-mm intervals would require a value of 4.0 for HINC.
NEND Cols. 15–16	has the values −1, 0, or +1 only. −1 implies that the program will return for new values of NDIM, LIM, FINC AND HINC after one calculation; i.e. new data format is to be accepted. 0 implies the end of input data and final program halt. +1 implies return for more input data under the same values of NDIM, LIM, FINC AND HINC.

Example:

Column #	123	456	7890	123456	78
	050	041	40.0	004.00	+1
	A	B	C	D	E

A: 50 line-source response function values.
B: MTF to 1 cycle/cm.
C: MTF at 0.025 cycle/cm intervals.
D: line-source-response-function values at 2.5-mm intervals.
E: return for more input data using same increments and limits.

Card #2: Line-source response values.
Each card contains 20 values of the line-source response function in F4.1 format. The program will read-in these values until it has read-in sufficient values to fulfill the condition imposed by NDIM. The values should read from left to right across the line-source response function with the 100% value appearing in the (NDIM/2) position. If there are 32 samples of line-source-response-function values, then the 100% must appear at the 16th position and value 31 will correspond to value number 1.

Output Data:

The program will print out three columns of information. These are headed NO., FREQ., MTF and they are, respectively, the sequence number of the MTF determination, the frequency in cycles/cm and the corresponding value of the MTF.

Example:

NO.	FREQ.	MTF
1	0.000	1.000
2	0.050	0.982
3	0.100	0.929
4	0.150	0.846
5	0.200	0.742
6	0.250	0.624
7	0.300	0.503
8	0.350	0.387
9	0.400	0.283
10	0.450	0.196
11	0.500	0.126
12	0.550	0.075
13	0.600	0.040
14	0.650	0.018
15	0.700	0.007
16	0.750	0.003
17	0.800	0.003
18	0.850	0.005
19	0.900	0.007
20	0.950	0.008
21	1.000	0.008