A Simple Method for Determining the Modulation Transfer Function in Digital Radiography

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***Abstract*— We developed a simple method for determining the presampling modulation transfer function (MTF), which includes the unsharpness of the detector and the effect of the sampling aperture, in digital radiographic (DR) systems. With this method, the presampling MTF is determined by the Fourier transform of a "finely sampled" LSF obtained with a slightly angulated slit in a single exposure. Since the effective sampling distance becomes much smaller than the original sampling distance of the DR system, the effect of aliasing on the MTF calculations can be eliminated. We applied this method to the measurement of the presampling MTF of a computed radiographic (CR) system and discussed the directional dependence, the effect of exponential extrapolation, and the effect of different sampling distances. We showed that the technique of multiple slit exposure and exponential extrapolation of the LSF tail, which has been commonly used in analog screen-film systems, can be employed in DR systems. Furthermore, we determined the glare fraction, by means of a lead-disk method, in order to estimate the component of low-frequency drop mainly due to "glare." The results showed that the value of glare fraction was 5–6.5% and slightly dependent on the sampling distance.**

I. Introduction

MODULATION transfer function (MTF) has been used to characterize the resolution properties of conventional analog X-ray imaging systems and their components, such as screen-film systems [1]. However, the MTF's in digital radiographic (DR) imaging systems need to be interpreted carefully because of the aliasing effect, which is caused by discrete data sampling [2].

A DR system generally consists of an x-ray source, a detector which records X-ray photons transmitted through the patient, a data acquisition system with analog-to-digital conversion with a log or linear amplifier, a computer system for data processing, and a display device. The "overall" two-dimensional MTF in the digital system [2] can be expressed by

$$\mathrm{MTF}(u,v) = \left\{ [\mathrm{MTF}_A(u,v) \cdot \mathrm{MTF}_S(u,v)] \right. \quad (1)$$

$$\left. * \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} \delta(u - m/\Delta x, v - n/\Delta y) \right\} \cdot \mathrm{MTF}_F(u,v) \cdot \mathrm{MTF}_D(u,v) \quad (2)$$

where $\mathrm{MTF}_A(u,v)$, $\mathrm{MTF}_S(u,v)$, $\mathrm{MTF}_F(u,v)$, and $\mathrm{MTF}_D(u,v)$ are MTF's of analog input, sampling aperture, filter, and display aperture, respectively, and $*$ denotes convolution. The factors m and n are integers, and Δx and Δy are sampling distances in the x and y directions, respectively. The product of the $\mathrm{MTF}_A(u,v)$ and $\mathrm{MTF}_S(u,v)$ is referred to as the "presampling" MTF of a digital imaging system [2], $\mathrm{MTF}_{PRS}(u,v)$, which includes the geometric unsharpness if not negligible, detector unsharpness, and the unsharpness of the sampling aperture. The "digital" MTF of the system can be obtained by convolution of the $\mathrm{MTF}_{PRS}(u,v)$ with the comb function in the frequency domain. Thus, the overall MTF can be calculated by multiplying the digital MTF with $\mathrm{MTF}_F(u,v)$ and $\mathrm{MTF}_D(u,v)$, when we take into account the filter and display MTF's.

It should be noted that the digital MTF and the overall MTF as shown in (1) may incorrectly indicate the resolution capability of a digital system because both MTF's might include a false response due to aliasing, while the presampling MTF can characterize inherent resolution properties of a digital imaging system. Fujita *et al.* examined the presampling MTF of a digital subtraction angiography (DSA) system [3], and also reported the resolution properties of a computed radiographic (CR) system with photostimulable phosphor plate (so-called imaging plate or storage phosphor plate) in detail [4], [5]. In these reports, the presampling MTF was determined *in frequency domain*, by averaging the two (or four) Fourier transforms of two (or four) line spread functions (LSF's) obtained from two (or four) different alignments of the slit relative to the sampling coordinate.

In this paper, we describe a simple method for measuring the presampling MTF by the Fourier transform of a "finely sampled" LSF which is obtained with a slightly angulated slit *in spatial domain* [6]. Results obtained with a CR system for various digital parameters are discussed.

II. Methods

A. Determination of the Presampling MTF

The method for determining the presampling MTF is described below. Assume that a slit is positioned at a slight angle (usually $< 2°$) to the direction perpendicular to the

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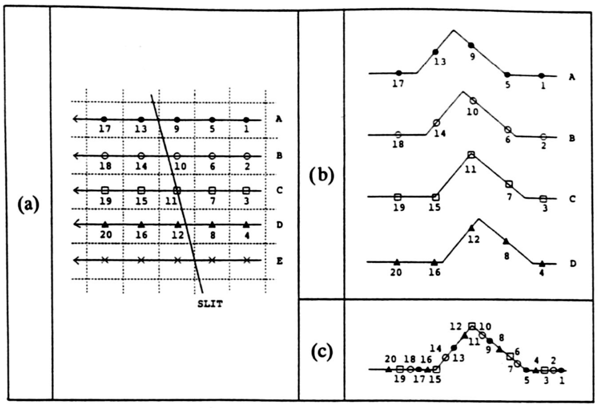

Fig. 1. Schematic diagram showing the generation of a composite (finely sampled) LSF (c) from the LSF's corresponding to the various alignments (b) of the slit (a) relative to the sampling coordinate.

scanning direction in deriving the LSF. Fig. 1(a) shows the slit placed in the direction approximately perpendicular to the scanning direction (for illustration, the slit angulation is exaggerated). Because of the slight angulation of the slit, four LSF's at locations A, B, C, and D shown in Fig. 1(b), which correspond to four different alignments of the slit relative to the sampling coordinate, can be obtained in the range between the two different half-pixel-shifted alignments [A and E in Fig. 1(a)]. Each LSF consists of five discrete data with the same sampling distance, Δx. Thus, a total of 20 combined data in the order 1, 2, 3, $\cdots$, 20, acquired from the four LSF's can be employed to generate a "composite LSF" ("finely sampled LSF") with a smaller sampling distance (effective sampling distance), as shown in Fig. 1(c). The composite LSF is then Fourier transformed to obtain the presampling MTF by employing the software which is basically the same as that used for MTF calculation for conventional screen-film systems. As mentioned above, since the effective sampling distance becomes smaller, the effect of aliasing on the measured MTF can be eliminated; thus, the presampling MTF is determined.

In the method described above, the effective sampling aperture $\Delta x'$ and the slit angle θ [the angle between the slit and the vertical direction in the example of Fig. 1(a)] can be simply obtained as $\Delta x/n$ and $\tan^{-1}(1/n)$, respectively, where the sampling distance in two orthogonal directions is assumed to be equal. Here, the value of n is obtained by adding 1 (one) to the number of pixels which exist between two different half-pixel-shifted (or center) alignments. In the case of Fig. 1(a), $\Delta x' = \Delta x/4$ and $\theta = \tan^{-1}(1/4) \fallingdotseq 14°$.

The positioning of the center and half-pixel-shifted alignments can be made by utilizing the "digital" MTF determined directly by Fourier transform of the various LSF's obtained from lines, A, B, C, $\cdots$, etc. The maximum and zero values of the digital MTF at the Nyquist frequency correspond to the center and half-pixel-shifted alignments, respectively [3]—[7]. In practice, when determining the composite LSF, the rearrangement of data from lines A–D in Fig. 1(b) is not required. On the contrary, the data can be rearranged from the direction parallel to the slit, namely in the order of 1–4, 5–8, $\cdots$, etc. In this procedure, the data should be continuous and smooth for 4→5, 8→9, and so on, as will be shown later.

Another method of rearranging the data for the composite LSF is described as follows. Geometrically, the pixel values at the four consecutive positions just above position 9 can be obtained and used in place of those at positions 8, 7, 6, and 5, respectively, in Fig. 1(a). Moreover, the pixel values at positions 4, 3, 2, and 1 can be obtained from the four consecutive positions further above positions 9 (in the order of 9, 8, 7, 6, 5, 4, 3, 2, and 1). Similarly, the pixel values at positions 13–16 and positions 17–20 can be determined by obtaining the pixel values from the eight consecutive positions just below position 12. Namely, if the data of a slit image approximately parallel to the slightly angulated slit are obtained [from the upperside to the bottom passing through positions 9, 10, 11, and 12 in Fig. 1(a)], another finely sampled LSF similar to that shown in Fig. 1(c) can be determined. Since a large number of data obtained with a long slit over a wide area of the image plane are required by this method, however, it may not be feasible to implement this method when geometrical distortion and nonuniformity of the imaging system are not be negligible. In addition, similar to the former method, accurate information about the position of center or half-pixel-shifted alignment will be necessary for accurate determination of the slit angulation by use of the relationship $\Delta x' = \Delta x \cdot \tan\theta$. In the present study, the former method for data rearrangement (as shown in Fig. 1) was employed.

B. Experimental

An FCR-101 computed radiographic system (Fuji Photo Film Co., Ltd., Japan) installed at Yamaguchi University Hospital (Ube City, Japan) was employed in our study. An imaging plate (IP: photostimulable phosphor plate), ST type II or III (for standard applications), used as an image detector was used for this investigation. The effect of the difference of the type of IP (II and III) on the presampling MTF was negligibly small [6], [7]. The sampling distances used for data acquisition were 0.1, 0.15, and 0.2 mm. These sampling distances are employed with the imaging plate having the different sizes of 251 × 200 mm (10″ × 8″), 251 × 302 mm (10″ × 12″), and 352 × 352 mm (14″ × 14″) and 352 × 428 mm (14″ × 17″), respectively. The signal from the laser readout system was logarithmically amplified and digitized with a 8-bit gray scale. For further analysis, the digital data (raw data without any image processing) were transferred to a PC-9801 model VX21 personal computer (NEC, Japan) via magnetic tape.

A slightly angulated lead slit ($< 2°$) of 0.01 mm slit width at 80 kV was employed in order to obtain the slit image. It should be noted that if the slit angle is too large, the sufficient number of data points in a composite LSF to fill the data in between the neighboring pixels may not be obtained. A finely sampled LSF was Fourier transformed to determine the presampling MTF using the technique described earlier. Here, the "digital" characteristic curves [8], [9] relating the pixel value to the relative exposure were measured and used for the linearization. In addition, the correction for the effect of the slit

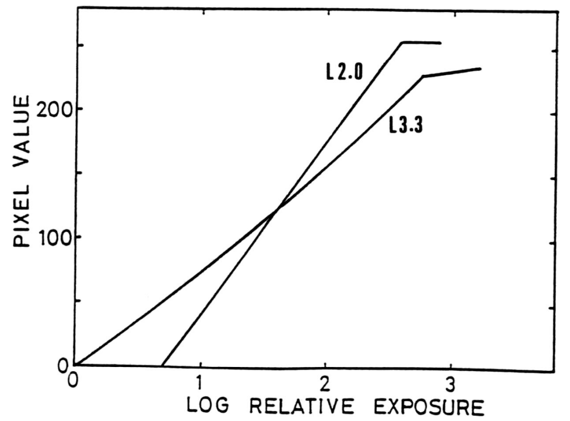

Fig. 2. Measured digital characteristic curves for two various latitude settings L, 2 and 3.3, where the sensitivity setting was kept at 200.

width was not included because the effect is negligibly small relative to the response (presampling MTF) to be measured.

C. Characteristic Curve

Fig. 2 shows the measured digital characteristic curves for two settings of latitude L, 2 and 3.3, where the setting of sensitivity was kept at 200. Initially, we used an inverse-square sensitometric technique to determine the digital characteristic curves. The X-ray exposure was made at 80 kV with 0.5 mm thick copper and 4 mm thick aluminum filters at the tube. We also experimentally confirmed that the time-scale technique was also feasible for determining the digital characteristic curves [10]. Details of the measurement of these curves were described elsewhere [4], [5], [10], [11].

D. Glare

One of the important factors degrading image contrast is "glare." Glare is mainly attributable to the scattering of light emitted from the IP during laser scanning of the IP for measuring the stimulated luminescence. The low-frequency drop in the MTF, which commonly results from veiling glare in an imaging intensifier [12], is sometimes included for evaluation of the system performance. In the determination of the presampling MTF, we eliminated the component of glare from the finely sampled LSF by truncating the tail portion of the LSF and then extrapolating it by an exponential function. However, in order to estimate the degradation due to glare, we determined the *glare fraction*, defined as the ratio of the glare component to the total light output level from the IP. We measured the glare fraction by means of a lead-disk method, which is similar to the method used for measuring scatter fraction [13]. The method involves obtaining the images of lead disks with various sizes and extrapolating the measured values to a zero disk diameter [14].

III. Results and Discussions

Fig. 3(a) and (b) show the finely sampled composite LSF's measured with the slit in the direction perpendicular (V-SLIT) and parallel (H-SLIT), respectively, to the laser scanning, where the sampling distance was 0.1 mm. Here, the measured MTF's by V-SLIT and H-SLIT are the presampling MTF's of the horizontal and vertical directions, respectively, with respect to the laser-scanning direction. For example, in the case of Fig. 3(a) the effective sampling distance and the slit angle were 2.7 μm and 1.55°, respectively. The sampling distance (SD) shown at the upper right corner of the figure was the original sampling distance of the system, while the interval between two consecutive dots corresponds to the effective sampling distance. It is apparent that the LSF data were finely sampled. It is noted that the LSF measured with H-SLIT is somewhat asymmetric compared to that with V-SLIT. An example of failure in obtaining a composite LSF is illustrated in Fig. 4. This composite LSF is not smooth and continuous. Fig. 5(a) and (b) shows LSF's when the tail portions of LSF's in Fig. 3(a) and (b) were truncated and then exponentially extrapolated. A truncation level of approximately 0.01, with respect to the maximum of the LSF, was employed. The exponential approximation was used for mathematical convenience. This extrapolation technique was employed because the lower portion of the LSF may include errors due to the glare and quantization effect. However, the MTF's calculated from the Fourier transform of the two LSF's [Fig. 3(a) and Fig. 5(a)], as shown in Fig. 6, indicated that the effect of the tail correction is not significant, and a subtle difference appeared only at low spatial frequencies. Moreover, there was no significant difference between the MTF measured with V-SLIT and that with H-SLIT. We have also confirmed that the new method produced consistent MTF data which agreed with that produced using the previous method within the experimental error.

Fig. 7 illustrates the MTF's measured with two different sampling distances, 0.1 and 0.15 mm. The variation in the MTF's measured with 0.1 and 0.15 mm sampling distances is considered to be related to the difference in scanning speeds of the laser scanner. Moreover, in the case of 0.15 mm sampling distance, the MTF measured with H-SLIT is greater than that obtained with V-SLIT. This difference is due to the effective sampling aperture size. A similar result was obtained when the sampling distance was changed to 0.2 from 0.1 mm [6].

In the slit method used for measuring MTF's of screen film systems, the tail portion of the LSF may not be obtained accurately. For reduction of the truncation error, therefore, a combination of two techniques has been employed, namely multiple-slit exposure and exponential extrapolation of the LSF tail [1], [15]. In the case that the dynamic range of a DR system is not wide enough, truncation error may occur. The LSF measured with the "one-slit" exposure method at a narrow setting of the system latitude (L) and the corresponding presampling MTF of the CR system are shown in Figs. 8 and 9, respectively, where the L value was set at 2 instead of 3.3. It is apparent in Fig. 9 that the MTF (dashed curve) exhibits oscillations (truncation error) due to the absence of a tail portion of LSF. The LSF measured with the "two-slit" exposure method and the corresponding MTF are illustrated in Figs. 10 and 11. The portions between two vertical lines (solid lines: two pairs) at both the right and left sides of Fig. 10 were obtained by extrapolating the LSF obtained from high

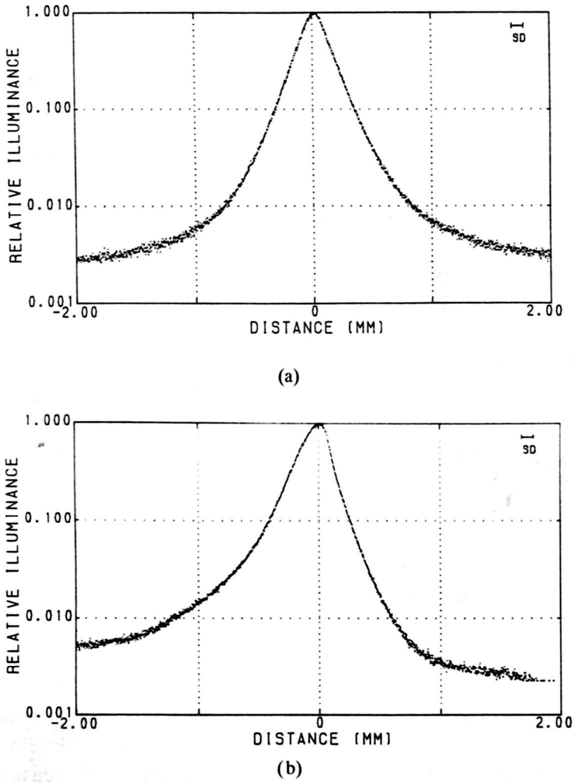

Fig. 3. The finely sampled LSF's measured with the slit in the direction perpendicular (a) (V-SLIT) and parallel (b) (H-SLIT), respectively, to the laser scanning, where the sampling distance and latitude setting were 0.1 mm and 3.3.

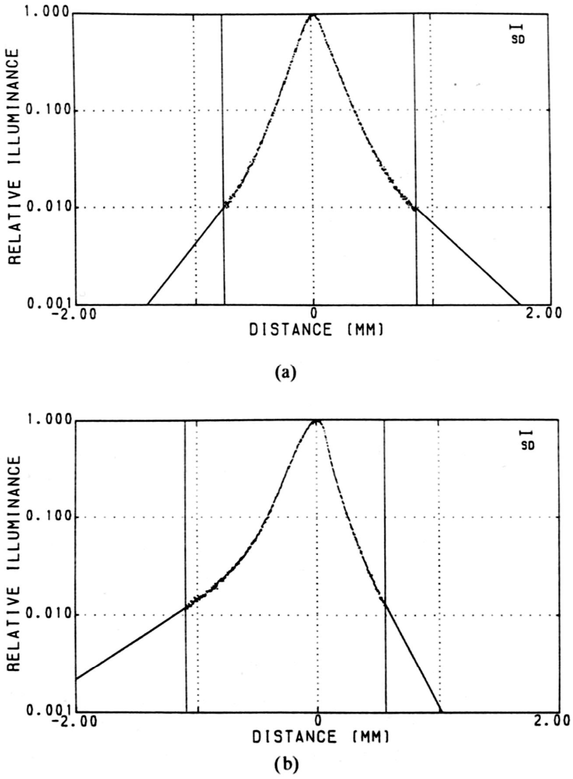

Fig. 5. The LSF's (a) and (b) obtained by truncating the tail portions of LSF's shown in Fig. 3(a) and (b), respectively, and exponentially extrapolating the long sweeping tail.

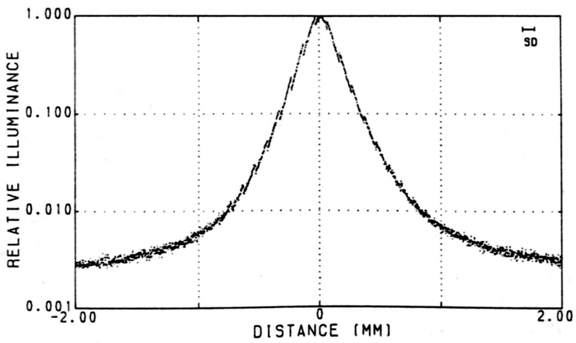

Fig. 4. An example of failure in the composition of a LSF.

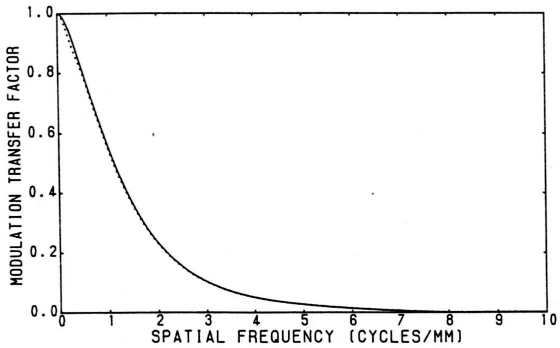

Fig. 6. Presampling MTF's determined from the Fourier transform of the two LSF's with (solid curve) and without (dashed curve) exponential extrapolation. The dashed and solid curves are related to the LSF's of Fig. 3(a) and Fig. 5(a), respectively.

exposure. The long sweeping tail of the LSF was then obtained by exponential extrapolation. The exposure times used for low and high exposures were 0.4 and 8 s, respectively. Fig. 11 shows the presampling MTF's measured with two latitude settings, 3.3 and 2. The difference in the MTF's is negligibly small. As described above, the multiple-slit exposure technique which has been commonly used for conventional screen-film systems can also be applied to the new method presented in this study. Furthermore, it should be noted that when the dynamic range of DR systems is narrow, these techniques need to be implemented.

Fig. 12 indicates that the glare fraction with 0.1 mm sampling distance was approximately 6.5%. With 0.15 mm and 0.2 mm sampling distances, the glare fraction was slightly smaller and was approximately 5%.

We believe that it is worthwhile to add one more discussion. After we submitted this paper, we noted two papers (indicated partly by referees) related to the subject of this study, namely

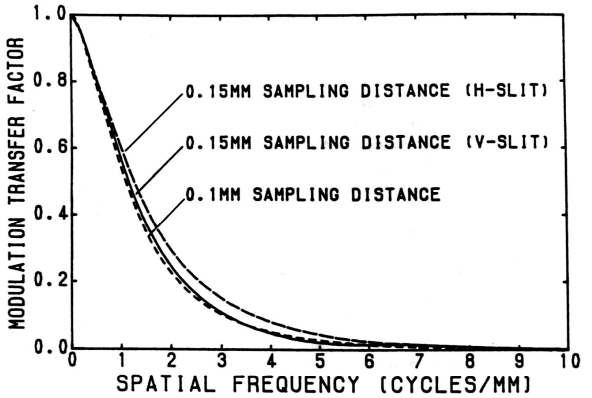

Fig. 7. Presampling MTF's for two different sampling distances as well as for two different directions. Presampling MTF's for V-SLIT and H-SLIT in case of 0.1 mm sampling are comparable, so only one curve is illustrated.

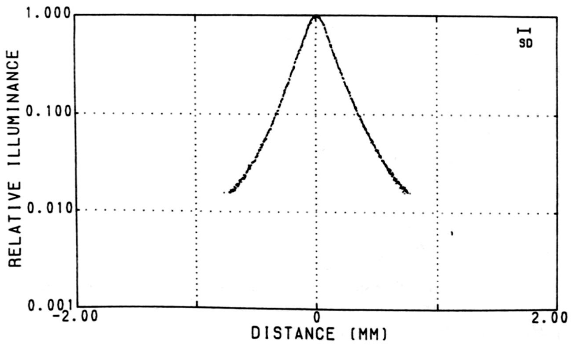

Fig. 8. LSF measured with the "one-slit" exposure method, where the sampling distance and latitude setting were 0.1 mm and 2.

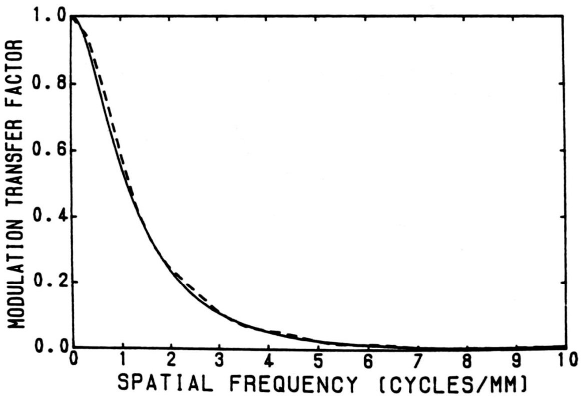

Fig. 9. The corresponding presampling MTF's obtained from the LSF shown in Fig. 8. The dashed curve is the MTF exhibiting truncation error due to truncation of the tail portion of LSF. The solid curve is the MTF in the absence of truncation error and is the same MTF (solid line) as in Fig. 6.

the previous paper by Judy [16] and the recent paper by Reichenbach *et al.* [17], both of which describe a similar approach using a step-edge response function obtained from the image of a knife edge for estimating the presampling MTF. These techniques were applied to determine the MTF's of a

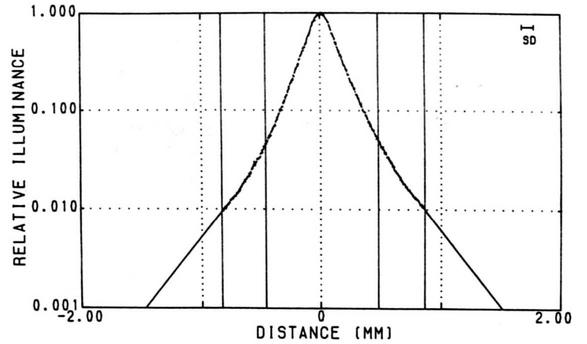

Fig. 10. LSF measured with the "two-slit" exposure method. Exponential extrapolation was also performed.

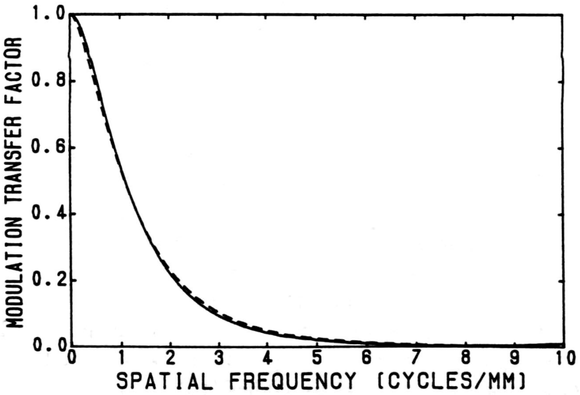

Fig. 11. The corresponding presampling MTF (dashed curve) obtained from the LSF shown in Fig. 10. The MTF with a solid curve is the same as that shown in Fig. 6.

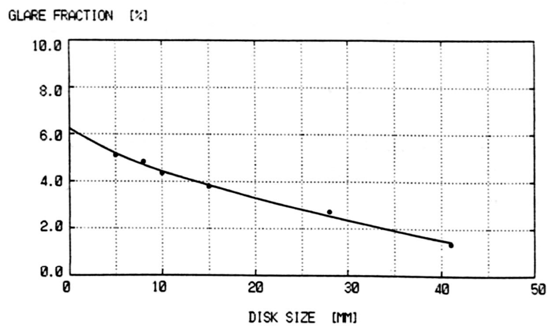

Fig. 12. Relationship between the measured glare fraction and the diameter of lead disks in the case of 0.1 mm sampling distance. The value of the glare fraction at 0 mm disk diameter was measured by extrapolation and was approximately 6.5%.

computer tomographic scanner [16] and a CCD digital camera [17], respectively. However, with these two methods, the first derivative of the edge response is required for obtaining the corresponding LSF, thereby even the smallest amount of noise included in the experimental edge trace may introduce a large error in the calculated LSF because the first derivative is very sensitive to fluctuations in the experimental data [18].

Moreover, it is difficult, with the edge-response method, to achieve an accurate determination of the tail portion of the LSF. It has been reported that noise reduction is important because noise not only leads to variability, but also to a positive bias in the estimate of the MTF whenever both cosine and sine terms in the Fourier transform are used to obtain the MTF [18]. For measurements of the MTF's of radiographic screen-film systems, the slit method is a widely used and well-established technique [18], [19]. Therefore, it is worthwhile to extend the slit method to the digital imaging systems, as shown in this study. The advantages of our extended slit method over the edge-response method are as follows:

1) Technical factors affecting the accuracy of MTF measurements for screen-film systems have been well understood, and this knowledge is available for application to DR systems.
2) A derivative calculation, which may introduce problems as described above, for estimating the LSF is not required. The slit method is simpler than the edge-response method.

In fact, similar to our experience with screen-film systems with the slit method, the influence of noise on the MTF results obtained in this study has not been observed. To achieve it, however, the peak intensity of the LSF used for MTF measurement must be very large. The LSF shown in Fig. 3(a) or (b) was smoothed, and the MTF was, however, identical to the one obtained without smoothing. These results are much different from that obtained by differentiation of the step-edge response, which tends to result in amplification of noise. Moreover, in previous studies [16] and [17], the issue of veiling glare which exists in the II–TV system (DSA) and CR systems employed in the present work has not been dealt with.

In conclusion, we developed a simple method for determining the presampling MTF in DR systems. With this method, the presampling MTF is determined by the Fourier transform of a finely sampled LSF (composite LSF) which is derived from many originally sampled LSF's obtained with a slightly angulated slit. This method was applied to measure the presampling MTF's of a computed radiographic system. This application suggests the potential usefulness of our new technique.

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