

原著

Development of a semi-automatic measurement method for presampled MTF using virtual slit images

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Abstract: We have been researching the use of a virtual slit method on the presampled modulation transfer function (MTF). The virtual slit method obtains a virtual slit image by subtracting the edge image from an image shifted one pixel in the vertical direction. In our previous study, the measurement of the edge angle and synthesis of a line spread function (LSF) were fully manual processes, which affected the MTF calculation error. The aim of the present study was developing semi-automatic software for the virtual slit method. We used four simulation edge images (edge angles: 1.5°, 2.0°, 2.5°, and 3.0°) and obtained three experimental edge images with an indirect flat panel detector. Our software can measure the edge angle, generate the LSF, and calculate the MTF semi-automatically. The measurement error of the edge angles was within 0.01° in all simulation images and within 0.02° in all experimental edge images, respectively. The error ratio of the simulated and theoretical MTFs was within 1.0% at the Nyquist frequency. The average standard deviation of the MTFs with the experimental edge images was within 0.0006 (maximum: 0.0013). Thus, we developed semi-automatic software for the virtual slit method. Our results showed that the software can stably measure the MTF. We consider the software to be a useful semi-automatic assistant for the virtual slit method.

Key words: modulation transfer function, virtual slit image, edge angle, semi-automatically measurement

1. Introduction

Photostimulable storage phosphor (PSP) and the flat panel detector (FPD) are used in a digital X-ray detector. The modulation transfer function (MTF) is used to evaluate the resolution property of the digital X-ray detector for quality assurance (QA) and quality control (QC). The slit and edge methods are usually used to measure the MTF for the digital X-ray detector [1, 2]. The International Electrotechnical Commission (IEC) recommends the edge method for digital X-ray detectors [3].

The edge method uses an edge image of a slightly slanted tungsten edge device on the digital X-ray detector. The edge image is used to generate a composite oversampled edge spread function (ESF), which is differentiated to obtain a synthesis line spread function (LSF). Finally, the MTF is calculated by Fourier transform of the synthesis LSF. Although the edge method is simpler than the slit method, the former requires accurate measurement of the edge

angle from the edge image. The measurement error of the edge angle influences the accuracy of the MTF, so the edge angle is used to calculate the MTF. In addition, the edge method complicates the LSF generation process and requires a great deal of experience with its measurement. Many researchers were reported the precise of edge angles [5, 6].

We previously proposed the “virtual slit” method, which uses an edge image [7]. The virtual slit method is a simplified MTF measurement process based on the edge method. Our original approach obtains a virtual slit image by subtracting the original edge image from the same image shifted one pixel in the horizontal direction. However, the virtual slit method has a problem in that the measurement error of the edge angle depends on a manual measurement process using ImageJ (National Institutes of Health, USA) [8]. The virtual slit method requires an accurate measurement of the edge angle because it is based on the edge method. For the virtual slit method, the

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measurement error of the edge angle has to be reduced to improve the MTF calculation accuracy.

Therefore, we developed software that semi-automatically measures the MTF by using the virtual slit method. The purpose of this study was to develop a semi-automatic method to reduce the measurement error from manual processes. Our software can measure the edge angle, generate the synthesis LSF, and calculate the MTF semi-automatically. In this paper, we discuss the accuracy of the edge angle and MTF with the proposed method and describe the usefulness of our software.

2. Materials and methods

2.1. Simulation edge image

We simulated images by using a Lorentzian-shaped function [6]. The simulation images had a matrix size of 65×512 pixels, gray-level resolution of 16 bits, and sampling pitch of 0.0875 mm/pixel. The Nyquist frequency (N_y) was 5.71 cycles/mm. Figure 1 shows four simulation images with edge angles of 1.5° , 2.0° , 2.5° , and 3.0° .



Fig. 1 Simulation images with edge angles of (a) 1.5° , (b) 2.0° , (c) 2.5° , and (d) 3.0° .

2.2. Experimental measurements

We used three experimental edge images that were the same as those used in our previous study [7]. These images were obtained with an indirect FPD detector (PLAUDR, Konica Minolta, Tokyo, Japan) and the tungsten edge device. The FPD was implemented with a CsI-based phosphor. We removed the X-ray scatter reduction grid and disabled all image processing. The RQA5 spectrum was used for all measurements by adding 21 mm of aluminum to a 74 kV X-ray beam to provide an approximate half-value layer of 7.1 mm of Al. The experimental edge images had a matrix size of $1K \times 1K$ pixels, resolution of 16 bits, and sampling pitch of 0.139 mm/pixel. N_y of the edge images was 3.60 cycles/mm. The tungsten edge device was slightly slanted at $1.5^\circ - 3^\circ$ relative to the vertical direction of the pixel matrix on the FPD. Our software used a region of interest (ROI) image with a matrix size of 768×512 pixels from the experimental edge image to measure the MTF. Figure 2 shows an example ROI image with the tungsten edge device on the right side.



Fig. 2 Example ROI image obtained from the experimental edge image. The right side shows the tungsten edge device with a slight angle.

2.3. Semi-automatic processing

Figures 3 (a) and (b) show flowcharts comparing the processes of our previous study and our software. The dotted lines in Fig. 3 (b) indicate the semi-automated process in our software.

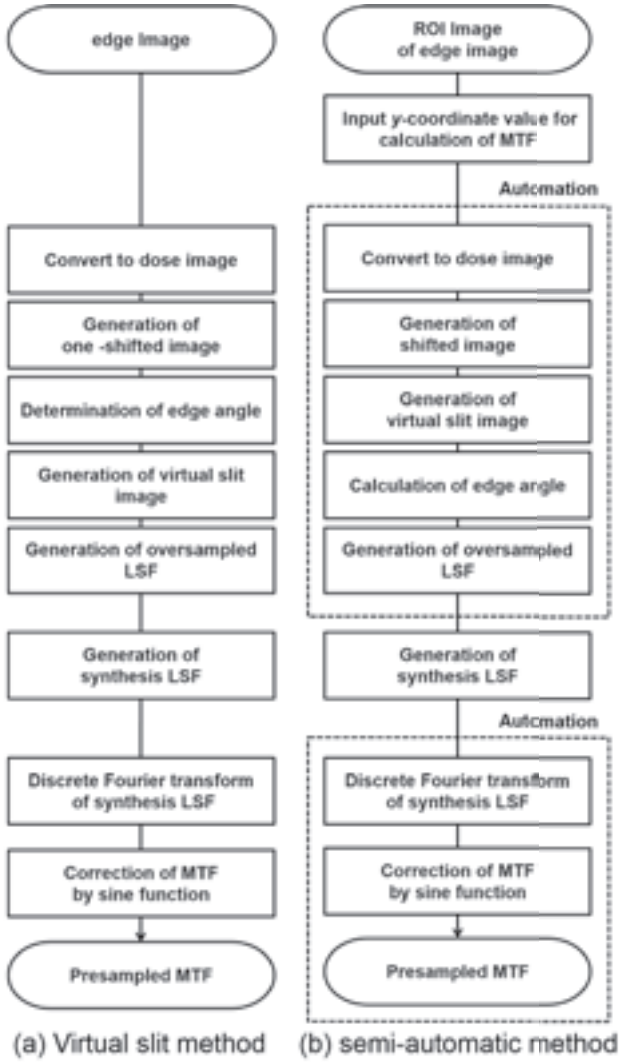


Fig. 3 Comparison of the process flows in the previous study and with the semi-automatic MTF calculation software: (a) flowchart of the previous study [7] and (b) flowchart of our semi-automatic method.

2.4. Dose image

A pixel is a saved digital value in a digital image obtained by using FPD. We can convert the digital value (DV_i) into the dose value (d_i) in each pixel by using Eq. (1) on the measurement MTF:

$$d_i = a \times e^{b \cdot (DV_{max} - DV_i)} \quad (1)$$

where a and b are coefficients obtained from the digital characteristic curve and DV_{max} is the maximum digital value in the ROI image. In this study, a was 1.058, and b was 0.014.

2.5. Virtual slit image

Here, we describe the generation of the virtual slit image in Fig. 4. First, we shift the dose image by one

pixel in the horizontal direction, as shown in Figs. 4 (a) and (b). The virtual slit image is obtained by subtracting the dose image from the shifted image, as shown in Fig. 4 (c). Figure 4 (d) shows an example virtual slit image of the experimental edge image.

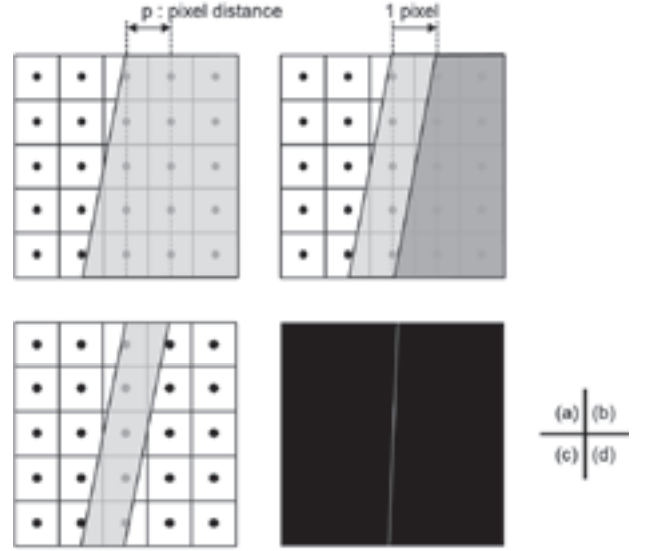


Fig. 4 Generation of a virtual slit image: (a) schematic diagram of a dose image, (b) shifted image generated by moving the dose image by one pixel to the horizontal direction, (c) subtraction image obtained by subtracting the dose image from the shifted image, and (d) example virtual slit image in the experiment.

2.6. Measurement of the edge angle

Our proposed method measures the edge angle by using the maximum pixel in each row of the virtual slit image. Our software can objectively measure the edge angle by using the maximum image. The maximum image is obtained by extracting the maximum value of each row in the virtual slit image, as shown in Fig. 5a. The maximum pixels are continuous in the maximum image, as shown in Fig. 5b. Thus, we extract the maximum pixel value from the continuous maximum pixels, as shown in Fig. 5c. The edge angle is calculated by using the x -axis and y -axis coordinates of the discrete maximum pixel value in the maximum image. The edge angle is calculated as follows:

$$\alpha = \tan^{-1} \left(\frac{y_{upper} - y_{lower}}{x_{lower} - x_{upper}} \right) \quad (2)$$

where x_{upper} and y_{upper} are the x - and y -axis coordinates for the upper row, and x_{lower} and y_{lower} are the x - and

y -axis coordinates for the lower row in the maximum image, as shown in Fig. 5 (d).

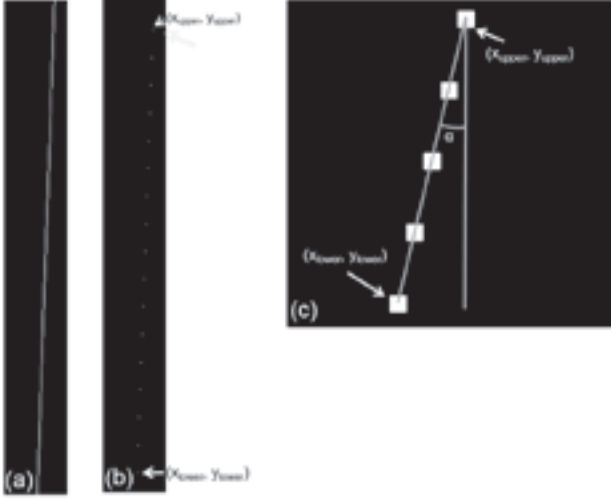


Fig. 5 Calculation of the edge angle using the maximum image: (a) maximum pixel values of each row in the virtual slit image, (b) maximum pixel value in each sequential column of the maximum pixel value, as shown in Fig. 3 (a), and (c) edge angle calculated from the coordinate information for the maximum pixel value in the upper and lower rows of the maximum image.

2.7. Calculation of the integer number N

The edge method uses the integer number N to generate the synthesis LSF [8]. We obtain the N as follows:

$$N = \frac{1.0}{\tan \alpha} \quad (3)$$

where α is the edge angle.

2.8. Generation of the synthesis LSF

Our software extracts an ROI with $\pm 2N$ rows around the center y -coordinate to measure the MTF in the virtual slit image, as shown in Fig. 6 (a). We can obtain the synthesis LSF by repositioning the pixels within the ROI in the virtual slit image [1], as shown in Fig. 6 (b).

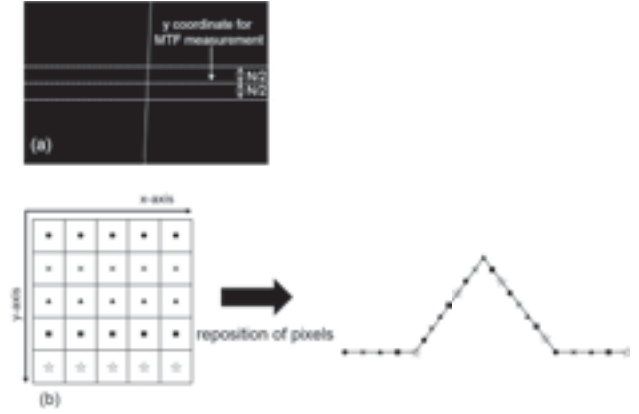


Fig. 6 Generation of a synthesis LSF: (a) ROI region of N rows extracted from the virtual slit image and (b) synthesis LSF obtained from repositioning the pixels in the ROI from Fig. 6 (a).

2.9. Generation of averaged synthesis LSF

We use three synthesis LSFs to calculate an MTF. The maximum value positions are different for each synthesis LSF as shown in Fig. 7a. To obtain the averaged synthesis LSF as shown in Fig. 7b, the peak coincides with each synthesis LSF, and the average value of these LSFs is calculated. We verify the peak of each synthesis LSF using the Excel spreadsheet application (Microsoft Corporation, Redmond, WA, USA).

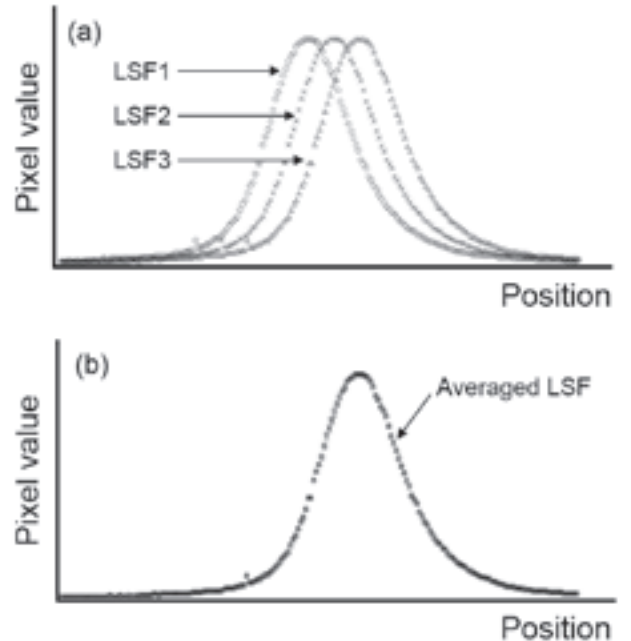


Fig. 7 Generation of the averaged synthesis LSF: (a) the positions of maximum value are different in each synthesis LSF; (b) the positions of the maximum pixel values are repositioned to coincide with the maximum pixel value position in each LSF to obtain the averaged LSF.

2.10. Calculation of the resampled MTF

The presampled MTF (MTF_o) is obtained by using discrete Fourier transform (DFT) on the synthesis LSF. We correct the presampled MTF (MTF_p) with the sinc function as follows [9]:

$$MTF_p = \frac{MTF_o}{\frac{\sin(f \cdot \pi \cdot \cos \alpha \cdot s)}{(f \cdot \pi \cdot \cos \alpha \cdot s)}} \quad (4)$$

where f is the spatial frequency, α is the edge angle, and s is the sampling pitch of the input image.

2.11. Calculation of the theoretical MTF

The theoretical MTF of the edge image can be analytically computed and is given by a Lorentzian-type function. The theoretical MTF (MTF_t) is calculated by using Eq. (5) [8] and then corrected by the sinc function [9]. Equation (5) uses the regular subsampling pitch given by the lateral distance between two adjacent pixels p divided by the number of lines N corresponding to a lateral shift of the edge by one pixel:

$$MTF_t = \frac{r^2}{r^2 + (2\pi f)^2} \times \frac{\sin(f \cdot \pi \cdot \cos \alpha \cdot s)}{(f \cdot \pi \cdot \cos \alpha \cdot s)} \quad (5)$$

where r is the value of $(1/p)$ for the edge parameter, as shown in Fig. 4a, f is the spatial frequency, α is the edge angle, and s is the sampling pitch of the input image.

2.12. Calculation of the error ratio of MTF

We can calculate the error ratio between the MTF of the simulation images (MTF_{si}) and MTF_t by using Eq. (6) to estimate the accuracy of MTF_{si} .

$$\text{error ratio} = \frac{MTF_{si} - MTF_t}{MTF_t} \times 100 \quad (6)$$

3. Results

3.1. Measurement of the edge angle in simulation images

We measured the edge angles in simulation edge images by using Eq. (2), and the results are presented in the second column of Table 1. We calculated the errors between the edge angle of the simulation images and our results to estimate the accuracy of our method.

The measured edge angle in the simulation images is presented in the third column on of Table 1. The measurement error of the edge angle was within 0.01° for all of the simulation images.

Table 1 Edge angles measured by our software in four simulation images

Edge angle in simulation images [degree]	Our software [degree]	Error ^a
1.5	1.50	0.00
2.0	2.00	0.00
2.5	2.51	0.01
3.0	3.00	0.00

a = error is between our software and the average of the manual measurement

3.2. Measurement of the edge angle in experimental edge images

We measured the edge angles in the experimental edge images by using Eq. (2), and the results are presented in the first column of Table 2. The edge angle was manually measured by two radiological technologists (RTs) independently, and the results are presented in the second and third columns of Table 2. The maximum error was 0.04 by RT1, and the minimum error was 0.01 . We calculated the average edge angle of each experimental edge image by the two RTs. We calculate the errors between the averaged and semi-automatically measured results to estimate the accuracy of our method. The measurement error of the edge angle was within 0.02° for all of the experimental edge images.

Table 2 Comparison between the edge angles with our software and manual measurement in three experimental edge images

Image number	Our software [degree]	Manual measurement [degree] (error ^a)		
		RT1	RT2	Average
1	2.32	2.35 (0.03)	2.31 (-0.01)	2.33 (0.01)
2	2.32	2.36 (0.04)	2.31 (-0.01)	2.34 (0.02)
3	2.32	2.35 (0.03)	2.31 (-0.01)	2.33 (0.01)

a= error is between our results and the average of the manual measurement
RT= radiological technologist

3.3. Presampled MTFs of the simulation image

Figure 8 (a) - (d) compares the simulation and theoretical MTFs. The error ratio of these MTFs was within 1.0% (at $Ny/2$ and Ny), as given in Table 3.

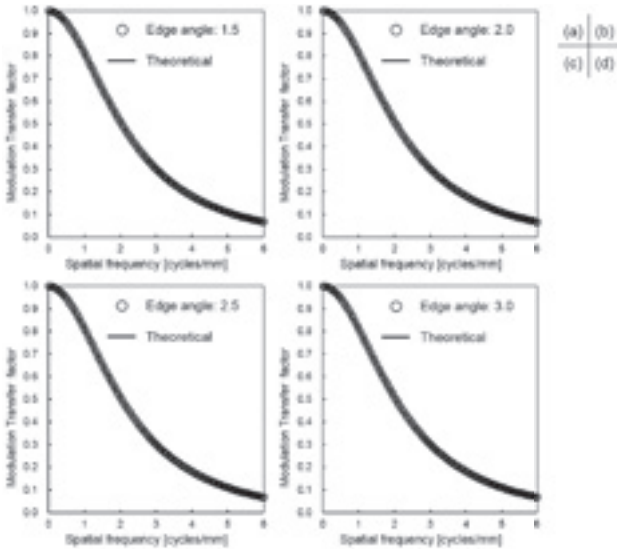


Fig. 8 Comparison between the MTFs of four simulation images and the theoretical values. The MTF with edge angles of (a) 1.5°, (b) 2.0°, (c) 2.5°, and (d) 3.0°.

Table 3 Comparison between the error ratios of the MTFs in four simulation edge images

Edge angle of simulation image [degree]	error ratio [%] at $Ny/2$	error ratio [%] at Ny
1.5	-0.03	-0.17
2.0	-0.05	-0.68
2.5	0.05	-0.07
3.0	0.04	-0.02

Ny = Nyquist frequency, $Ny/2$ = Half of the Nyquist frequency

3.4. Presampled MTF of the experimental edge image

Figure 9 (a) - (c) compares three MTFs of the experimental image and the averaged MTF of the three MTFs. The averaged standard deviation (SD) was 0.0006 (maximum: 0.0013) among the three MTFs.

4. Discussion

We developed a semi-automatic measurement software for the virtual slit method to realize accurate measurement of the edge angle. The edge angle affects the accurate calculation of the MTF because it is used to calculate N in Eq. (3). Therefore, evaluating the accuracy of the edge angle measurement with our software was important.

In our previous study, the edge angle was measured through a manual process [7]. In this study, our proposed method can semi-automatically measure the

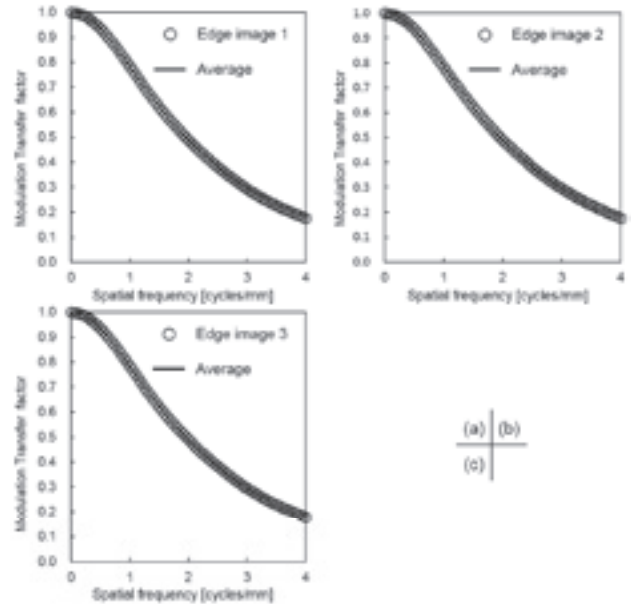


Fig. 9 Comparison between MTFs of three FPD images and the average value. The MTF with (a) edge image 1, (b) edge image 2, and (c) edge image 3.

edge angle by using the coordinates of the maximum pixel in the edge image. This approach can reduce the subjective error depending on the manual process and assure a reproducible measurement of the edge angle. The measurement results of our software matched the edge angles in the simulation images and experimental edge images, as given in Tables 1 and 2. The maximum error of the edge angle was 0.02° . We calculated the MTFs for edge angles of 2.30° , 2.34° , and 2.36° and compared them with an MTF for an edge angle of 2.32° , as shown in Fig. 10. The first three MTFs approximately coincided with the last MTF, and the SD for the four MTFs was 7.5×10^{-4} . We concluded that the error of the edge angle did not influence the calculation of the MTF and that our software can accurately measure the edge angle.

The SD of the MTFs for the simulation images was within 1.0% (at $Ny/2$ and Ny), as given in Table 3 and Fig. 8. The results showed that our method can approximate the theoretical MTF. The maximum error ratio of our result was -0.68 at 2° in the simulation image. In Bhur et al.'s study, the error was within 1.0% at 2° in simulation images [6]. Our proposed method can reduce the relative error of the MTF in simulation images.

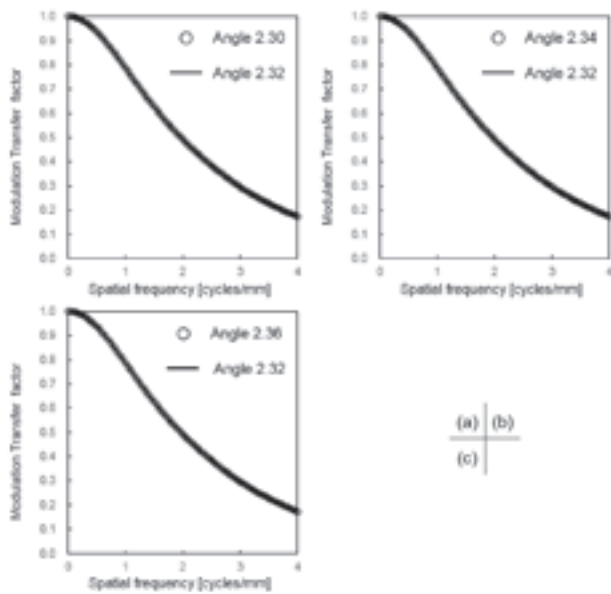


Fig. 10 Comparison between MTFs with edge angles of 2.32° and (a) 2.30°, (b) 2.34°, and (c) 2.36° in experimental edge image 2.

For the simulation image with an edge angle of 2.0°, the error was higher than in other simulation images. This error may have been due to the N value used to generate the synthesis LSF. Although we obtained a true N of 28.59 with Eq. (3), our method used the integer N of 29 in the semi-automatic process. The difference between the true N and integer N affected the accuracy when the synthesis LSF was generated. Further investigation is needed to reduce the influence of the error between the integer N and true N on the virtual slit image.

The averaged SD of the MTFs in the experimental edge images were within 0.0006 (maximum: 0.0013), and the MTFs coincided in value for the three images, as shown in Fig. 9. Our edge measurement method can measure the edge angle accurately and objectively because it uses the coordinates of the maximum pixel for the edge angle. Our proposed method can reduce the subjective error of the edge angle due to manual measurement and improve the reproducibility of the MTF. The results showed that our method can help with realizing stable and highly reproducible measurement of the MTF for edge images. We consider our results useful for MTF measurement in QA and QC of digital X-ray detectors.

In addition, our method can freely set parameters for the sampling pitch, digital coefficient of the characteristic curve, and edge angle. The features of our method can be used for detailed analysis of the influence of each parameter during the MTF measurement process and will be the subject of future research.

Currently, our software is Character user interface with the command line tool, and we require ImageJ and spreadsheet to confirm our output data. We will develop a graphical user interface to upgrade usability.

5. Conclusion

We developed a semi-automatic measurement software to assist with presampled MTFs using virtual slit images. The results show that our software can accurately measure the edge angle and stably calculate the MTF. Further research is to develop an automatically generate the averaged synthesis LSF from some synthesis LSFs. Therefore, this software is useful for measuring the MTF when using a virtual slit image.

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Conflict of interest

The authors have no conflicts of interest to declare.

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