Simulation Analysis on the Performance of a Circular-Edge Technique in Measurements of the Modulation Transfer Function

Sho Maruyama

Department of Radiological Technology, School of Radiological Technology, Gunma Prefectural College of Health Sciences, Maebashi, Japan

Abstract

The modulation transfer function (MTF) plays an important role in characterizing medical imaging systems. For such characterization, the circular-edge technique has become a prevalent task-based methodology. When determining the MTF with complicated task-based measurements, error factors must be well understood to properly interpret the results. In this context, the aim of this work was to study the changes in measurement performance in the analysis of the MTF using a circular edge. To eliminate the systematic error related to the measurement and suitably manage the error factors, images were generated by Monte Carlo simulation. Further, a performance comparison with the conventional method was conducted; in addition, the influence of the edge size and contrast and the setting error of the center coordinates were investigated. The difference from the true value and the standard deviation relative to the average value were applied to the index as the accuracy and precision, respectively. The results demonstrated that the smaller the circular object used and the lower the contrast, the grater the deterioration in the measurement performance. Furthermore, this study clarified the underestimating of the MTF in proportion to the square of the distance with respect to the setting error of the center position, which is important for the synthesis of the edge profile. Evaluations in the backgrounds wherein there are multiple factors affecting the results are complex, and the system users must properly judge the validity of the characterization results. These findings provide meaningful insight in the context of MTF measurement techniques.

Keywords: Circular edge, image quality, modulation transfer function, simulation

Received on: 21-06-2022 **Review completed on:** 27-11-2022 **Accepted on:** 07-12-2022 **Published on:** 18-04-2023

Introduction

The modulation transfer function (MTF) is a quantitative index for evaluating resolution characteristics, which expresses the signal transfer characteristics of an imaging system as a function of spatial frequency.[1] It plays an important role in characterizing the performance of medical imaging systems such as digital radiography (DR) and computed tomography (CT).[2-7] There are several methods for measuring the MTF;[8,9] however, the International Electrotechnical Commission (IEC) recommends the use of a square metal plate (conventional edge method) because of the ease of device handling and data acquisition.[10] Obtaining an accurate MTF is important from the viewpoint of system performance evaluation and image characteristic analysis; therefore, various related studies are being continued to achieve this.[11-15]

The circular-edge method, which is an MTF measurement technique, uses a cylindrical device as a measurement object, and the edge part around the imaged circle is used for the calculation.[16] Because the shape of mass lesions on medical images, along with most signals used in the visual evaluation, are circular, the MTF obtained by this method can be easy for consideration in its relationship with diagnostic image quality.[17] Therefore, by matching the signal strength and noise level to the clinical imaging task, there would be less discrepancy between the results of physical and visual evaluations. For this reason, the circular-edge technique is becoming widespread as a methodology that can measure not only the performances peculiar to the system but also the

Address for correspondence: Dr. Sho Maruyama,
323-1 Kamioki-Machi, Maebashi 371-0052, Gunma, Japan.
E-mail: maruyama@gchs.ac.jp

Access this article online	
Quick Response Code:	**Website:** www.jmp.org.in
	DOI: 10.4103/jmp.jmp_54_22

How to cite this article: Maruyama S. Simulation analysis on the performance of a circular-edge technique in measurements of the modulation transfer function. J Med Phys 2023;48:90-7.

properties of image quality in each task that depend on imaging conditions and processing algorithms.[18-20] This property is called as task-based rather than system specific.

When determining a task-based MTF, the qualities of images are in various states (i.e. subject size, contrast, and intensity of a noise are not constant); therefore, the error factors in the analysis must be understood to interpret the evaluation results correctly.[8,9,21] In particular, MTF measurement using the circular-edge method has not been sufficiently verified, and there is room potential for consideration of various parameters.[22-24] Therefore, the purpose of this study is to determine the change in measurement performance caused by each parameter related to the analysis in the circular-edge method utilizing images with a known MTF obtained by Monte Carlo simulation. Image processing by nonlinear algorithms has been performed even for two-dimensional projection data such as DR images,[25,26] and it would be beneficial to focus on the evaluation of their task-based characteristics. In this context, this study examined the methodology of the circular-edge technique, which is focused on task-based assessment, in detail and summarized it clearly.

Materials and Methods

Modulation transfer function measurement by the circular-edge method

In the MTF evaluation of the digital images, "presampled" characteristics that are unaffected by aliasing are measured.[27,28] In the conventional edge method,[29,30] to measure the presampled MTF, various edge spread functions (ESFs) that cross the edge part with different pixel values can be measured by placing the linear edge obliquely to the pixel array of the detector. Subsequently, the process of synthesizing these multiple ESFs is performed. As a result, the effective data interval for measurement can be made very fine, and the influence of aliasing can be avoided by increasing the Nyquist frequency (f_{Ny}). By contrast, in the circular-edge method, the profile is synthesized based on the distance between the center point of the imaged circle and each pixel. The measurement principle[16] is briefly summarized as follows.

First, the region of interest (ROI) that includes the circle is determined. Next, the center of the ROI is aligned to the center of the circle. The distances (d[μm]) from the center coordinates are determined by each pixel position, which are calculated using the pixel size (p[mm]) and can be expressed as follows:

$$d = 1000 \times p \times \sqrt{\left(x - x_c\right)^2 + \left(y - y_c\right)^2}, (1)$$

Where x and y are the coordinates in the ROI, and x_c and y_c are the center coordinates of the circle. The two-dimensional distribution of pixel values in an ROI, represented by $R(x.y)$, can be projected onto a one-dimensional profile $R(d)$ using Eq.(1). $R(d)$ is the composition of profiles extending radially from the center of the circle in 360° directions and represents the above-mentioned processing of the synthesized ESF. The subsequent calculation processes, such as binning[30] or differentiation for obtaining the line-spread function (LSF), are the same procedures as those used in the conventional-edge method described in IEC 62220–1.

Generation of simulation images

To properly evaluate the measurement performances, systematic errors related to measurements must be minimized. Therefore, to precisely manage error factors, which can be complicated and overlapping, this study performed an approach utilizing Monte Carlo simulation. For the verification, Electron Gamma Shower Version. 5: EGS5 (KEK, Tsukuba, Ibaraki, Japan) was used to simulate the X-ray images.[31]

An edge image of arbitrary size and subject contrast was created using the simulation. Figure 1 shows the fundamental simulation settings and sample images obtained using this geometry. The edge object was placed above the detector, and a 30 keV single-spectrum X-ray photon was incident perpendicular to the edge and the detector (plane source); the reason for using a plane source was to eliminate the influence of geometric blur and an oblique beam. Furthermore, the X-ray energy was the average effective energy of the X-ray spectrum used in general radiography. The detector was an air layer to exclude the influence of scattering in the sensor, assuming an ideal system that detected all incident photons with a pixel size of 0.2 mm × 0.2 mm. The number of incident photons was set to be 1 × 10^5 mm^{-2} in the area that was not covered by the edge. Next, to verify the measurement performance of the MTF, a Gaussian function-shaped blur component[32] was artificially added to the process of the image acquisition to have a known MTF; Figure 2 shows the MTF components of the simulation image.

Five images were generated by independent simulations with different random values in the program each condition. In the simulated image, the linearity of input–output characteristics was established for the incident number of photons and the pixel value of the output image.

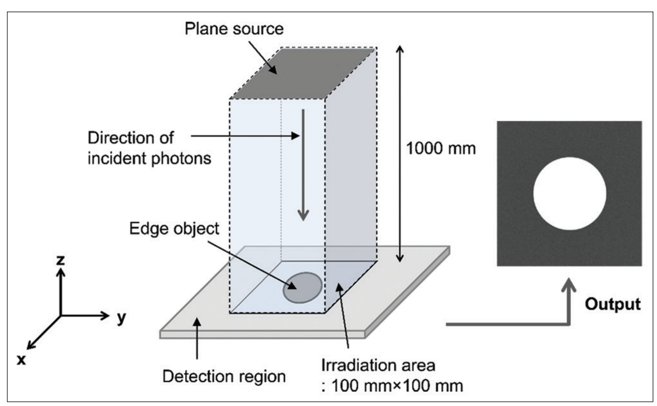

Figure 1: Descriptions of simulation geometry. A simulated image with pixel values corresponding to the number of photons incident on the detection region is output; black area indicates a high number of incident photons and white area is a low number of incident photons

Comparison with conventional edge method

First, the measurement performances of the circular-edge method were compared with the MTF measured using the conventional edge method, which is generally used to determine the detective quantum efficiency. Circular and rectangular edge images were obtained using the simulation settings described in the previous section. Both edge materials were 1-mm thick tungsten (W) to generate the simulation images. The circular edge was 50 mm in diameter, and the size of the rectangular edge was 100 mm × 100 mm.

The analysis for the MTF calculations was performed in an ROI of size 400 × 400 pixels for both methods. In this verification, the synthesized ESF was binned with a width of 0.02 mm (10% of the pixel size), and the data points of the LSF obtained by differentiating the ESF were processed to be 512. Finally, this LSF was fast Fourier transformed using Microsoft Excel to calculate the MTF.

Influence of the size of circular edge

One of the advantages of using the circular-edge method is that the edge size used for measurement can be adapted to the imaging task for clinical practice.

In this section, the measurement performances when the diameter of the circular-edge was changed to 10, 30, 50, and 70 mm are discussed. The edge material targeted here was 1-mm-thick W. The ROI size for measurement was adjusted according to the diameter of the edge and set to 70 × 70, 210 × 210, 350 × 350, and 500 × 500 pixels. The MTF calculation process was identical to that described in the previous section. However, for the 10 mm diameter, the number of data points that can be used for the calculation was small, and matching calculation conditions for other diameters could not be determined. Therefore, in the 10 mm diameter edge, the bin size was 0.03 mm, and the number of LSF data points was 128.

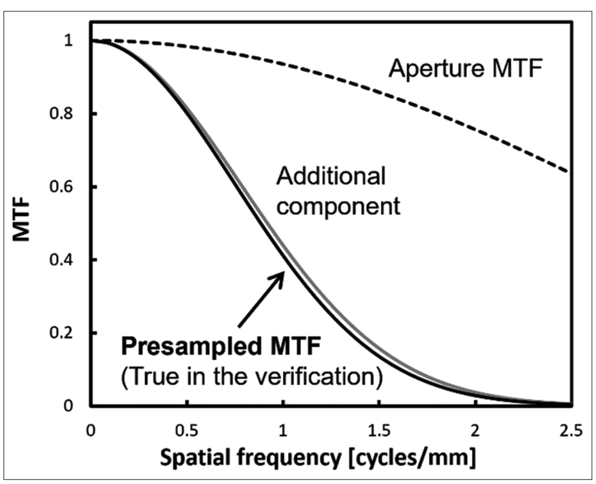

Figure 2: MTF components of the simulation image. Presampled MTF illustrated in the graph is the true value in this verification. MTF: Modulation transfer function

Influence of the contrast of circular edge

In the circular-edge method, the contrast of the edge may be changed to reproduce the desired image quality condition.

In this section, the edge diameter was kept constant at 50 mm, and the effect of changing the edge contrast was examined. Polymethyl methacrylate (PMMA) with a thickness of 5 mm, aluminum (Al) with a thickness of 2 mm and 3 mm, and W with a thickness of 1 mm were used as the materials for the circular edge to change the contrast. The ROI size for the measurement was 350 × 350 pixels according to the edge diameter. As mentioned in the previous sections, the synthesized LSF was acquired such that the data points were 512, and the MTF was calculated.

In addition, to calculate the contrast of the target edge image, the ROI of 100 × 100 pixels was set in the edge center and background (BG) area, as shown in Figure 3, and the contrast-to-noise ratio (CNR) was calculated as follows:

$$CNR = \frac{S_{BG} - S_{edge}}{\sqrt{\sigma_{BG}^2 + \sigma_{edge}^2}}, (2)$$

where S_{BG} and S_{edge} are the mean pixel values of the BG area and the edge center, respectively, and σ_{BG} and σ_{edge} are the standard deviation (SD) of each area.

Influence of the setting error on the center position of the circular edge

In the conventional edge method, the angle of inclination of the edge must be accurately estimated with respect to the pixel array. However, in the circular-edge method, the center coordinates of the circular image must be properly identified.[33]

In this section, the MTFs were calculated by shifting the center coordinates by 0.5, 1, and 1.5 pixels in the x-axis direction from the true center. A simulation image obtained under the condition of 1-mm-thick W with a diameter of 50 mm was

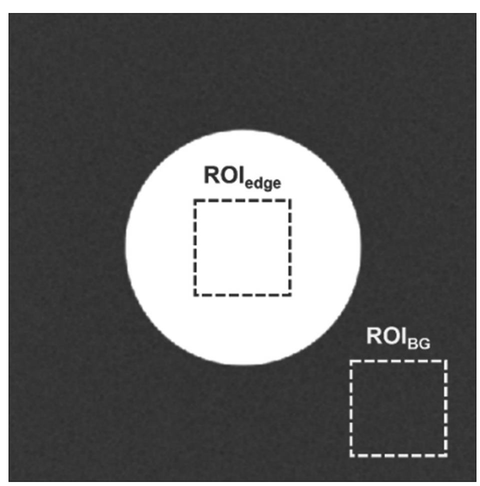

Figure 3: ROI settings in the circular-edge image for the calculation of the CNR. ROI: Region of interest, CNR: Contrast-to-noise ratio

used. The conditions for the MTF calculation were the same as those described in the previous section.

Evaluation of measurement performance

The measurement performances of the MTF were evaluated using the difference from the true MTF value as the accuracy index and the SD relative to the average MTF value as the precision index. These indices were calculated from the MTF value of each spatial frequency based on the MTFs obtained from five independent edge images and represented as a function of spatial frequency.

In this study, data involving the acquisition of the human body or personal information were not handled, and the results of observation experiments conducted on a human participant were not included in the evaluation of images.

Results

Figure 4 shows the results of the MTF calculated from the circular-edge and rectangular-edge images used in the conventional method. When the vertical axis of the MTF graph was on a logarithmic scale, a slight difference from the true MTF was observed in the high spatial frequency range close to $f_{Ny} = 2.5$ cycles/mm. There was no clear difference between the circular-edge and conventional methods in terms of the variation in the calculated MTF values over five measurements. In terms of the accuracy, the MTF obtained by the circular-edge method tended to be higher than the true value; however, the conventional method tended to be lower in the middle spatial frequency, such as approximately 1.0 cycles/mm. Although there was a difference from the true value, the absolute errors were small for both measurement methods, and the simulation images used in this verification and the algorithm of the MTF calculation program could be considered valid.

Next, the effect of the edge diameter on the MTF measurement performance was evaluated, and the results are shown in Figure 5. Here, the smaller the edge size, the greater the variation in the MTF value and the difference from the true MTF; under the conditions of this verification, no significant effect on the measurement performance was observed for edge diameters of 30 mm or larger. Table 1 shows that the number of available data points varies with the bin size used to create the synthesized profile for the MTF calculation. In other words, when the edge size was small, depending on the condition, no data were included in the bin, and arbitrary edge profiles could not be created.

Figure 6 shows the effect of the subject contrast of the circular edge on measurement performance. The lower the contrast of the edge, the lower the precision evaluated by the variation in measurements and the accuracy confirmed by the difference from the true value. The CNRs calculated by setting ROIs

Table 1: Summary of the number of available data points for modulation transfer function calculations, which varies with the edge diameter and the bin size used to create the synthesized profiles

	Diameter of circular edge			
	10 mm	30 mm	50 mm	70 mm
Bin size: 0.02 mm (f_{Ny}: 25.0 cycles/mm)				
Number of data pointsin a bin	0.98	2.95	4.91	6.87
Available length from the center to edge (number of bins)	250	750	1250	1750
Bin size: 0.03 mm (f_{Ny}: 16.7 cycles/mm)				
Number of data points in a bin	1.47	4.42	7.36	10.31
Available length from the center to edge (number of bins)	166	500	833	1166

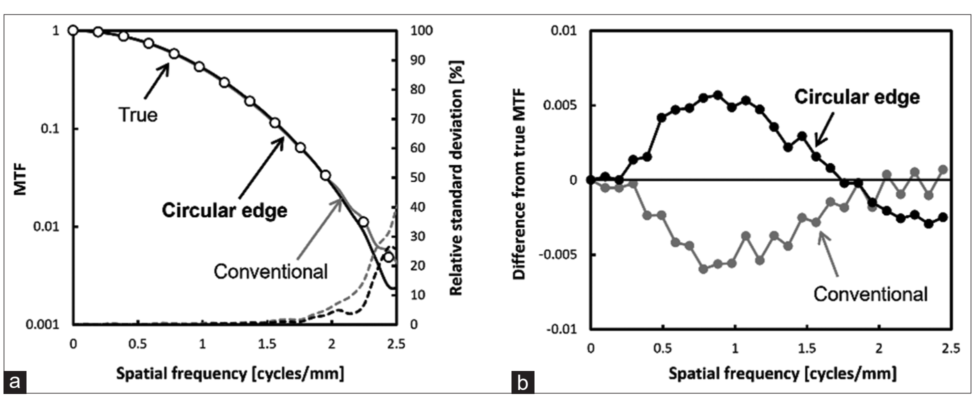

Figure 4: (a) Comparison of the MTF obtained by different measurement methods (average of five measurements). The MTF is displayed on the logarithmic axis, and the relative SD with respect to the MTF value is also shown. The circle plot is the true value, the solid black line is the MTF calculated by the circular-edge method, and the solid gray line is the MTF obtained by the conventional method. The dash line represents the relative SD. (b) Differences from the true MTF value. MTF: Modulation transfer function, SD: Standard deviation

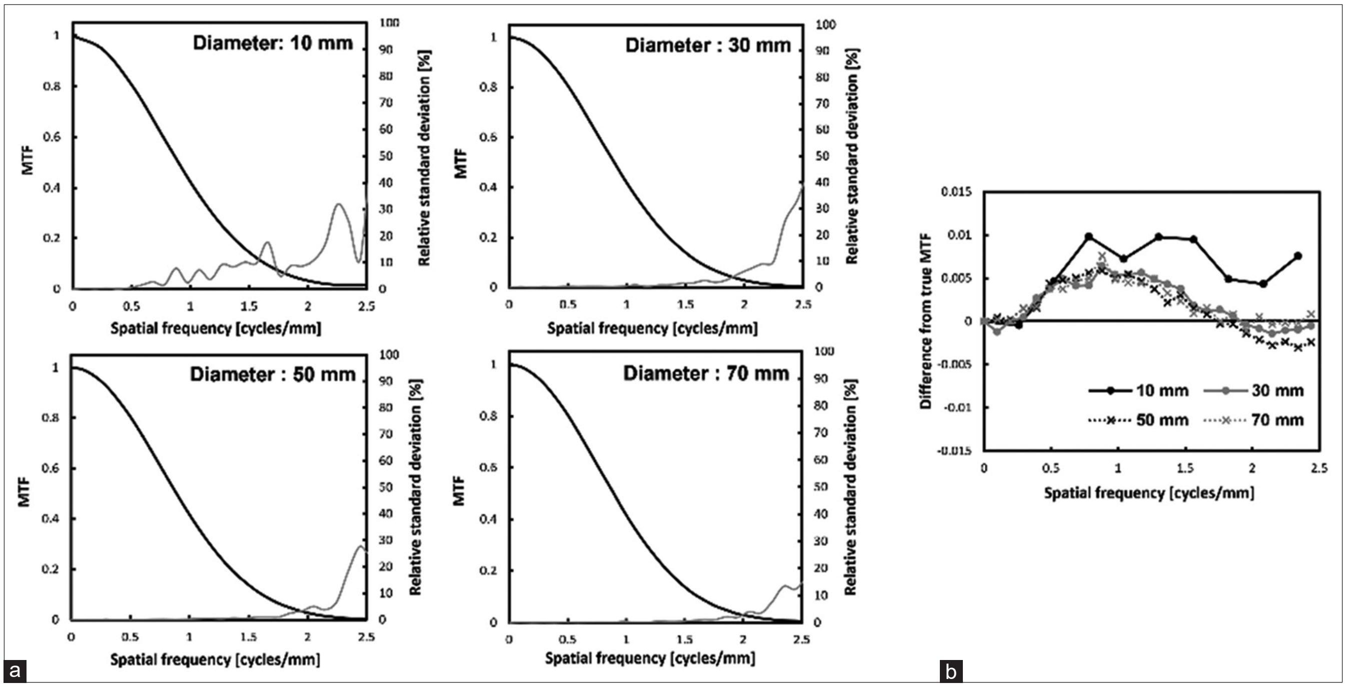

Figure 5: (a) Comparison of the MTF and the variation obtained for different diameters of the circular edge. The black line is the MTF (average of five measurements), and the gray line is the relative SD. (b) Differences from the true MTF value. MTF: Modulation transfer function, SD: Standard deviation

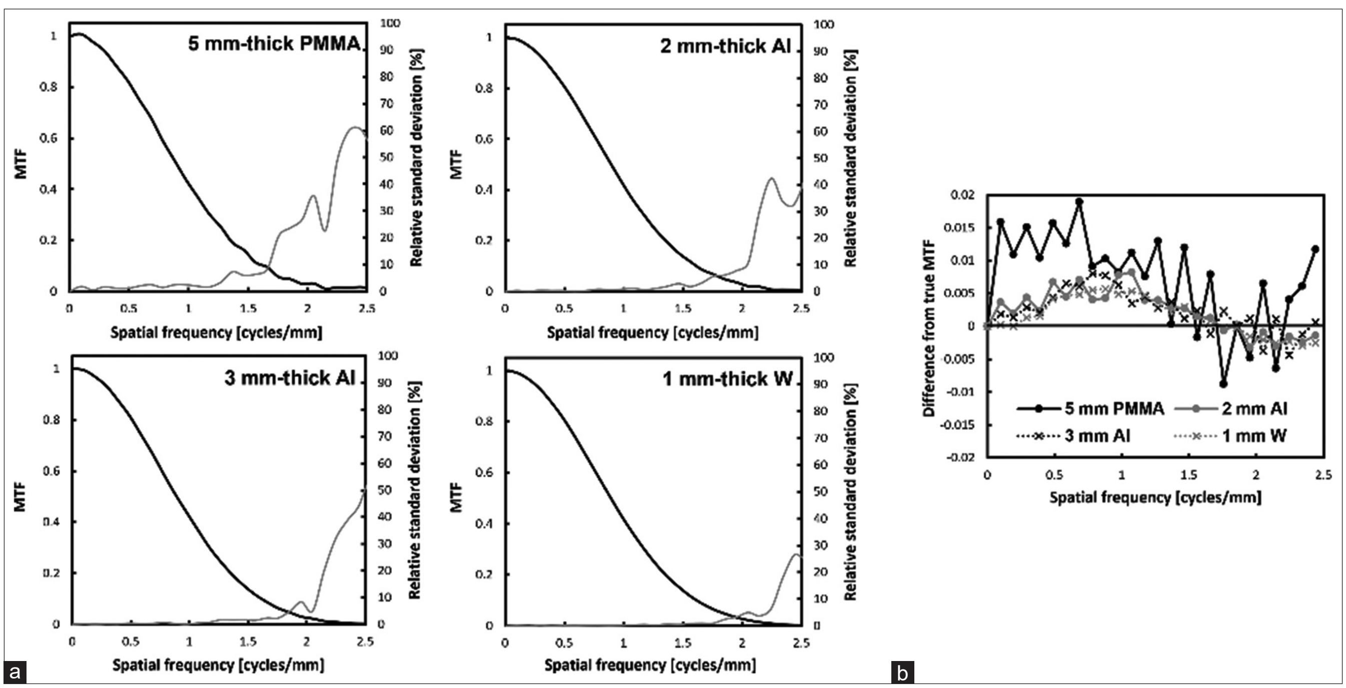

Figure 6: (a) Comparison of the MTF and the variation obtained for different contrast of the circular edge. The black line is the MTF (average of five measurements), and the gray line is the relative SD. (b) Differences from the true MTF value. MTF: Modulation transfer function, SD: Standard deviation

in the edge center and BG region were 24.1 for 5-mm thick PMMA, 75.7 for 2-mm-thick Al, 103.6 for 3-mm thick Al, and 227.0 for 1-mm thick W.

Figure 7 shows the results of measuring the MTF by changing the setting position of the edge center to obtain a synthesized profile. From the results, the farther the setting position was from the true center position, the lower the measured MTF, and the more the accuracy deteriorated. Figure 7b demonstrates the calculated MTF values of 0.5 cycles/mm and 1.0 cycles/mm with the amount of deviation of the center-setting position as a variable. Although the coefficients were different for each, they were accurately fitted using a quadratic function approximation expressed in the following equations ($R^2 > 0.999$).

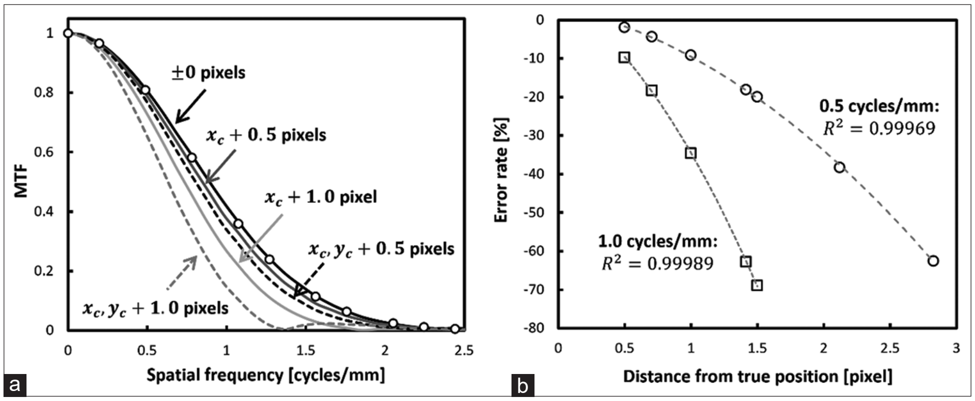

Figure 7: (a) Variation of the MTF when center setting position is changed. The ESF was obtained by slightly changing the center position from the true coordinates to generate a synthesized profile, and the MTF was calculated. (b) Error rate relative to the true MTF value as a function of the deviation distance from the true center position. The circle plot is the MTF value of 0.5 cycles/mm, and the square plot is the value of 1.0 cycles/mm. MTF: Modulation transfer function

0.5 cycles/mm: $y = -5.76x^2-7.11x+3.32$

1.0 cycles/mm: $y = -19.5x^2-20.7x+5.63$

Discussion

This study investigated the effect of several conditions on the measurement performance of the MTF measurement of medical X-ray images on the application of the circular-edge method. The accuracy and precision were evaluated based on the difference from the true MTF value and the variation of the measured MTF, respectively. In addition, images were generated using Monte Carlo simulation to conduct the analysis after determining the true MTF value.

Under the validation conditions, the variation in the measured MTF tended to be higher in the high-frequency range close to f_{Ny} in both methods; the accuracy of the MTF measured by the circular-edge method was equivalent to that of the conventional method, and the measured values were similar to the true MTF. However, an error of approximately 1% from the true value tended to occur around 1 cycle/mm; in this region, the circular-edge method overestimated the true MTF value, whereas the conventional method estimated a lower value. The error factor in this simulation approach was purely the shape of the edge object (circular or straight). Therefore, the changes in the edge portion formed by the different edges and the variation in the ESF synthesis algorithm were expressed as features for the MTF calculation.

Although the circular-edge method reportedly is unaffected by the diameter of the circular object used (30–100 mm)[15] in terms of measurement accuracy, the results of this study indicate that the use of smaller objects leads to variations in the measured values and deviations from the true values. As shown in Table 1, a small object cannot provide the sufficient number of data points required to create a synthesized ESF. Under such conditions, it is assumed that noise reduction by binning[30] did not work effectively. Further, it means that the MTF cannot be measured with an arbitrary spatial frequency resolution. In addition, it was clarified that there should be a minimum object size for measuring the MTF from the viewpoint of the number of data points in the measurement principle of the circular-edge method. In the conventional edge method using a rectangular metal plate, the analysis length of the ESF used for the MTF calculation affects the measured value; this is due to the nonuniformity of the dose distribution and structural noise of the detector.[34] Because such structural nonuniformity increases in proportion to the square of the incident dose,[35] the circular-edge method, in which the area covered by the object is smaller than that of the rectangular edge used in the conventional method, may be significantly affected by these influences. Therefore, researchers should be aware of such concerns before performing MTF measurements.

The effect of the contrast of the edges was also examined; the smaller the contrast, the lower the measurement accuracy, which indicates that the signal strength (CNR) of the edge image affects the accuracy of the MTF. This is consistent with the results of previous studies showing that the uncertainty for the MTF increases as the CNR of the edge image decreases.[8,9,21] Because the degree to which the CNR of an image affects the accuracy of the MTF changes depending on the image quality and analysis conditions, it is necessary to verify whether the MTF obtained is a stable result, and recognizing the degree of accuracy and precision can be achieved by referring to the results of this study.

In the measurement of the MTF, the angular measurement of slightly inclined edges is very important in the conventional edge method, and a measurement error can cause the MTF value to decrease.[29,30] The effect of the distance from the scan center to the edge in CT imaging has been reported as an error factor related to alignment settings in the circular-edge method. Another important factor is the accurate identification of R (x_c, y_c), which is the center coordinate of a circular object. In the circular-edge method, each pixel value distributed in two dimensions is projected into one dimension according to the distance from the center to create a synthesized

ESF. Therefore, the setting error of the center position is considered to correspond to the angle measurement error in the conventional method. In this verification, the effect on the MTF when the center position was changed was determined for accurate center coordinates obtained using the simulation. The results show that the error rate increased in proportion to the square of the distance from the center position. Under the present condition, even a deviation of <1 pixel in one direction resulted in an estimated MTF that was approximately 30% lower at 1 cycle/mm, indicating that accurate identification of the center position is required.

It is important for users of medical imaging systems to be able to quantitatively measure physical image quality characteristics, such as the MTF. Recently, the comprehensive characteristics of the entire system, including the influence of various image quality factors, have been examined. The approach in this study is expected to be significant because it is performed under complicated conditions similar to those in clinical practice, and the characteristics are obtained in consideration of their clinical relevance. However, it should be noted that the interpretation of the obtained results may not be simple if the evaluation or measurement are performed under conditions that have multiple factors influencing the results. In other words, system users must be able to judge the validity of the evaluation results of the characteristics appropriately. We believe that the results of this study provide meaningful information in this context.

The cross-section of the rectangular edge object used in the conventional method should be cut perpendicularly with high accuracy; however, there are no well-defined rules for the objects used in the circular-edge method. If the resolution characteristics are somewhat low, similar to CT imaging, it may be possible to calculate the MTF with a certain degree of accuracy, even without a precise cut surface. However, in the case of an image with high-resolution characteristics, the accuracy of the cut surface at the edge of a circular-edge object may affect the MTF value. Furthermore, it is assumed that the circularity or shape of the circle must also be considered. This study applied a simulation-based approach to analyze the factors inherent in the MTF calculation, excluding the uncertain effects and changes in results due to the oblique incidence of the beam for the circular edge. However, because these geometric issues are outside the scope, further verifications, including precise experimental measurements, are required.

Conclusion

In this study, the MTF measurement using the circular-edge method was investigated in detail by utilizing simulation images to evaluate changes in measurement performance caused by various parameters in the MTF analysis. The properties of the circular-edge method can then be concisely summarized as follows.

Under the conditions in this study, equivalent measurement accuracy can be obtained; however, the observed trend was slightly different trend from the conventional rectangular edge method specified in the IEC. The smaller the size of the circular object used and the lower the contrast, the lower the measurement performance. Furthermore, the MTF was underestimated in proportion to the square of the shift distance with respect to the error in setting the center position, which is important for the synthesis of the edge profile.

Financial support and sponsorship

Nil.

Conflicts of interest

There are no conflicts of interest.

References

1. Beutel J, Kundel HL, Metter RL. Handbook of Medical Imaging: Physics and Psychophysics. Vol. 1. Bellingham, USA: SPIE Press; 2000.
2. Samei E, Flynn MJ. An experimental comparison of detector performance for direct and indirect digital radiography systems. Med Phys 2003;30:608-22.
3. Rivetti S, Lanconelli N, Campanini R, Bertolini M, Borasi G, Nitrosi A, *et al*. Comparison of different commercial FFDM units by means of physical characterization and contrast-detail analysis. Med Phys 2006;33:4198-209.
4. Monnin P, Gutierrez D, Bulling S, Guntern D, Verdun FR. A comparison of the performance of digital mammography systems. Med Phys 2007;34:906-14.
5. Friedman SN, Fung GS, Siewerdsen JH, Tsui BM. A simple approach to measure computed tomography (CT) modulation transfer function (MTF) and noise-power spectrum (NPS) using the American College of Radiology (ACR) accreditation phantom. Med Phys 2013;40:051907.
6. Miura Y, Ichikawa K, Fujimura I, Hara T, Hoshino T, Niwa S, *et al*. Comparative evaluation of image quality among different detector configurations using area detector computed tomography. Radiol Phys Technol 2018;11:54-60.
7. Kawashima H, Ichikawa K, Takata T, Nagata H, Hoshika M, Akagi N. Technical Note: Performance comparison of ultra-high-resolution scan modes of two clinical computed tomography systems. Med Phys 2020;47:488-97.
8. Cunningham IA, Reid BK. Signal and noise in modulation transfer function determinations using the slit, wire, and edge techniques. Med Phys 1992;19:1037-44.
9. González-López A. Effect of noise on MTF calculations using different phantoms. Med Phys 2018;45:1889-98.
10. IEC 62220-1-1 Medical Electrical Equipment – Characteristics of Digital X-ray Imaging Devices – Part 1-1: Determination of the Detective Quantum Efficiency – Detectors Used in Radiographic Imaging International Electrotechnical Commission; 2015.
11. Samei E, Buhr E, Granfors P, Vandenbroucke D, Wang X. Comparison of edge analysis techniques for the determination of the MTF of digital radiographic systems. Phys Med Biol 2005;50:3613-25.
12. Kuhls-Gilcrist A, Jain A, Bednarek DR, Hoffmann KR, Rudin S. Accurate MTF measurement in digital radiography using noise response. Med Phys 2010;37:724-35.
13. Khodajou-Chokami H, Hosseini SA, Ay MR, Safarzadehaniri A, Ghafarian P, Zaidi H. A Novel Method for Measuring the MTF of CT Scanners: A Phantom Study. MeMeA; 2019. p. 1-6.
14. Tsai YW, Chu CH, Shih WH, Jin SH, Chen JC, Liang KC. Evaluation of different modulation transfer function measurement based on different edge spread function calculations. J Med Biol Eng 2019;39:901-11.
15. González-López A, Campos-Morcillo PA, Vera-Sánchez JA, Ruiz-Morales C. Performance of a new star-bar phantom designed for MTF calculations in x-ray imaging systems. Med Phys 2020;47:4949-55.
16. Richard S, Husarik DB, Yadava G, Murphy SN, Samei E. Towards

task-based assessment of CT performance: System and object MTF across different reconstruction algorithms. Med Phys 2012;39:4115-22.
17. Takata T, Ichikawa K, Mitsui W, Hayashi H, Minehiro K, Sakuta K, *et al*. Object shape dependency of in-plane resolution for iterative reconstruction of computed tomography. Phys Med 2017;33:146-51.
18. Sawa K, Takehara Y, Mitsuzuka J, Tanaka A, Kinoshita K, Kishida S. Development of MTF Measurement Algorithm for CT Images with High Noise by a Radial Edge Method. ISPACS; 2015. p. 426-30.
19. Khobragade P, Rupcich F, Fan J, Crotty DJ, Kulkarni NM, O'Connor SD, *et al*. CT automated exposure control using a generalized detectability index. Med Phys 2019;46:140-51.
20. Wang X, MacDougall RD, Chen P, Bouman CA, Warfield SK. Physics-based iterative reconstruction for dual-source and flying focal spot computed tomography. Med Phys 2021;48:3595-613.
21. Maruyama S. Assessment of uncertainty depending on various conditions in modulation transfer function calculation using the edge method. J Med Phys 2021;46:221-7.
22. Samei E, Richard S. Assessment of the dose reduction potential of a model-based iterative reconstruction algorithm using a task-based performance metrology. Med Phys 2015;42:314-23.
23. Takenaga T, Katsuragawa S, Goto M, Hatemura M, Uchiyama Y, Shiraishi J. Modulation transfer function measurement of CT images by use of a circular edge method with a logistic curve-fitting technique. Radiol Phys Technol 2015;8:53-9.
24. Narita A, Ohkubo M. A pitfall of using the circular-edge technique with image averaging for spatial resolution measurement in iteratively reconstructed CT images. J Appl Clin Med Phys 2020;21:144-51.
25. Lee M, Lee D, Kim H, Choi S, Kim D, Kim HJ. Development of a non-linear dual-energy technique in chest radiography. Radiat Phys Chem 2020;172:108811.
26. Gomi T, Hara H, Watanabe Y, Mizukami S. Improved digital chest tomosynthesis image quality by use of a projection-based dual-energy virtual monochromatic convolutional neural network with super resolution. PLoS One 2020;15:e0244745.
27. Giger ML, Doi K. Investigation of basic imaging properties in digital radiography. I. Modulation transfer function. Med Phys 1984;11:287-95.
28. Fujita H, Tsai DY, Itoh T, Doi K, Morishita J, Ueda K, *et al*. A simple method for determining the modulation transfer function in digital radiography. IEEE Trans Med Imaging 1992;11:34-9.
29. Samei E, Flynn MJ, Reimann DA. A method for measuring the presampled MTF of digital radiographic systems using an edge test device. Med Phys 1998;25:102-13.
30. Buhr E, Günther-Kohfahl S, Neitzel U. Accuracy of a simple method for deriving the presampled modulation transfer function of a digital radiographic system from an edge image. Med Phys 2003;30:2323-31.
31. Hirayama H, Namito Y, Bielajew AF, Wilderman SJ, Nelson WR. The EGS5 Code System. SLAC-R-730. Stanford: SLAC; 2007.
32. Maruyama S. Visualization of blurring process due to analog components in a digital radiography system using a simple method. Phys Eng Sci Med 2020;43:1461-8.
33. Zhang G, Stratis A, Marshall N, Bosmans H. Accurate Centroid Determination for Evaluating the Modulation Transfer Function with a Circular Edge in CT Images. Vol. 10573. SPIE Medical Imaging 2018 Proceedings of the SPIE; 2018. p. 1057344.
34. Carton AK, Vandenbroucke D, Struye L, Maidment AD, Kao YH, Albert M, *et al*. Validation of MTF measurement for digital mammography quality control. Med Phys 2005;32:1684-95.
35. Mackenzie A, Honey ID. Characterization of noise sources for two generations of computed radiography systems using powder and crystalline photostimulable phosphors. Med Phys 2007;34:3345-57.