MTF measurement method for medical displays by using a bar-pattern image

Katsuhiro Ichikawa
Yoshie Kodera
Hiroshi Fujita

Abstract — A modulation-transfer-function (MTF) measurement method that uses a bar-pattern image for medical displays such as liquid-crystal displays (LCDs) and cathode-ray tubes (CRTs) has been investigated. A specific bar-pattern image on the display was acquired with a high-resolution single-lens reflex-type digital camera equipped with a close-up lens. The MTF was calculated from the amplitudes of the fundamental-frequency components, which were extracted from the profile data across the bar patterns by using Fourier analysis. Actual comparisons with the conventional line technique were performed for a medical CRT. The adequate accuracy and excellent reproducibility of the method were confirmed. Furthermore, unlike the line method, an advantageous feature which can use an input signal with sufficient amplitude was theoretically proved. Horizontal and vertical MTFs at the central position of the display area were measured up to the Nyquist frequency for several medical displays. From these measurements, this method has the capability to detect slight differences between the displays measured. This proposed method is useful in understanding and quantifying the medical display's performance due to excellent reproducibility and accuracy.

Keywords — *Display, modulation transfer function, bar pattern, digital camera.*

1 Introduction

For recent medical-image diagnosis, a diagnostic style using a softcopy display is expanding to medical fields. This trend was brought about by the rapid progress of technologies that include medical digital imaging modality, image communications, display, *etc.* Many arguments have been made about the image quality of the display,[1–5] which is final display media for diagnostic image interpretation. As important physical components that influence the image quality of the display, luminance, contrast, resolution, and granularity are generally listed. Among them, the resolution is especially an important component, which is greatly related to image quality. In order to evaluate the resolution characteristic of displays, the visual evaluation method with specified test patterns and the quantitative evaluation method by MTF measurement have been proposed. The focus of this paper is a quantitative method of MTF for both medical liquid-crystal displays (LCDs) and cathode-ray tubes (CRTs). Recently, almost all the medical LCDs are connected to computers using digital interfaces. Thus, in this paper, all the descriptions of LCDs are related to LCDs with digital interfaces.

Several researchers have investigated the measurement methods of the MTF using the line-spread function (line method).[6–9] Since the characteristic curve of the display is non-linear, the amplitude of a single line with respect to the surroundings was small enough to stay in a quasi-linear domain. This small amplitude that causes a low signal-to-noise ratio influences the measurement accuracy of the MTF. In the actual measurement, averaging the LSF obtained from many positions was desired to improve the measurement accuracy. Moreover, the need for structure noise suppression by robust subtraction processing is reported for LCDs.[10,11] According to the line method, several methods using square waves with low amplitudes were also reported. On the other hand, our proposed method reported in this paper employs a bar-pattern image with sufficient amplitude as a test pattern. In this method (bar-pattern method), the bar-pattern image on the display was imaged with a high-resolution digital camera, and its CCD data was used for measurement. The MTF was calculated from the Fourier spectrum of the fundamental frequency in the obtained square-wave profiles. In this paper, we first described the calculation procedure of our method and the theoretical considerations regarding the sufficient amplitude permitted only in the bar-pattern method. Second, we described the methods and results for comparing the line method and the bar-pattern method and actual measurements for different displays using the bar-pattern method. In addition, we described a treatment of the impulse response for LCDs. Finally, we presented a summary of the discussions and conclusions.

2 MTF measurement with bar-pattern image

2.1 Calculation procedure

Figure 1 shows an outline of the calculation procedures of the bar-pattern method. The test pattern used in this study consists of five segments of bar-pattern including five bars with 1-, 2-, 3-, 4-, and 6-pixel widths and two uniform areas for measuring the bar and the background intensity located at just over and under the bar patterns. The frequency cor-

Katsuhiro Ichikawa is with the Graduate School of Medical Science, Kanazawa University, 5-11-80, Kodatsuno, Kanazawa, 920-0942, Japan; telephone +81-52-719-1554, fax -1506, e-mail: ichikawa@mhs.mp.kanazawa-u.ac.jp.

Yoshie Kodera is with the Department of Radiological Technology, School of Health Sciences, Nagoya University, 1-1-20, Daikou-minami, Higashi-ku, Nagoya, 461-8673, Japan.

Hiroshi Fujita is with the Department of Intelligent Image Information, Division of Regeneration and advanced Medical Science, Graduate School of Medicine, Gifu University, Japan.

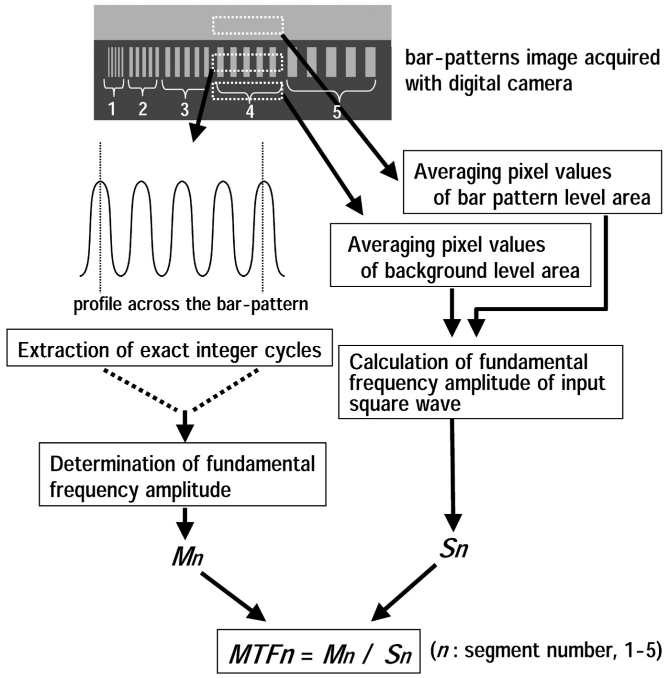

FIGURE 1 — Outline of the calculation procedures for the bar pattern method. The amplitude of the fundamental frequency of each segment (M_n) and corresponding input square wave (S_n) were calculated from acquired image data. Then, the MTF was calculated by M_n/S_n.

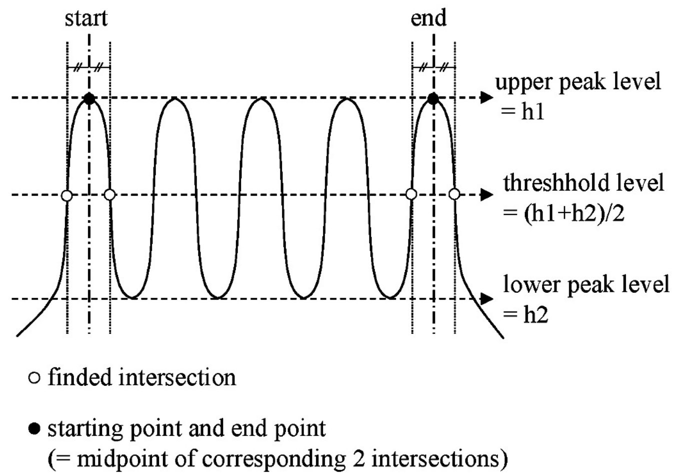

FIGURE 2 — Schematic diagram of the determination of the starting point and the end point for the integer cycles extraction.

responding to each segment is 1, 0.5, 0.333, 0.25, and 0.167 Nyquist frequency of the display, respectively. The following steps were made in individual segments to determine the MTF value.

(1) A one-dimensional (1-D) profile across a segment scanning was obtained with a synthetic slit (averaging CCD pixels in a direction perpendicular to the scanning direction).

(2) Exact integer cycles (usually four associated with five bars) were extracted from the obtained profile using semi-automatic waveform analysis.

(3) Calculating the amplitude of the fundamental frequency component (M_n, n: segment number) with the discrete Fourier transformation was performed.

(4) The amplitude of the fundamental frequency of the input square wave (S_n) was calculated from the bar and background level obtained from two uniform areas. Then, MTF_n was calculated by using the ratio of M_n and S_n.

In order to obtain 1-D profiles from the bar-pattern image data, we scanned CCD image data with a synthetic slit[12,13] with 1×40 CCD pixels which have a longer direction perpendicular to the scanning direction. By using this synthetic slit, we could obtain the 1-D profile for extracting the 1-D section from the 2-D spectrum. Especially, since an LCD has a complex pixel structure which is very non-uniform and non-isotropic, this profile acquisition method is very convenient for analyzing the MTF in the horizontal and vertical directions. The pixel number of the longer direction of the slit was determined as a sufficient length to obtain the stable results experimentally.

The extraction of exact integer cycles from the obtained square-wave profile was very important for precise amplitude determination of the fundamental frequency component. In order to determine the starting point and end point for the extraction, we performed a semi-automatic waveform analysis by threshold calculation and a search of the intersections of the threshold and profile (Fig. 2). If the results of the automatic determination shown on a computer screen were not accepted perceptually, the operator set the correct points by mouse cursor pointing. In most cases, the automatic extraction was performed correctly. In our method, we did not employ discrete fast Fourier transforms (FFTs) for frequency analysis because the periodic component of the extracted profile had the known frequency (cycle number) and the data number of the profile was not fixed. Since the extracted profile was perfectly periodic, the spectrum of the fundamental frequency was detected as a very strong and sharp one, and therefore the amplitude calculation became more accurate. The combination of using a synthetic slit, the extraction of exact integer cycles, and discrete Fourier transformation achieved the correct amplitude calculation of the fundamental-frequency component. Therefore, the determination of more-accurate sinusoid response from the square wave was made possible by using these procedures.

2.2 Consideration of amplitude

In the MTF measurement of a display, the non-linear characteristic of the display gamma, which the display originally has, needs to be taken into consideration. The line method therefore requires single line with small amplitude in order to satisfy the quasi-linear system requirements. In the guidelines of the American Association of Physicists in Medicine (AAPM),[14] the suggested amplitude of the single line is 12% of the pixel value contrast of the background.

The composition of the system with special reference to the horizontal frequency characteristic of a CRT display with an analog interface is shown in Fig. 3. LPFs is the low-

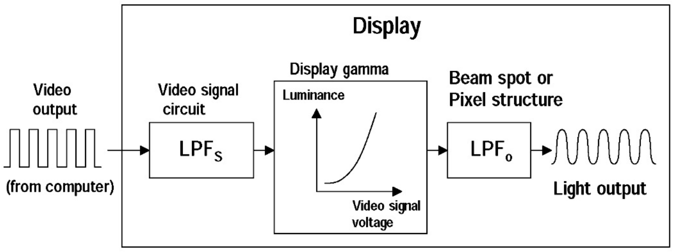

FIGURE 3 — The composition of the system with special reference to the horizontal frequency characteristic of a CRT. LPFs is the frequency characteristics of the video circuits before display gamma. LPFo is the response function of the optical part such as beam-spot profile on the phosphor screen.

pass filtering by the video circuits before the display gamma and LPF_o is the response function of the optical part such as the beam spot profile on the phosphor screen. The display gamma represents the non-linearity of the relation between luminance and video signal voltage. The video signal waveform of the bar pattern from a video interface of a computer is generated from ideal square-wave data stored in the video memory of the computer. This waveform is low-pass-filtered by LPFs, and is then converted to have the non-linear gamma characteristic of the video-signal–luminance conversion, and is finally influenced by LPFo. If the line method is performed with a high amplitude line, the resultant MTF shows a higher value in order for the influence of LPFs to decrease by the nonlinearity of the display gamma. This consideration is required only by the CRT display with an analog video interface to the computer system because LPFs dose not exist in LCDs with digital interfaces.

Here, an input square-wave signal $V(x)$ as a function of horizontal position x is expressed as

$$V(x) = D + \frac{4A}{\pi}\left(\sin(2\pi f_o x) + \frac{1}{3}\sin(2\pi 3 f_0 x) + \frac{1}{5}\sin(2\pi 5 f_0 x) + \frac{1}{7}\sin(2\pi 7 f_0 x) + \cdots\right), \quad (1)$$

where D represents the direct-current level of the input signal, A is the amplitude of the square wave, and f_0 represents a fundamental frequency. The signal before LPF_o according to this input signal in case of display gamma = 2 is expressed by

$$V^2(x) = D^2 + \frac{8DA}{\pi}F_s(f_0)\sin\left[2\pi f_0 x + \phi(f_0)\right] + \frac{16A^2}{\pi^2}F_s(f_0)^2\sin^2\left[2\pi f_0 x + \phi(f_0)\right] + \cdots, \quad (2)$$

where $F_s(f)$ and $F_o(f)$ are the frequency characteristics of LPF_s and LPS_o, respectively, and $\Phi(f)$ denotes the phase shift by LPF_s. The amplitude of the fundamental frequency component becomes $(8DA/\pi)\cdot F_s(f_0)$, and consequently the amplitude of output signal becomes $(8DA/\pi)\cdot F_s(f_0)\cdot F_o(f_0)$, and therefore, the resultant amplitude at f_0 becomes proportional to $F_s(f_0)\cdot F_o(f_0)$. Accordingly, resultant MTF obtained by bar-pattern method is not affected by the input signal amplitude. Thus, the bar-pattern method, which can use a square-wave signal with sufficient amplitude as the input signal, is advantageous in the measurement accuracy of the line method.

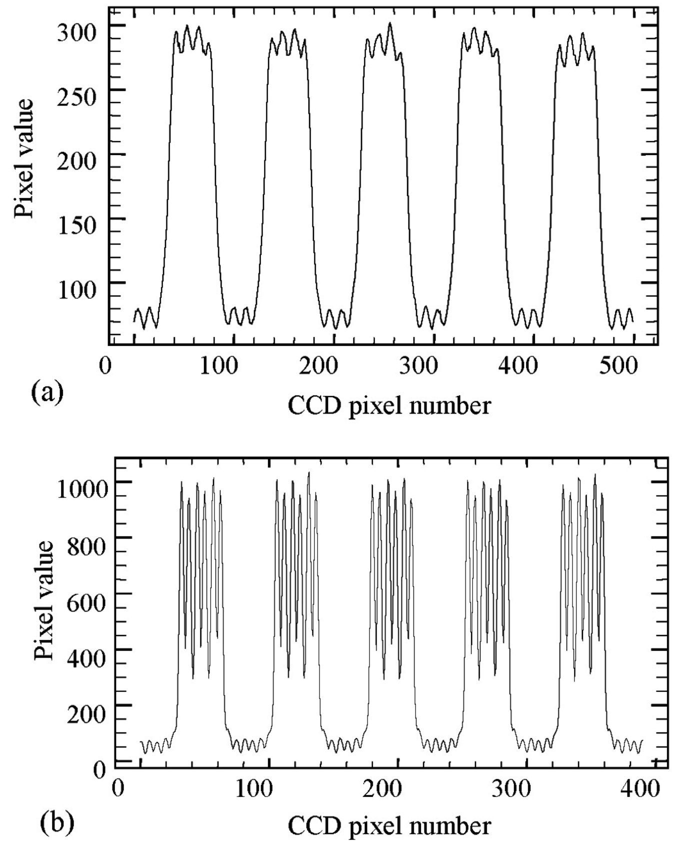

FIGURE 4 — A bar-pattern profile example of an LCD and a CRT. The fine periodic signals with small amplitude involved in coarse square waves are generated from (a) the raster line of CRT and (b) the pixel structure of LCD. For the line method, these unnecessary fine periodic signals become an obstacle of correct MTF calculation. The bar-pattern method ignores them as unconcerned frequencies.

2.3 Consideration of pixel structure and raster line

Figure 4 shows the profile examples of the bar pattern with a four-pixel width bar for a CRT and an LCD. The fine periodic signals with a small amplitude involved in coarse square waves are generated from the raster line of the CRT and the pixel structure of the LCD. For the line method, these unnecessarily fine periodic signals become an obstacle in correcting the MTF calculation.[10,11] In contrast, since the bar-pattern method targets only the fundamental frequency of a given waveform, these fine periodic components are ignored as unconcerned frequencies. Therefore, unlike the line method, the bar-pattern method does not need special data pre-processing such as the structure noise suppression by using the robust subtraction technique. This feature is very useful for high precision and simple measurement.

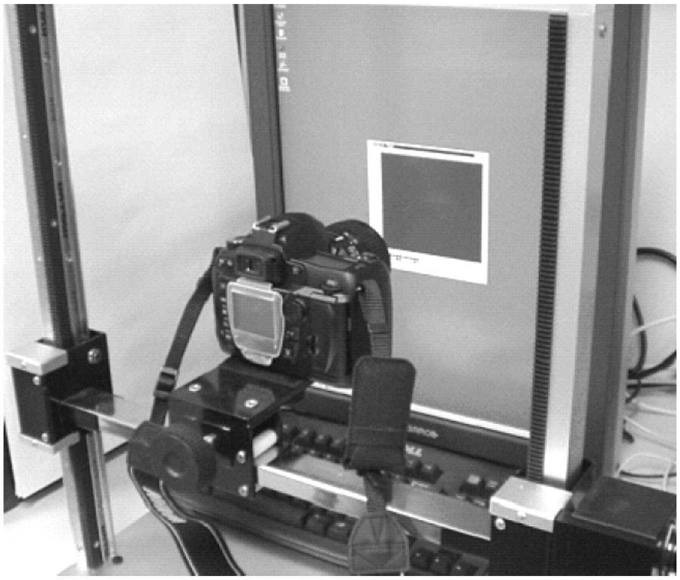

FIGURE 5 — Outline of the experimental setup. The camera was installed on a custom gantry, which enables fine linear movement in the horizontal and vertical directions.

3 Methods

3.1 Data acquisition

The test pattern was imaged with a single-lens reflex-type digital camera (D70, Nikon Corporation, Tokyo, Japan) equipped with a close-up lens (Micro-Nikkor f2.8D, Nikon Co.). This camera has a CCD sensor array with a 3008 × 2000 elements and a contrast resolution of 14 bits. The lens was set to the highest magnification, such that the sampling pitch of the CCD image was set to about 0.08 mm. In order to obtain a well-focused image, the lens used a small aperture with an *f*-stop of *f*/32 to ensure the camera had a relatively large depth of field. The camera was installed on a custom gantry, which enable fine linear movement for horizontal and vertical direction (Fig. 5). The alignment of the camera with respect to the display was adjusted using a small tiled grid image. The coarse-tuning of alignment was performed by using a camera viewfinder, and subsequent fine-tuning was performed by checking the acquired grid image.

3.2 Camera evaluation

The inherent resolution performance of the camera was measured with a single line image of very fine width of 0.01 mm on film for an X-ray photograph. The sampling pitch of the close-up image of the single line was set to about 0.08 mm. The MTF was calculated from the image data of the single line inclined slightly using a previously published method.[13]

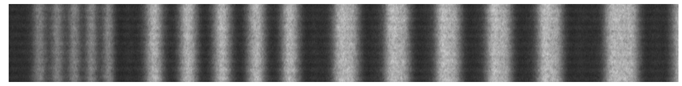

FIGURE 6 — A partial-image example of an acquired bar-pattern image for a CRT measured in this study.

3.3 Comparison of line method and bar-pattern method

For comparison of the line and bar-pattern method, horizontal MTF measurements with a 1600 × 1200 pixel monochrome CRT (MDM2130, Ikegami Tsushin Co., Tokyo, Japan) were examined. Its measured display gamma was about 2.13. Test patterns including a single pixel-wide vertical line with 12% (recommended in a published guideline[14] and 40% pixel value contrast from the background were used, and also the test patterns including the bar pattern with contrast as well as the line were provided. The backgrounds of all patterns were set to a low value of 25% of the maximum in order to avoid the effect of the spread of the electron beam. These two contrasts were used to investigate the comparison of the consistency and the amplitude dependence for the two methods. Figure 6 shows an example of partial image of an acquired bar-pattern image.

3.4 Measurements of medical displays using the bar-pattern method

Three different medical displays were evaluated with the bar-pattern method, as listed in Table 1. The G31S and G31S-p have the same IPS-type panel, and the G31S-p is a prototype display without the anti-glare filter. These two displays were used in order to investigate the effect of an anti-glare filter on the resolution. Because the difference of the MTF between these two displays was expected to be slight, we considered that this selection will be good for investigating the accuracy of the bar-pattern method. Both LCDs were calibrated to the Digital Imaging and Communications in Medicine (DICOM) standard.[15] The CRT display, MDM2130, maintained its original gamma characteristic

TABLE 1 — Description of the three medical displays evaluated in this study. The G31S and G31S-p have the same IPS-type panel, and the G31S-p is a prototype display which is not equipped with an anti-glare filter.

	MDM2130	G31S	G31S-p
Manufacturer	Ikegami Tsushin Co. Tokyo, Japan	Nanao Co. Ishikawa, Japan	Nanao Co. Ishikawa, Japan
type	CRT	LCD	LCD
Additional properties			prototype without anti-glare filter
Matrix size	1600x1200	1536x2048	1536x2048
Display area	380 mm x 285 mm	318 mm x 424 mm	318 mm x 424 mm

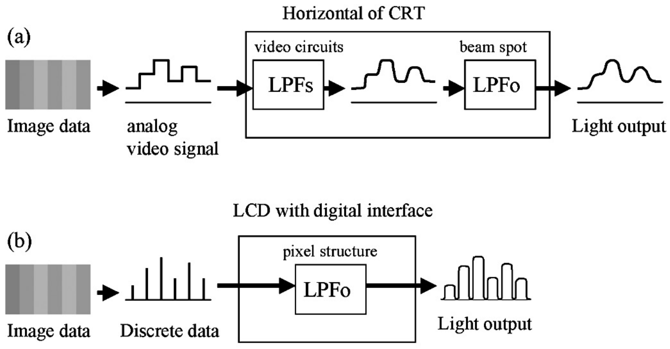

FIGURE 7 — Outline of signal transfer for the horizontal direction of a CRT and an LCD. An LCD is different from the horizontal of a CRT in that the input signal is discrete and the LPFs does not exist. The horizontal direction of a CRT can be treated as well as the pure analog imaging devices.

because it did not have a DICOM function. All measurements were performed in a perfect dark room.

3.5 Treatment of the impulse response for LCDs and the vertical direction of CRTs

Figure 7 shows the outline of the signal transfer for the horizontal of a CRT and the horizontal and vertical direction of an LCD. LCD is different from the horizontal of the CRT in that the input signal is discrete and the LPFs does not exist. The horizontal profile of light output in CRT is produced without any intervention of digitizing process. Therefore, the horizontal MTF of the CRT can be treated as well as the MTF for pure analog imaging devices. On the other hand, for an LCD, a different consideration for the MTF calculation should be needed due to the discrete input signal and its pixel structure. For the vertical direction of the CRT, since the raster lines are almost independent in the time domain, it is considered that the potential input signal by each line is almost discrete. Thus, the vertical direction of CRT can be treated as well for an LCD.

For an LCD, the discrete data as the input signal is blurred (deformed) by the pixel structure as shown in Fig. 7(b). We considered that these blurring factors are the main purpose of MTF measurement of the LCD. When based on this consideration, the resolution characteristic of LCDs mostly depend on the inherent luminance profile according to one pixel structure. In the line method, it is necessary to divide the MTF by the *sinc* function associated with the width of a single pixel in order to correct the mis-estimation owing to the pixel width.[10,11] However, for LCDs, any continuous analog video signal is not used and its impulse response mostly depends on pixel structure. Even if an ideal LCD with pixels in shape of exact squares and a fill-factor of 100% exists, its impulse response remains a square pulse with the width of one pixel and its MTF is equal to corresponding *sinc* function. This consideration is very important in order to obtain essential MTF values for the impulse response. In other words, the result of the conventional method that includes dividing by *sinc* function

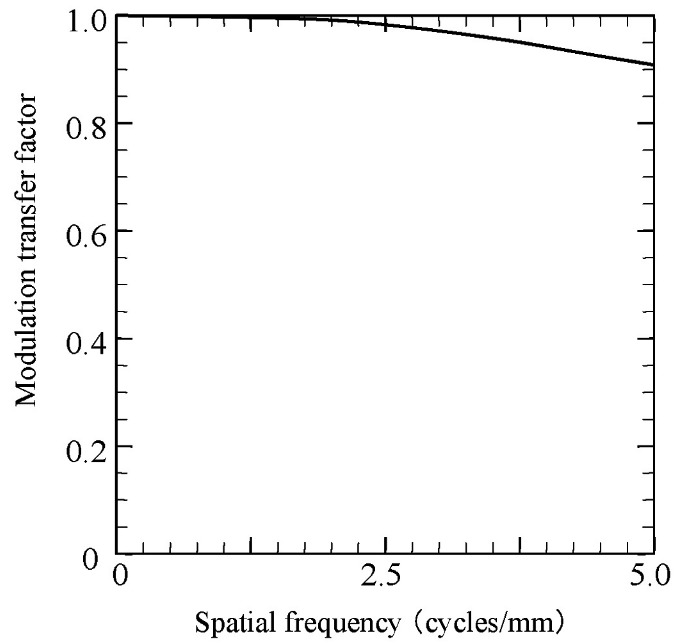

FIGURE 8 — Measured inherent MTF of the digital camera D70. The camera provided a very-high-resolution property over the frequency range of interest.

involves overestimations in LCDs. We considered that its result represents a response of a square pulse. Thus, for LCDs, we propose a calculation method that excludes dividing by the *sinc* function in order to evaluate the impulse response.

In the bar-pattern method, since the square wave (is equal to a square pulse train) is used as the input signal, the result is naturally overestimated. Therefore, resultant MTF values shown in this paper were multiplied by the above-mentioned *sinc* function to correct the overestimations. After all, the MTF as the impulse response of an LCD is defined as

$$MTF_{LCD}(f) = MTF_R(f) \cdot \sin(\pi \cdot f \cdot p)/(\pi \cdot f \cdot p), \qquad (3)$$

where $MTF_{LCD}(f)$ represents the desired MTF, $MTF_R(f)$ represents the original response obtained by square-wave analysis, f denotes the spatial frequency, and p denotes pixel pitch.

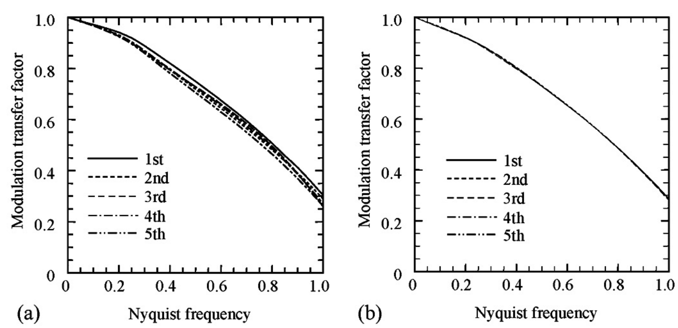

FIGURE 9 — Measured horizontal MTFs of the (a) line method and (b) bar-pattern method for the CRT. MTF values were calculated up to the Nyquist frequency determined by the display pixel size.

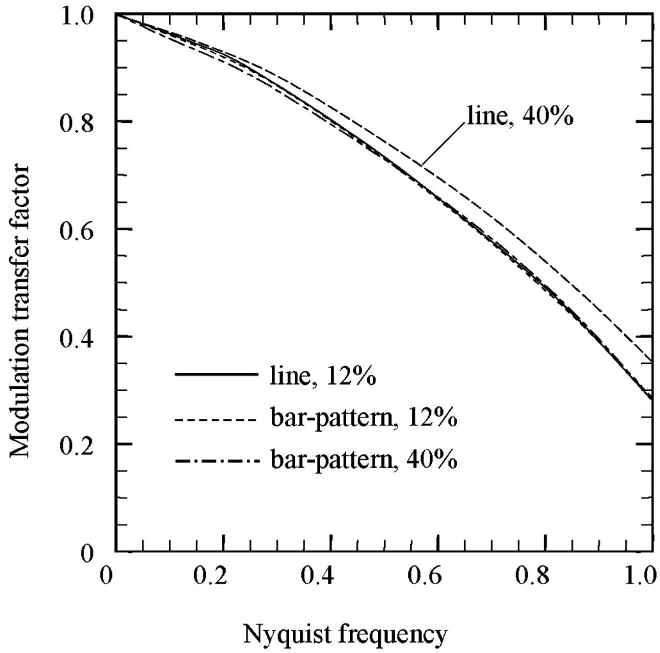

FIGURE 10 — Comparison of the averaged results of the two methods. Percentage values in the figure express the pixel value contrast from the background. The result of the bar-pattern and line with 12% contrast were well in agreement. The MTF value of the line with 40% contrast was evidently higher than other results due to the non-linearity of the display.

4 Results

Figure 8 shows the result of the inherent MTF of the camera. The camera provided a very high-resolution property over the frequency range of interest. The MTF value of 0.91 at 5 cycles/mm indicated that the camera has a sufficient resolution for the MTF measurement. Thus, we did not correct for the camera blurring. Figure 9 shows the measured horizontal MTFs of the line method and the bar-pattern method. MTF values were calculated up to the Nyquist frequency determined by the display pixel size. Table 2 shows the fluctuations of five measurements for two methods at the Nyquist frequency. The fluctuation of the line method was evidently higher than the bar-pattern method. Figure 10 shows a comparison of the averaged results of two methods for each contrast. The results of the bar-pattern and the line with 12% contrast were well in agreement. The MTF of the line with 40% contrast was evidently higher than other results, and indicated the misestimation caused by high contrast. Figure 11 shows the measured horizontal and vertical MTFs by using the bar-pattern method for the three displays. The CRT, MDM2130, was obviously inferior to the other two LCDs. The G31S-p shows a slight higher MTF than that for a G31S.

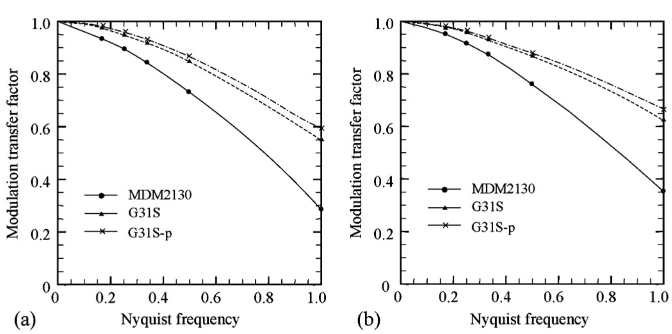

FIGURE 11 — The measured (a) horizontal and (b) vertical MTFs by the bar-pattern method for the three displays. The CRT, MDM2130, was obviously inferior to other two LCDs. The G31S-p showed a slightly higher MTF than the G31S.

TABLE 2 — MTF values for two methods at the Nyquist frequency obtained by five measurements. The average and the standard deviation (SD) of the MTFs were calculated. The fluctuation of the line method was evidently higher than the bar-pattern method.

Measurement	Line method	Bar-pattern method
1st	0.306	0.285
2nd	0.289	0.283
3rd	0.258	0.280
4th	0.269	0.288
5th	0.261	0.282
Average	0.276	0.283
SD	0.020	0.003

(at Nyquist frequency)

5 Discussion

The agreement of the resultant MTFs for the line method with low contrast and the bar-pattern method proved the consistency of measurement theorem for the bar-pattern method, and also showed that the method could derive exact results. Also, the very small standard deviation of the bar-pattern method proved that the method is excellent and suitable for measurement in both laboratory and clinical settings. In the line method, the small amplitude of the line is indispensable to stay in a quasi-linear domain. This restriction yields the unavoidable increase in the statistical fluctuation of the result, and induces the necessity for the averaging process with many profiles of the line. In contrast, the bar-pattern method is able to use input signal with sufficient amplitude, and realizes excellent reproducibility. Furthermore, this method does not need the processing which removes the structure noise of the LCD pixel or the CRT raster line. This feature also contributes to the improvement of the measurement accuracy. In fact, though the difference between G31S and G31S-p was only the existence of the anti-glare filter, the bar pattern method distinguished a small difference between the two displays clearly. We considered that this capability would be very important for various quantitative performance evaluations and the developments of improved displays.

In this study, we did not have an opportunity to measure a CRT display with a DICOM display function. Generally, the CRT corresponding to the DICOM standard achieves the DICOM display function by digitizing the input video signal and subsequent digital gamma conversion. However, the parts following the conversion are equivalent to the ordinary CRT. Therefore, since the waveform of the input square wave does not change by the conversion part except in amplitude, we considered that the digital conversion processing does not influence the resultant MTF measured from the screen output. However, we considered that continued research would be needed to verify the influence of this conversion processing.

One of the shortcomings of this method is that the number of the measurable points is only five. Especially, the frequency interval between a one-pixel width bar and a two-pixel width bar was a little wide (range of 0.5 Nyquist frequency). The MTF curves shown in this paper were produced with third-order spline interpolation. Thus, at an intermediate frequency between 0.5 and 1.0 Nyquist frequency, certain misestimations might be caused. However, the MTF characteristics of the displays commonly show smooth curve shapes.[8,10,16] It was believed that the misestimations in the MTF shown in this paper were comparatively small. Another shortcoming we consider is that the influence of the luminance uniformity may not be avoided due to the occupying area size of the bar pattern. There are two uniform areas to measure bar and background intensity in the test pattern, and the measured intensities from two areas are used for determining the input signal amplitude. When the non-uniformity, which cannot be disregarded, influences those intensities, the error of the MTF measurement may increase. In order to reduce this influence, the bar pattern we used in this study has a relatively small vertical size of 40 display pixels, and thus each bar pattern and two uniform areas become very close. Therefore, it is believed that the influence of uniformity can be reduced effectively.

6 Conclusion

We have investigated the MTF measurement method for medical displays using a specific bar-pattern image. This method was designed for simple and accurate measurement for the MTF of medical displays. From actual comparisons with the line method, we proved the bar-pattern method, which can use square-wave signals with sufficient amplitude as the input signal, is advantageous in measurement accuracy to the line method. Then, from actual measurements with several medical displays, we confirmed that this method has the capability to detect slight differences between the displays we measured. We believe that the resolution characteristic estimation using the bar-pattern method is useful in understanding and quantifying the medical display's performance.

Acknowledgment

We thank NANAO Corp. and SS-giken Corp. for their support and equipment loans.

References

1 L Cook, G Cox, M Insana, and T Hall, "Comparison of a cathode-ray-tube and film for display of computed radiographic images," *Med Phys* **25**, No. 7, 1132–1138 (1998).

2 H Blume, H Roehrig, M Browne, and T Ji , "Comparison of the physical performance of high-resolution CRT displays and films recorded by laser image printers and displayed on light boxes and the need for a display standard," *Proc SPIE* **1232**, 97–114 (1990).

3 H Roehrig, H Blume, T Ji, and M Broune, "Performance test and quality control of cathode ray tube display," *J Digit Imag* **3**, No. 3, 134–145 (1990).

4 H Roehrig, C Willis, and M Damento, "Characterization of monochrome CRT display systems in the field," *J Digit Imag* **12**, No. 4, 152–165 (1999).

5 H Blume, P Steven, M Cobb, A Ho, F Stevens, S Muller, H Roehrig, and J Fan, "Characterization of high-resolution liquid-crystal displays for medical images," *Proc SPIE* **4681**, 23–28 (2002).

6 E Samei and M J Flynn, "Method for in-field evaluation of the modulation transfer function of electronic display devices," *Proc SPIE* **4319**, 599–607 (2001).

7 Badano, S J Hipper, and R J Jennings, "Luminance effects on display resolution and noise," *Proc SPIE* **4681**, 305–313 (2002).

8 S Chawla, H Roehrig, J Fan, and K Gandhi, "Real-time MTF evaluation of displays in the clinical arena," *Proc SPIE* **5029**, 734–745 (2003).

9 H Roehrig, J Gaskill, J Fan, A Poolla, and C Martin, "In-field evaluation of the modulation transfer function of electronic display devices," *Proc SPIE* **5367**, 456–463 (2004).

10 R S Saunders, Jr, and E Samei, "Resolution and noise measurements of five CRT and LCD medical displays," *Med Phys* **33**(2), 308–319 (2006).

11 E Samei, A Badano, D Chakraborty, K Compton, C Cornelius, K Corrigan, M J Flynn, B Hemminger, N Hangiandreou, J Johnson, D M Moxley-Stevens, W Pavlicek, H Roehrig, L Rutz, J Shepard, R A Uzenoff, J Wang, and C E Willis, "Assessment of display performance for medical imaging systems: executive summary of AAPM TG18 report," *Med Phys* **32**(4), 1205–1225 (2005).

12 M L Giger, K Doi, and H Fujita, "Investigation of basic imaging properties in digital radiography. 7. Noise Wiener spectra of II-TV digital imaging systems," *Med Phys* **13**(2), 131–138 (1986).

13 H Fujita, K Ueda, J Morishita, *et al*, "Basic imaging properties of a computed radiographic system with photostimulable phosphors," *Med Phys* **16**(1), 52–59 (1989).

14 American Association of Physicists in Medicine (AAPM), Task Group 18, *"Assessment of display performance for medical imaging systems."*

15 NEMA PS 3 14-2000 Digital Imaging and Communications in Medicine (DICOM). Part 14: Grayscale Display Standard Function.

16 H Blume, P Steven, A Ho, F Stevens, A Abileah, S Robinson, H Roehrig, J Fan, A Chawla, and K Gandhi, "Characterization of liquid-crystal displays for medical images – Part 2," Medical Imaging, *Proc SPIE* **5029**, 449–473 (2003).

Katsuhiro Ichikawa is a Research Assistant at the School of Health Sciences, Nagoya University. He received his B.S. degree from the Nagoya University College of Medical Technology in 1983 and his M.S. and Ph.D. degrees from Gifu University in 2000 and 2004, respectively. His current research is in the development of new technologies for medical displays.