Novel MTF Measurement Method for Medical Image Viewers Using a Bar Pattern Image

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ABSTRACT

A novel MTF(modulation transfer function) measurement method using a bar pattern image for medical image viewers such as DICOM viewer was developed. A bar-pattern image produced by a personal computer was displayed on a cathode-ray-tube (CRT) display and was imaged with a high resolution single-lens reflex digital camera equipped with a close-up lens. The discrete blurred square-waveform data acquired from the imaged bar patterns were interpolated using the waveform reproduction technique with Fourier analysis in order to obtain interpolated wave curves. All of the measured pixel values in this process were converted into luminance data. The MTF was calculated from the amplitude values of the extracted basic frequency components in the square-waveform, in which an aliasing error was excluded. Actual measurements were performed with two models of medical image viewer equipped with monochrome displays. Horizontal and vertical MTFs at the central position of display area were measured up to Nyquist frequency. Resultant MTFs clearly indicated the difference in resolution for two viewers, as well as visual evaluation did. The standard deviations of MTF values of 5 measurements at Nyquist frequency were 0.004 and 0.01 for horizontal and vertical directions, respectively. Employment of a commercial single-lens reflex digital camera enabled easy and correct focusing and simple data handling. In conclusion, our method may be useful in the medical field due to good reproducibility and easy operativity.

Keywords : display, MTF, bar pattern, digital camera

1. INTRODUCTION

In the recent medical image diagnosis, a new diagnostic style using the image viewer equipped with the CRT (cathode-ray tube) display or the LCD(liquid crystal display) attracts attention instead of a diagnostic style using the conventional films. This trend was brought by rapid progress of the digitization technology for the medical imaging modality and the image transmission and mass storage technology. Hot discussions are being made focusing on comparison with the image quality of conventional films and the displays.[1,2]

As important physical components, which influence the image quality of a display, the contrast, resolution, granularity, brightness, etc., are generally listed. Among them, the resolution is especially an important component, which is greatly related to image quality. In order to measure the resolution characteristic of displays, the visual evaluation method with a simple test pattern and the objective evaluation method by measurement of MTF (modulation transfer function) have been proposed. Since the MTF measurement has been mainly used for conventional analog imaging devices such as screen-film system, it is thought that the MTF is useful as a quantitative index of resolution properties for displays. From previous researches,[3-5] the MTF measurement methods are classified into three. One is an impulse method with a single line pattern, and an another is a sine-wave method with cyclic sine-wave test patterns produced by signal generator. The remaining one is a square-wave method with cyclic bar patterns.

Recently, Kanazawa et al. reported the accuracy of the impulse method and the sine-wave method using a signal generator and CCD (charge-coupled device) line sensor as an image acquisition device.[6] In this report, they pointed out that the impulse method was not able to reflect the frequency properties of electric video circuit correctly, and concluded that the sine-wave method is suitable. However, in the medical fields, performance evaluation of a display is performed in many cases for a QC(quality control), so their method using special

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equipment is difficult in application. Then, Roehrig et al. employed a remodeled commercial CCD digital camera for imaging a bar pattern, and calculated the square-wave response function from the peak-to-peak value.[7] However, their method needed photographing at many phases of square-wave in order to acquire the correct peak value and could measure the square-response function only. Therefore the effective and simple MTF measuring method suitable for the medical fields is not yet proposed.

Generally, the medical image viewer such as DICOM (Digital Image Communication of Medicine) viewer is composed of a computer and a display, and the overall resolution of the viewer is influenced by performance of both the display and the video interface of a computer. Therefore, for the purpose of QC in the hospital, the overall MTF measurement is useful rather than separate MTF measurement of the display and the video interface.

In this paper, we present a simple and accurate MTF measurement method using a bar pattern for medical image viewer. This method was designed for easy measurement of the overall MTF of the display and the video interface of a computer. The bar pattern was imaged with a single-lens reflex digital camera, and the waveform data obtained from the image data was processed by the interpolation technique based on a sampling theorem.[8] MTF was then calculated by frequency analysis of the interpolated data with Fourier analysis.

2. OVERALL MTF OF MEDICAL IMAGE VIEWER

The composition of the system with special reference to the frequency characteristic of a medical image viewer is shown in **Fig.1**. LPF$_{s1}$ and LPF$_{s2}$ are the frequency characteristics of the video circuit in the video interface of a computer and a display, respectively. LPFo is the frequency characteristic of the optical part such as electron beam spot and the structure of a phosphor.[9] Generally, the video circuits in a video interface of a computer system and display can be regarded as a series of circuits, and then LPFs can be defined as total frequency characteristic by the product of LPF$_{s1}$ and LPF$_{s2}$. The signal waveform of the bar pattern outputted from a video interface is generated from the ideal square-wave data stored in the video memory of the video interface. This waveform is low-pass filtered by LPFs, and is converted with the nonlinear gamma characteristic of video signal (V)-luminance (B) conversion, and finally is influenced by LPFo.

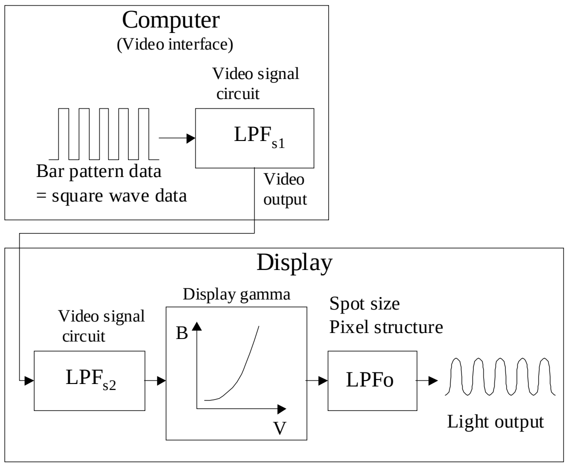


Fig.1 Composition of a medical image viewer.

In MTF measurement of the display of a medical image viewer, it is required to choose the method that can measure the overall influence by LPFs and LPFo correctly. Kanazawa et al. reported that the impulse method does not reflect influence of LPFs correctly because of non-linear gamma characteristic of the display and the sine-wave method is therefore suitable.[6] On the other hand, since the square-wave method by the bar pattern proposed in this paper analyzes only the basic frequency component based on the property that the square-wave contains a fundamental frequency component and harmonics components,[10] this method is equivalent to the sine-wave method and can measure the overall MTF by LPFs and LPFo. Where D is the DC level, A is the amplitude of sine-wave, and f is the frequency of the sine-wave, the input signal $V(x)$ of the fundamental frequency is expressed with the following equation,

$$V(x) = D + A\sin(2\pi fx). \qquad (1)$$

If the frequency characteristic of LPFs and LPFo is set to $F_1(f)$ and $F_2(f)$, respectively, $V(x)$ is influenced by $F_1(f)$, and is converted to luminance by the gamma characteristic, and is finally influenced by $F_2(f)$. Therefore, the output $B(x)$ from the display gamma part is given by the following equation,

$$B(x) = [D + F_1(f)A\sin(2\pi fx)]^2, \qquad (2)$$

where the display gamma is assumed to be 2.
The Fourier transformation result $R_1(f)$ of $B(x)$ is expressed as

$$R_1(f) = \left| \int_{-\infty}^{\infty} B(x) \cdot \exp(-j2\pi fx) dx \right| = 2DAF_1(f). \qquad (3)$$

Then the Fourier transformation result $R_2(f)$ of final output is given by the following equation,

$$R_2(f) = 2DAF_1(f)F_2(f), \qquad (4)$$

when $F_1(f)$ and $F_2(f)$ equal to 1, and $R_2(f)$ becomes $2DA$. Therefore, $MTF(f)$ is finally expressed as the following equation,

$$MTF(f) = \frac{2DAF_1(f)F_2(f)}{2DA} = F_1(f)F_2(f). \qquad (5)$$

Thus, the square-wave method using Fourier analysis can reflect the influence of LPFs and LPFo correctly.

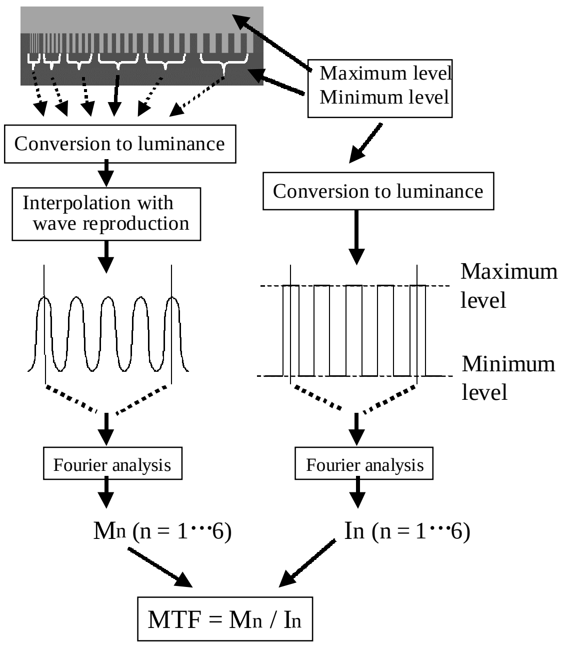
3. METHODS

3.1 Analysis of the bar pattern image

Fig.2 shows the outline of the square-wave method with Fourier analysis of a bar pattern. In our proposed method, two key techniques were employed. One is interpolation of sampling data with wave reproduction based on sampling theorem. This interpolation creates very fine data faithful to an original waveform, and improves the accuracy of frequency analysis. The other is extraction process of the fundamental frequency component from square-wave output image with Fourier analysis. This extraction enables MTF measurement from a square-waveform without using Coltman method. The procedures of the MTF measurement with a bar pattern are as follows:

1) Test pattern

The test pattern used in this study consists of 6 segments (the bar pattern of five cycles of 1-6 pixel width), and two uniform areas for measuring the maximum and the minimum values located at just over and under the bar patterns. To reduce influence of display shading, minimum and maximum values corresponding to each segment are picked up from the portions adjacent to the segment in the uniform areas. Since the beam spot size of the CRT changes with signal level,[6] the amplitude of square-wave should be set up as low as possible. Therefore, the amplitude and the DC level were set at 30% and 50% of the video signal level.



(M_n, I_n : amplitude of fundamental frequency)

Fig.2 The outline of MTF measurement method using frequency analysis of a bar pattern image.

2) Imaging test pattern

The created test pattern imaged with a single lens reflex type digital camera (DCS-330, Eastman Kodak Co.) equipped with a macro lens (Micro Nikkor f60, Nikon Co.) so that the sampling pitch may become sufficiently fine. In this case, the sampling pitch should be set to the appropriate one considering the frequency components of a bar pattern mentioned in the following section. MTF of a digital camera was measured if required, and was used for compensation of a measurement result.

3) Digital value - brightness conversion

A profile of a direction perpendicular to the bar of the bar patterns was created from the obtained image data, and was converted into the brightness value with the pixel value-brightness curve (**Fig. 3**) created using the luminance meter (LS-100, Minolta Camera Co.). Thereby, the nonlinear property that exists between the two is avoided.

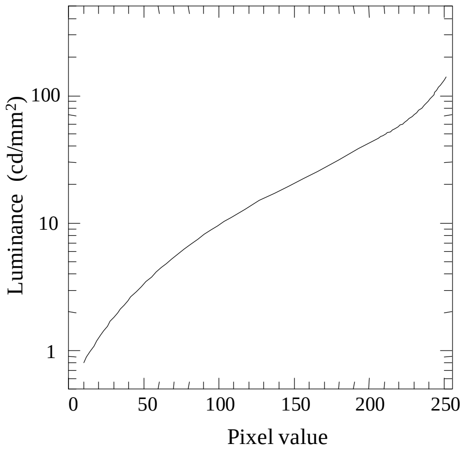


Fig.3 Relation between the pixel value of a digital camera and luminance.

4) Interpolation processing using waveform reproduction

Interpolation processing by the waveform reproduction based on the sampling theorem is performed for obtained profile data, and the data were converted to finer interval data representing the original waveform. This interpolation is an important processing in order to minimize the leak of a frequency analysis by correctly distinguishing the starting point and the terminal point of wave cycles .

Since the sampling data satisfying the sampling theorem contain all the original frequency components, the original waveform reproduction becomes possible by simple calculation processing. **Fig.4** shows the outline of the waveform reproduction of the square-wave low-pass filtered by LPFs and LPFo. The waveform reproduction[11] can be done by inverse Fourier transformation of multiplying frequency domain data by the window function(where 1: below Nyquist frequency, 0 : above Nyquist frequency). **Fig. 5** shows sampling data of 1-pixel width bar pattern and reproduced wave data. In this figure, the sampling interval was set to about 0.05 mm for a pixel pitch of 0.3 mm. The data of about 0.002 mm interval were obtained by waveform reproduction, and interpolated between sampling data without inconsistency.

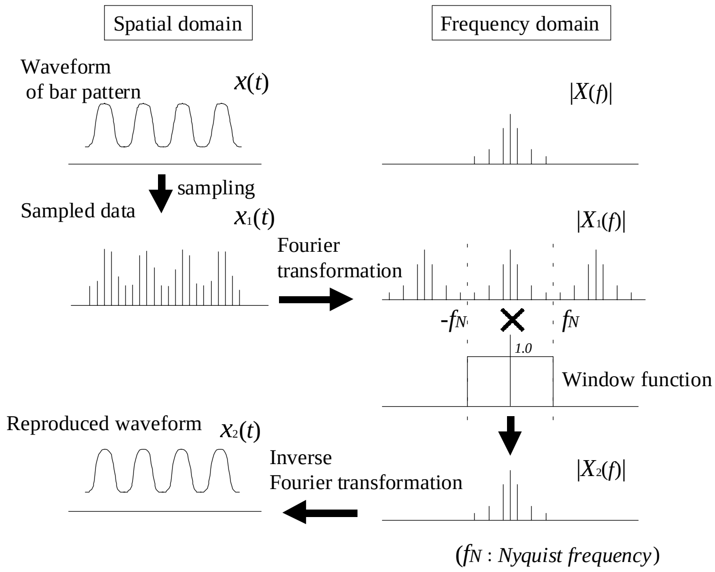


Fig.4 The outline of waveform reproduction.

5) Analysis of interpolated data

The component value of a fundamental frequency, *Mn* (*n* : segment number) was calculated from exact integer cycles data extracted from the interpolated profile data. This extraction is very important for performing accurate Fourier analysis for cyclic waveform.[11] Here, *x* (*i*) is extracted wave data, *N* is the number of data, and *W* is the number of cycles. *Mn* can be calculated by the following equation,

$$Mn = \frac{2}{N}\sqrt{\left(\sum_{i=0}^{N-1} x(i)\sin(2\pi ki)\right)^2 + \left(\sum_{i=0}^{N-1} x(i)\cos(2\pi ki)\right)^2} \quad (6)$$

,

where $k = N/W$.

6) Calculation of MTF

In order to calculate MTF from obtained *Mn*, it is necessary to calculate the inputted component value *In* of the fundamental frequency. *In* is calculated from the maximum and the minimum values measured from two uniform areas mentioned chapter(1). Using *Mn* and *In*, MTF at frequency u_n is given by the following equation.

$$MTF(u_n) = \frac{Mn}{In}, \quad (7)$$

where $u_n = 1 / (2pC_n)$ (*p* : pixel pitch, C_n : pixel width of bar pattern of segment *n*). In actual measurement, since a pixel pitch often changes with image viewers, the frequency normalized with the Nyquist frequency determined by the pixel pitch was used.

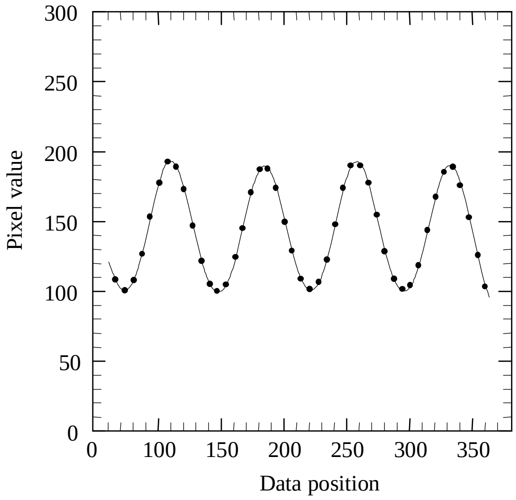


Fig.5 Sampled data (points) of bar pattern image and interpolated waveform obtained by the waveform reproduction (solid line).

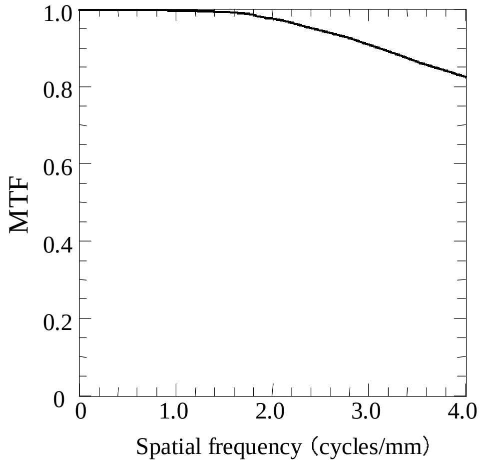


Fig.6 Horizontal MTF of a digital camera.

3.2 Imaging with digital camera

In actual imaging, the room light was switched off to avoid its influence. Since high flexibility and high performance were required of the digital camera to be used, a single-lens reflex type digital camera was employed. The CCD of this camera has the number of effective pixels of 2008 x 1504 and 10 bits gradation per pixel. The combination of this camera and macro lens can picturize display surface at very fine sampling pitch. For example, when the field size of about 50 mm x 40 mm can be imaged at a distant of about 20 cm from the display surface, the sampling pitch becomes about 0.025 mm. The sampling pitch in this geometry is sufficiently fine for display pixel pitch of about 0.2-0.3 mm. Two medical image viewers were examined in this study, which were equipped with 2 models of monochrome CRT displays. Respective viewers (viewer A and B) have image fields of 392mm x 294 mm and 400 mm x 300 mm and pixel numbers of 1280 x 1024 (pixel pitch about 0.3 mm) and 1200 x 1600 (pixel pitch about 0.25 mm).

3.3 Resolution property of digital camera

When it is assumed that optical resolution of a macro lens and the frequency characteristic of the signal-processing part of digital camera have sufficient performance, the total resolution property of a digital camera is greatly influenced by the pixel size that determines the sampling aperture size at the display surface. If the shape of the aperture is rectangular, MTF of the digital camera at the display surface is expressed by the following formula.

$$MTF(u) = \frac{\sin(2\pi ud)}{2\pi ud}, \qquad (8)$$

where d is a half of pixel size and u is a spatial frequency.

Here, in case of the display pixel pitch of 0.2 mm, when the sampling pitch is set to one fifth of the pixel pitch of a display, MTF at Nyquist frequency (= 2.5 cycles/mm) given by equation (8) becomes about 0.98 and the MTF value is sufficiently good. In this case, the Nyquist frequency by the sampling pitch becomes 5 times larger than the Nyquist frequency of the display, and can respond to the 2nd harmonic generated from the bar pattern of 1-pixel width. The 2nd and 3rd harmonics located at more than 10 cycles/mm are decreased by LPFs and LPFo and become to slight amplitude, therefore it is considered that the sampling pitch that we determined hardly causes the aliasing error. If the number of pixels of the digital camera is known, the determination of the imaging field size for required sufficient sampling is easy. Because DCS-330 used in this examination has horizontal pixels of 2008, required horizontal field size should be set to about 400-pixel width. **Fig.6** shows horizontal MTF of DCS330 in case of the horizontal field size of 80 mm. MTF value of 0.95 in 2.5 cycles/mm was also slightly lower than a value given from equations (8), and it was shown that DCS-330 has sufficient resolution property.

4. RESULTS

The measurement results of 2 models of image viewers are shown in **Fig.7**. The test patterns for both models were displayed in the center of screens. The horizontal axis of the graphs shows Nyquist frequency determined from the pixel pitch of displays. In both models, vertical resolution is higher than horizontal one, and as for horizontal resolution, MTF fells markedly as frequency becomes high. Furthermore, in both models, horizontal MTFs at the Nyquist frequency (viewer A: 1.67 cycles/mm, viewer B: 2.0 cycles/mm) become lower than 0.5 and the result showed that both models did not have sufficient resolution property. Also, in visual comparison, the resolution of viewer A was inferior to that of viewer B. The MTF values represented the result of visual comparison quantitatively. **Table 1** shows variation in 5 measurements at the Nyquist frequency of viewer A. The result shows that this method has good reproducibility in horizontal and vertical directions.

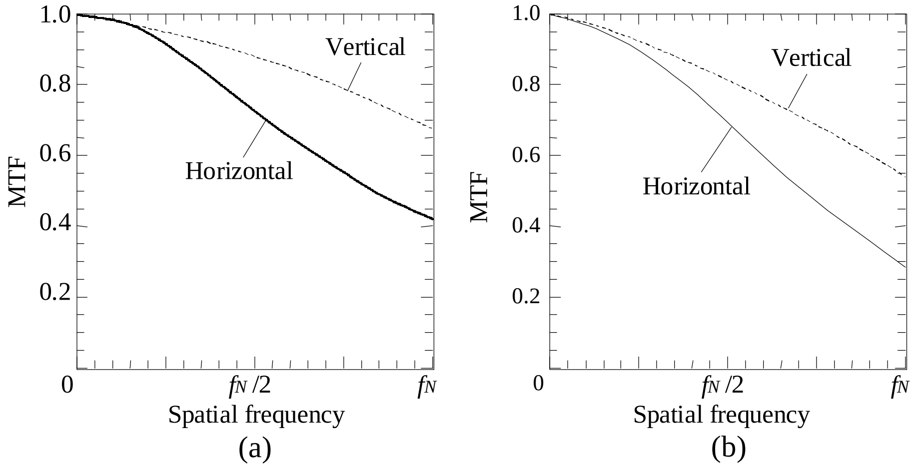


Fig.7 MTFs for 2 models of medical image viewer, (a) viewer A and (b) viewer B. f_N : Nuquist Frequency.

Table1 MTF values in Nyquist frequency obtained by five different measurements. Average and standard deviation (SD) of the MTFs were calculated.

Measurement	Horizontal	Vertical
1	0.408	0.705
2	0.404	0.686
3	0.403	0.690
4	0.411	0.696
5	0.410	0.710
Average	0.407	0.697
SD	0.004	0.010

(at Nyquist frequency)

5. DISCUSSION

Generally, the medical image viewer is composed of a computer and a display. The resolution of the viewer depends not only on the resolution of the display but also on the resolution of the video interface of a computer. As a technique of measuring these overall MTF(s), one may consider to measure the MTF of display and video interface separately. However, since MTF measurement of the frequency higher than the Nyquist frequency is difficult for the video interface, the frequency range of overall MTF measurement is inevitably restricted to below the Nyquist frequency. Furthermore, for medical image observation, the resolution of the frequency higher than the Nyquist frequency is not important. Therefore, even if measurement at higher than the Nyquist frequency is impossible with this method, the limited frequency range may not be a weak point.

In MTF measurement of the display using the sine- or square-wave test pattern, how the peak positions and waveform shapes are caught correctly influences measurement accuracy. Kanazawa et al. performed data collection changing the phase of the signal from a signal generator by 45 degrees.[6] Blume et al. reported a method of imaging the limited narrow field at intervals of the very fine sampling pitch of 0.01 mm or less.[12] In the former method, many data acquisitions are needed at each frequency, and in the latter method, imaging field becomes extremely narrow. Therefore, both methods are associated with complicated measurements and data processing. On the other hand, our method allows high accuracy measurement by practical imaging field and one-time data acquisition when the sampling theorem is fulfilled (five or more points between pixel pitch). Also, in consideration of the influence of shading of display, this method has the feature of being hardly influenced by shading compared with the technique of measuring peak value. However, if the areas for the minimum and maximum value measurement to obtain input amplitude: *In* are influenced of shading, some errors are produced in measured value. In order to reduce this influence, the pixel number of vertical direction of the bar patterns was made as small as 15 pixels and the areas for minimum and maximum values were placed just over and under the bar patterns.

In this study, since most high-resolution image viewers for medical diagnosis are equipped with a monochrome display, the adaptation of this method was considered only as monochrome display. This method was aimed to be readily used in medical fields. Therefore, the simple measuring method was developed by using a combination of a commercial single lens reflex type digital camera and a commercial macro lens. Moreover, image data also can be dealt with simple computer programs by the high flexibility data format.

6. CONCLUSION

We have presented a new MTF measurement method for medical image viewer using a bar pattern image and proved that this method has sufficient accuracy by actual measurement. This method was designed for easy measurement of the overall resolution of the display and the video interface of a computer. MTF was then calculated by frequency analysis of the interpolated data obtained by wave reproduction technique. Due to the simple operativity and accuracy, we believe that this method could grow into the useful MTF measurement technique in the future era of monitor diagnosis.

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