White Paper

Benefits of an Aperture Modulation LCD Panel

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1 Overview

The number of displayable grayscale tones is one of the key criteria in selecting a medical LCD monitor. The question is often discussed whether 8-bit or 10-bit simultaneous grayscale display meets the necessary requirements for accurate medical imaging. Recently, there is growing interest in 11-bit and even 12-bit simultaneous grayscale display. Although the image-observing ability may vary between individuals, the human eye can recognize subtle grayscale tone differences. Therefore, we can assume that the ideal solution would be to use monitors, which can precisely display the subtle tonal differences in the image data. To this end, medical display monitor manufacturers have been carrying out continuous research and development to achieve a higher number of displayable grayscale tones.

EIZO's new 3 megapixel monitor, the RadiForce G33, adopts what is called an aperture modulation LCD panel to achieve a higher number of displayable grayscale tones. Aperture modulation is multi-grayscale technology that applies "space modulation" technology and "frame rate control" (FRC) technology to an aperture modulation LCD panel, which has a different aperture area ratio of 2:4:1 for each sub-pixel (patent pending). Aperture modulation provides a 13-bit Look-Up Table (LUT) that produces a palette of 8,161 grayscale tones. This not only offers higher correction accuracy for 8-bit (256 tones) display and 10-bit (1,021 tones) display, but also makes possible 11-bit (2,048 tones) and 12-bit (4,096 tones) simultaneous grayscale display. It is also partly confirmed that its unique sub-pixel structure improves the MTF (Modulation Transfer Function) characteristics or the contrast response characteristics. (Under continuous assessment. See explanation on pages 12 – 13.)

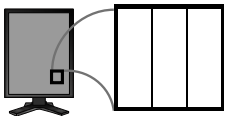


Fig 1: Standard Aperture Sub-pixel

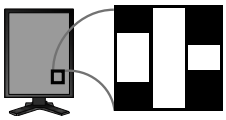
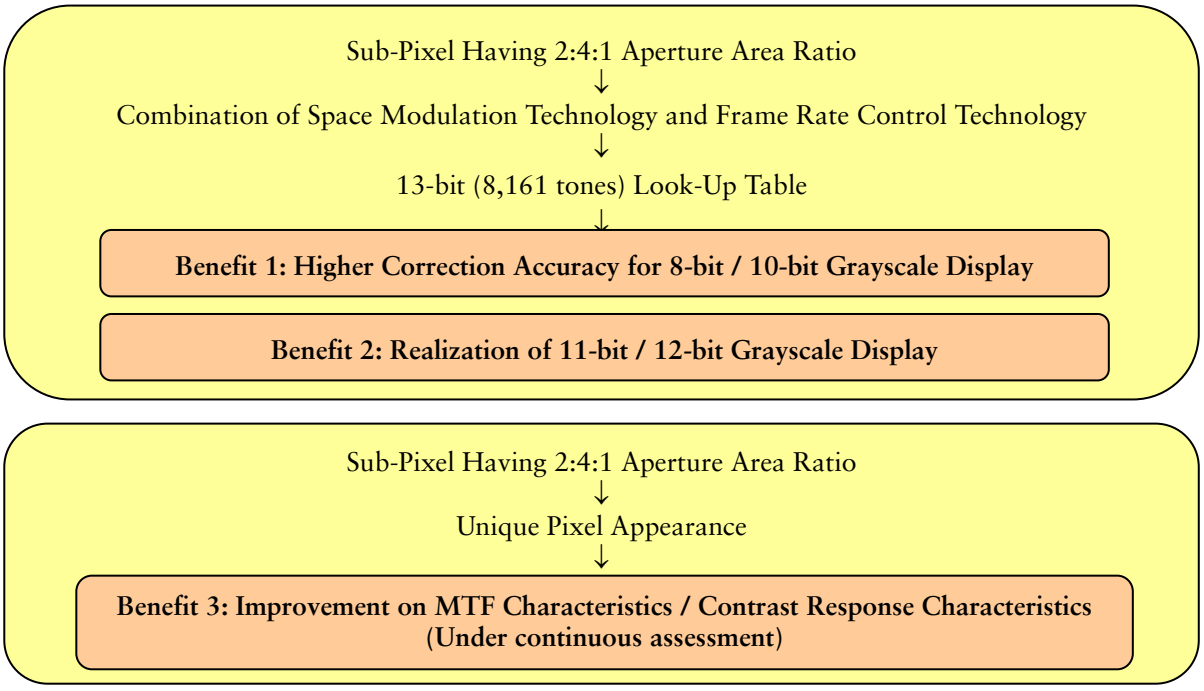


Fig.2: 2:4:1 Aperture Sub-pixel



This white paper will explain and illustrate the above three benefits for medical display monitors derived from an aperture modulation LCD panel.

2 Multi-Grayscale Technology

2.1 Standard Multi-Grayscale Technology

What types of multi-grayscale technology is commonly adopted by medical display monitor manufacturers? Whereas a standard LCD monitor usually receives image data in 8-bit (256 tones) from a computer and displays it in the same 8-bit (256 tones), a medical display monitor is required to incorporate technology that allows for a display of ideal grayscale tones selected from a built-in LUT that contains a wider range of grayscale tones than the image data sent out from a computer. This is necessary in order to meet the Grayscale Standard Display Function (GSDF) requirements or the gamma value. The technologies normally used to create a higher number of grayscale tones for a LUT than the input signal from the computer are "**space modulation" technology** and "**framed rate control" (FRC) technology**.

2.1.1 Space Modulation Technology

We will begin by explaining space modulation technology. A color LCD monitor, which is dominant in the standard LCD monitor market today, incorporates a color LCD panel. The color LCD panel consists of a number of pixels or picture elements, each of which is composed of three sub-pixels with three different color filters, red, green, and blue by which the color is realized. As for a monochrome LCD monitor for medical imaging, its panel has the same structure as the color monitor except for the color filters (Fig. 3).

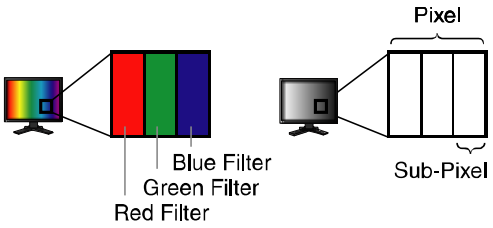


Fig 3: Color and Monochrome LCD monitors

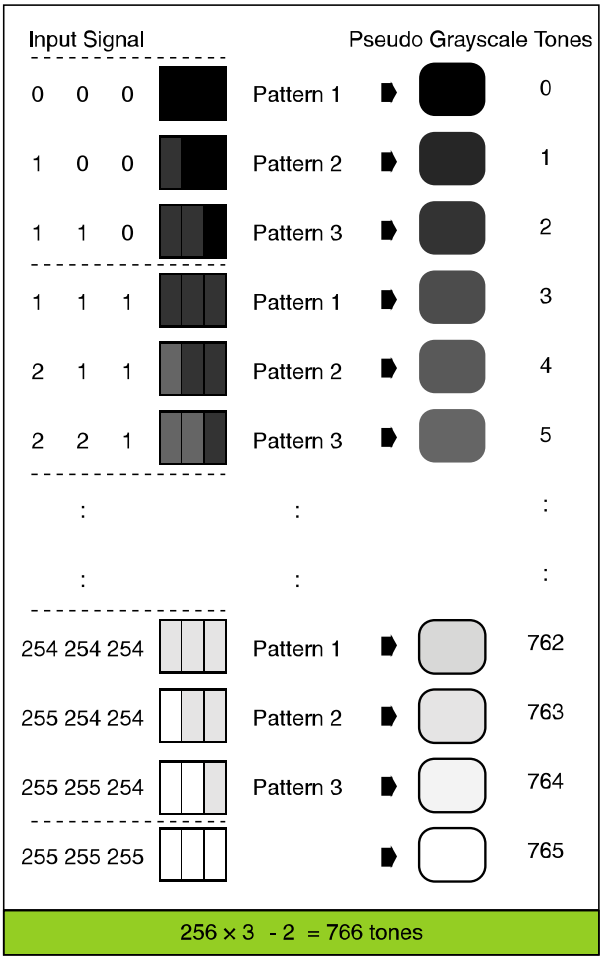


Fig. 4: Space Modulation

Normally, each pixel on a monochrome LCD monitor produces 0 to 255 grayscale tones. However, space modulation technology enables each pixel to produce more grayscale tones by taking advantage of the visual effect that the human eye will recognize in the difference of brightness as the space of the light source changes when passing through the pixel. With this technology, each sub-pixel is controlled by 8-bit or 256 signals to differentiate the space that the light source is coming through. Therefore, each pixel with three equally sized sub-pixels can create three different patterns of lighted space (Fig. 4). This means that each pixel can produce three different pseudo grayscale tones with one input signal and thereby, a monochrome LCD monitor using space modulation technology is capable of having **256 x 3 – 2 = 766 tones (9.5-bit)**. The 255th input signal can produce only one tone and therefore two is subtracted ("-2") from the total multiplication.

2.1.2 Frame Rate Control (FRC) Technology

Frame rate control (FRC) technology is one of the temporal modulation technologies which switch over the displayed two different grayscale tones at the speed of light to create pseudo grayscale tones in between.

Here is how four different grayscale tones are created within one input signal range. An LCD monitor can only refresh the display every 1/60 second, which is referred to as one frame. Therefore, four frames, which are 4/60 seconds, are considered as one cycle to create pseudo grayscale tones with FRC technology in this case. The first frame displays input signal 1 and the other three displays input signal 0 to create one pseudo grayscale tone. Next, the first two frame displays input signal 1 and the other two displays input signal 0 to create another new pseudo grayscale tone, and so on (Fig. 5). Using this FRC technology, a monochrome LCD monitor is capable of multiplying four grayscale tones between each input signal creating **256 x 4 –3 = 1,021 tones (10-bit)**.

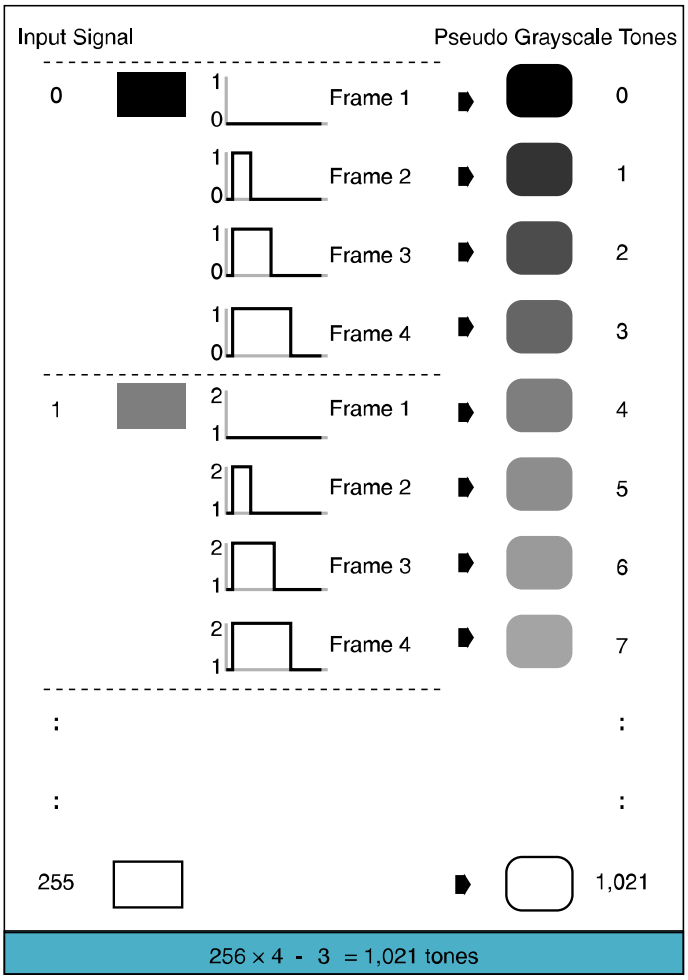


Fig. 5: Frame Rate Control (FRC)

2.1.3 Combination of Space Modulation Technology and FRC Technology

When both the above mentioned space modulation technology and FRC technology are applied, the number of available grayscale tones on a monochrome LCD monitor can multiply to 1,531 tones or 3,061 tones. The EIZO RadiForce G21, G20 and G11 incorporate a built-in 10.5-bit (1,531 tones) wide LUT, which has been realized by multiplying the original 256 tones to 766 tones with Space Modulation technology and additionally multiplying **766 x 2 – 1 = 1,531 tones (10.5-bit)** with two frames per cycle of FRC technology.

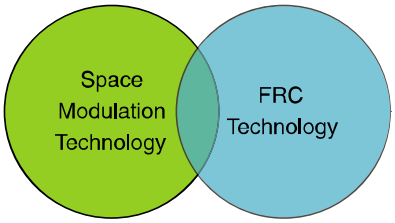


Fig. 6: Combination of Two Technologies

The RadiForce G51, G31 and G22 are enabled to have a built-in 11.5-bit (3,061 tones) wide LUT by multiplying the original 256 tones to 766 tones with Space Modulation technology and additionally multiplying **766 x 4 – 3 = 3,061 tones (11.5-bit)** with four frames per cycle FRC technology.

2.2 Aperture Modulation LCD Panel

2.2.1 Sub-Pixel Having 2:4:1 Aperture Area Ratio

EIZO's new monochrome LCD monitor, the RadiForce G33, employs an aperture modulation LCD panel to achieve a higher number of displayable grayscale tones. Aperture modulation is multi-grayscale technology that applies "space modulation" technology and "frame rate control" (FRC) technology to an aperture modulation LCD panel, which has a different aperture area ratio of 2:4:1 for each sub-pixel (Fig. 8) (patent pending). This technology allows the G33 to incorporate a 13-bit (8,161 tones) LUT. The following section gives a technical explanation of how aperture modulation achieves a 13-bit LUT.

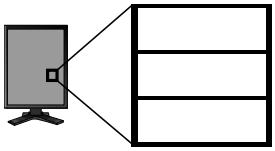


Fig. 7: Standard 1:1:1 Aperture Area Ratio

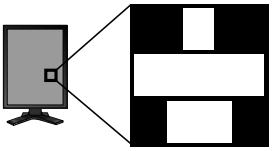


Fig. 8: RadiForce G33's 2:4:1 Aperture Area Ratio

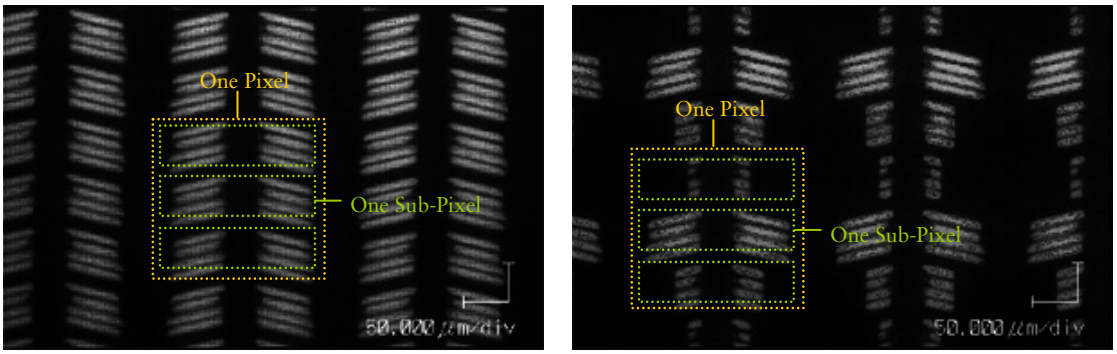


Fig. 9: Actual Image Comparison of the Pixel Structure (Enlarged)

2.2.2 Space Modulation Technology with an Aperture Modulation LCD Panel

As explained in the chapter 2-1-1, space modulation technology with a standard monochrome LCD panel having 1:1:1 aperture area ratio produces three pseudo grayscale tones with one pixel within one input signal. The maximum number of tones produced with one pixel within one input signal is limited to three due to the fact that all three sub-pixels have the same-sized aperture ratio. However, with an aperture modulation LCD panel having three different-sized aperture ratio sub-pixels, it becomes possible to create seven different patterns of lighted space as illustrated in Fig. 10. By creating seven pseudo grayscale tones with one pixel within one input signal, the aperture modulation LCD Panel is able to multiply its grayscale tones to **256 x 7 – 6 = 1,786 tones.**

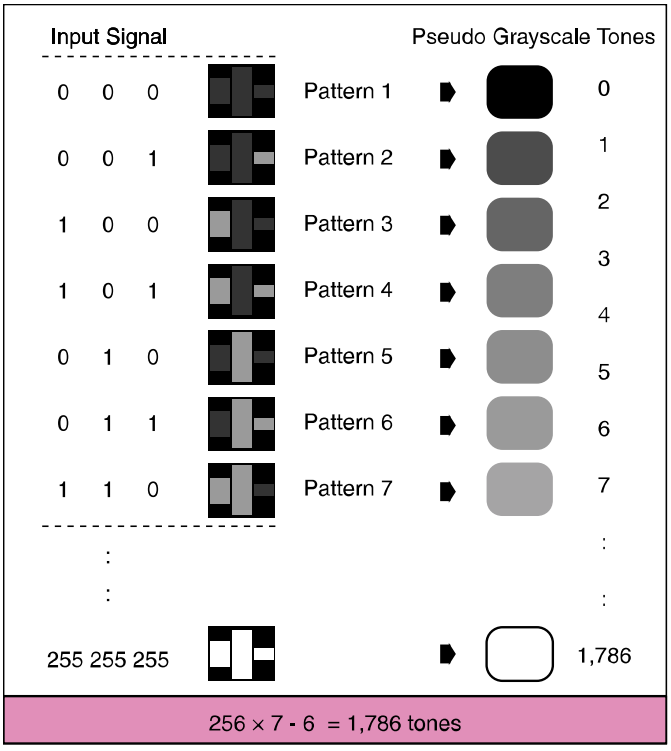


Fig. 10 Aperture Modulation

2.2.3 Space Modulation and FRC Technologies with an Aperture Modulation LCD Panel

Furthermore, an aperture modulation LCD panel can also combine FRC technology explained in chapter 2-1-2. When FRC technology together with space modulation technology is applied to an aperture modulation LCD panel, one pixel can create 90 pseudo grayscale tones from one input signal. Among those 90 pseudo grayscale tones, 32 tones of which mostly keep the linearity and accuracy are selected (Fig. 11).

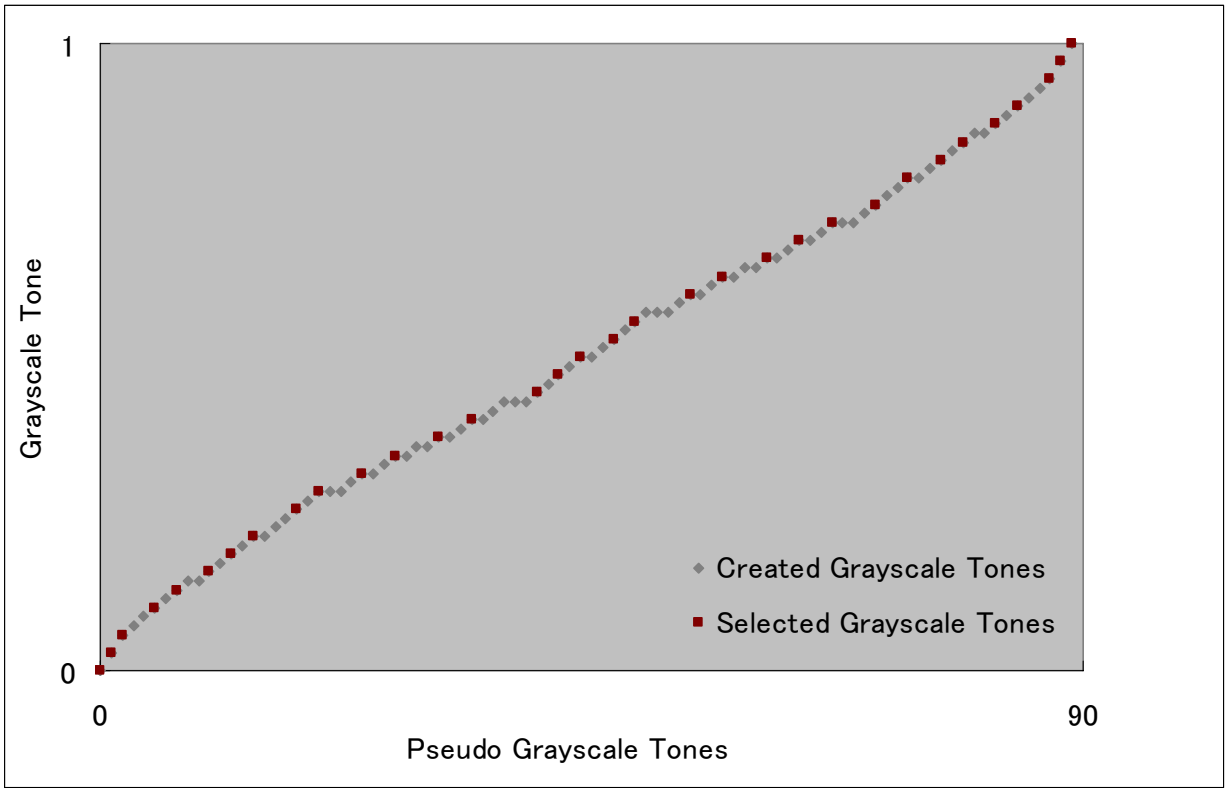


Fig. 11: Selected 32 Pseudo Grayscale Tones

This is how the RadiForce G33 achieves **256 x 32 – 31 = 8,161 tones (13-bit)** LUT with an aperture modulation LCD panel.

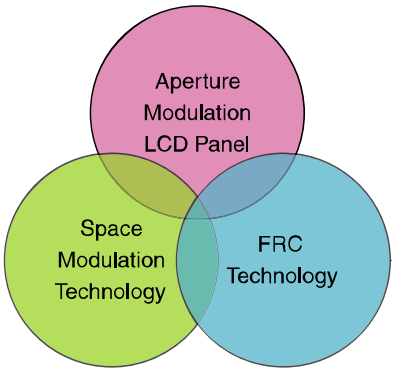


Fig. 12: Space Modulation and FRC Technologies with Aperture Modulation LCD Panel

3 Benefit 1: Correction Accuracy Improvement with a 13-bit Look-Up Table

What is the benefit of having a Look-Up Table (LUT) that multiplies to 8,161 tones (13-bit)? We will compare the new RadiForce G33 monitor incorporating a 13-bit (8,161 tones) LUT with the current RadiForce G51, G31 and G22 monitors having an 11.5-bit (3,061 tones) LUT.

3.1 Correction Accuracy Improvement on an 8-bit Monitor System

An 8-bit wide input means that an original 12-bit wide DICOM medical image is reduced to 8-bit wide data while being transferred through the viewer software and the graphics board. The change of the data bit width at each processing stage on an 8-bit monitor system is shown in the following Table 1.

	DICOM Image		Viewer Software		Graphics Board		Look-Up Table		Display on Monitor
Current	12-bit	→	8-bit	→	8-bit	→	11.5-bit (3,061 tones)	→	8-bit
New	12-bit	→	8-bit	→	8-bit	→	13-bit (8,161 tones)	→	8-bit

Table 1: Data Processing Flow of an 8-bit Monitor System

A medical display monitor usually corrects its grayscale characteristics by selecting the ideal tones from the LUT with a wider bit width than from the signal sent out from a computer. The standard from which the monitor is corrected by is the DICOM curve or the GSDF (Grayscale Standard Display Function). (Refer to White Paper No. 04-001 “Accurate Grayscale on Medical Display Monitors” for details.) Fig. 13 and 14 respectively plot the estimated error rate of the DICOM curve and the corrected grayscale characteristic curve at each grayscale tone on an 8-11.5-8-bit monitor system and an 8-13-8-bit monitor system. The curves of the 8-11.5-8-bit monitor system have a margin of error of about 0.3% in low grayscale tone areas, whereas the curves of the 8-13-8-bit monitor system have a lesser margin of error of about 0.1%.

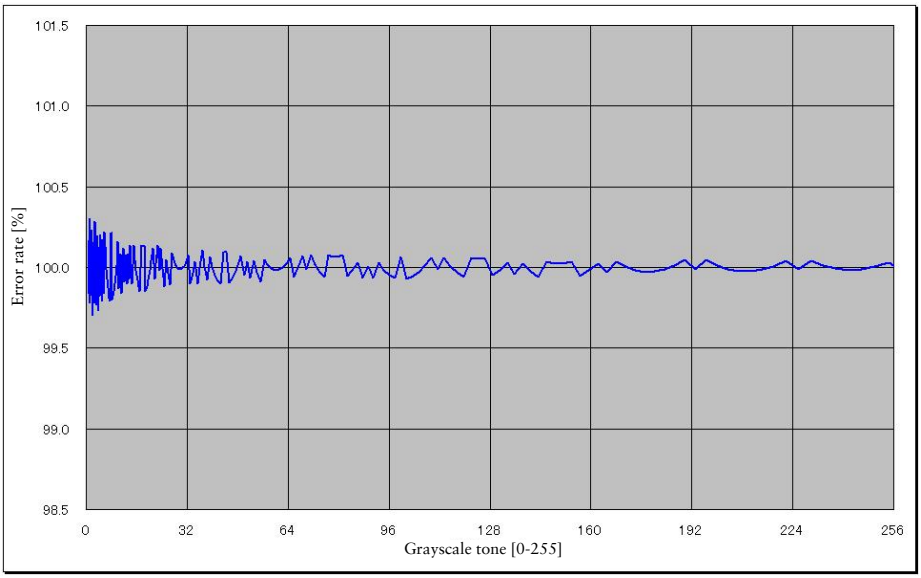


Fig. 13: Error Rate of an 8-11.5-8-bit Monitor System

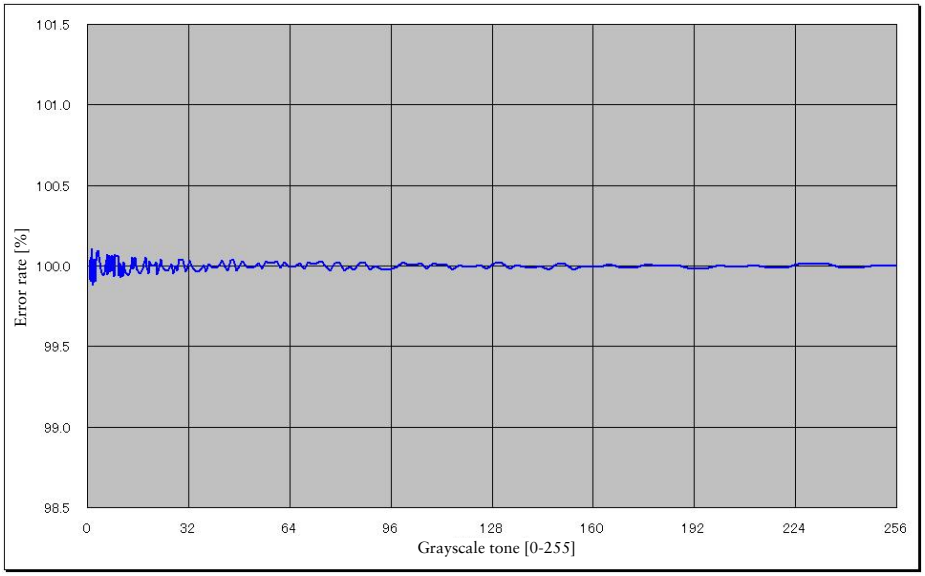


Fig. 14: Error Rate of an 8-13-8-bit Monitor System

For the display of 8-bit data, the estimation suggests that a RadiForce monitor with a 13-bit (8,161 tones) LUT offers a slight improvement in correction accuracy of grayscale characteristics than a monitor with an 11.5-bit (3,061 tones) LUT. This is because the monitor with a 13-bit LUT can select more ideal 8-bit grayscale tones than 11.5-bit LUT.

3.2 Correction Accuracy Improvement on a 10-bit Monitor System

Table 2 shows the changes of the data bit width at each processing stage on a 10-bit monitor system.

	DICOM Image		Viewer Software		Graphics Board		Look-Up Table		Display on Monitor
Current	12-bit	→	10-bit	→	10-bit	→	11.5-bit (3,061 tones)	→	10-bit
New	12-bit	→	10-bit	→	10-bit	→	13-bit (8,161 tones)	→	10-bit

Table 2: Data Processing Flow of a 10-bit Monitor System

Again, Fig. 15 and 16 respectively plot the estimated error rate of the DICOM curve and the corrected grayscale characteristic curve at each grayscale tone on a 10-11.5-10-bit monitor system and a 10-13-10-bit monitor system. The curves of the 10-11.5-10-bit monitor system have a margin of error of about 0.2% to 0.3% in low to middle grayscale tone areas, whereas the curves of the 10-13-10-bit monitor system have a lesser margin of error of only 0.1% in overall grayscale tone areas.

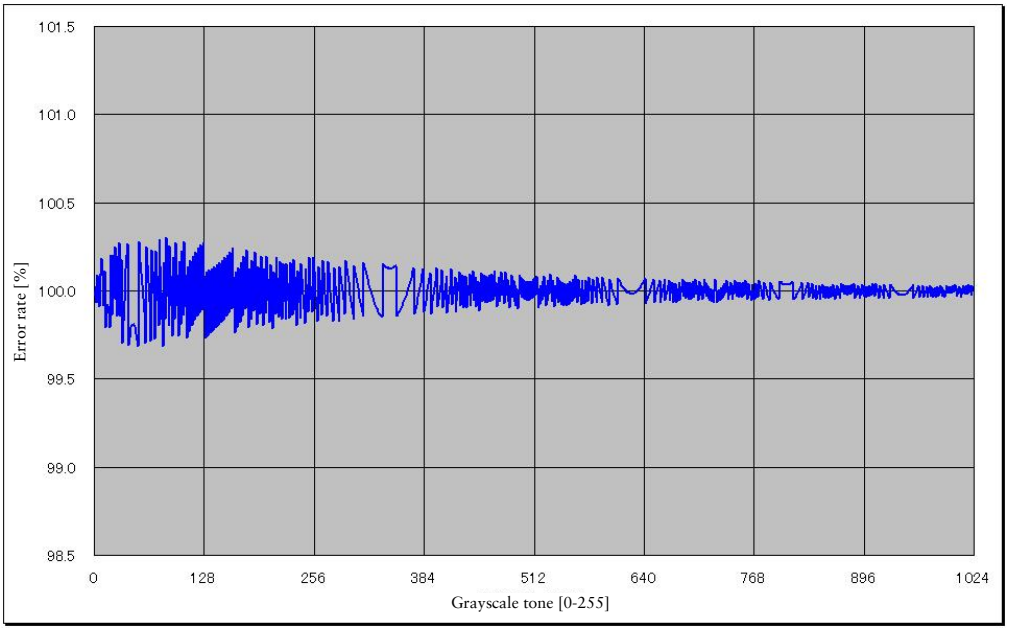


Fig. 15: Error Rate of a 10-11.5-10-bit Monitor System

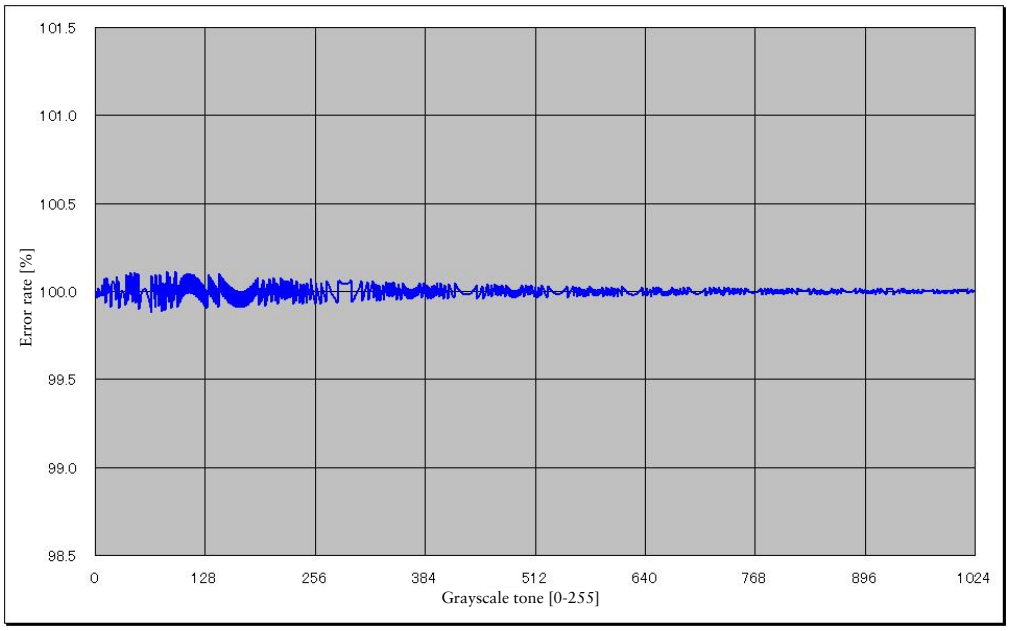


Fig. 16: Error Rate of a 10-13-10-bit Monitor System

As with the display of 10-bit data, the estimation suggests that a RadiForce monitor with a 13-bit (8,161 tones) LUT offers improvement in correction accuracy of grayscale characteristics than a monitor with an 11.5-bit (3,061 tones) LUT. This also is because the monitor with a 13-bit LUT can select more ideal 10-bit grayscale tones than an 11.5-bit LUT.

4 Benefit 2: Achievement of 11-bit / 12-bit Simultaneous Grayscale Display

4.1 11-bit / 12-bit Simultaneous Grayscale Display

Now, we will discuss the display of 11-bit / 12-bit data. Current monitors with an 11.5-bit LUT support up to 10-bit simultaneous grayscale display and their 3,061 tone palette is not rich enough to allot the ideal tones for 11-bit / 12-bit display. Therefore, the RadiForce G33 with a 13-bit (8,161 tones) LUT is the first RadiForce monitor that supports 11-bit / 12-bit simultaneous grayscale display. Table 3 shows the changes of the data bit width at each processing stage on an 11-bit / 12-bit monitor system.

	DICOM Image		Viewer Software		Graphics Board		Look-Up Table		Display on Monitor
New	12-bit	→	11-bit / 12-bit	→	11-bit / 12-bit	→	13-bit (8,161tones)	→	11-bit / 12-bit

Table 3: Data Processing Flow for 11-bit / 12-bit Monitor System

Since the current monitors do not support 11-bit / 12-bit grayscale display, we cannot compare the error rate of the DICOM curve and the corrected grayscale characteristic curve on an 11/12-13-11/12-bit monitor system and an 11/12-11.5-11/12-bit monitor system. Instead, we will compare the graphs that show the estimated number of JND steps between each tone (Refer to White Paper No. 04-001 “Accurate Grayscale on Medical Display Monitors” for the detail of JND). The constant and smaller JND steps, ideally less than 1 step, mean smoother grayscale display.

Fig. 17 shows the number of JND steps between each tone on a 10-11.5-10-bit monitor system. The average JND steps are less than one, which means that grayscale tone differences are relatively unnoticeable. However, the JND steps fluctuate at each tone. This means that the grayscale display is not smooth enough or may have banding and other degradations within the displayed images.

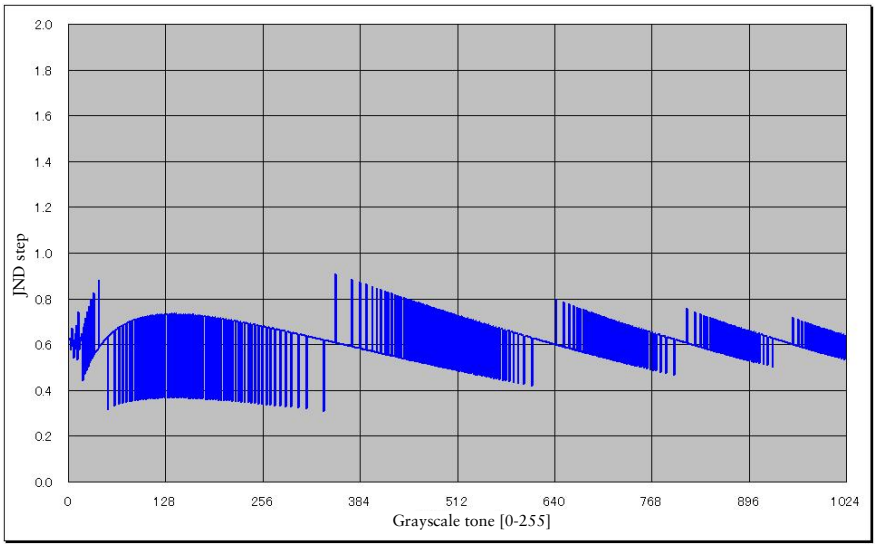


Fig. 17: JND Steps of a 10-11.5-10-bit Monitor System

Fig. 18 shows the estimated number of JND steps between each tone on a 12-13-12-bit monitor system. The average JND steps are less than 0.2, which means that grayscale tone differences are unnoticeable. In addition, the fluctuations of the JND steps between each tone are much smaller than that of a 10-11.5-10-bit monitor system. Therefore, the grayscale display of a 12-13-12-bit are less likely to have image quality degradations such as banding and tonal jumps compared to a 10-11.5-10-bit monitor system.

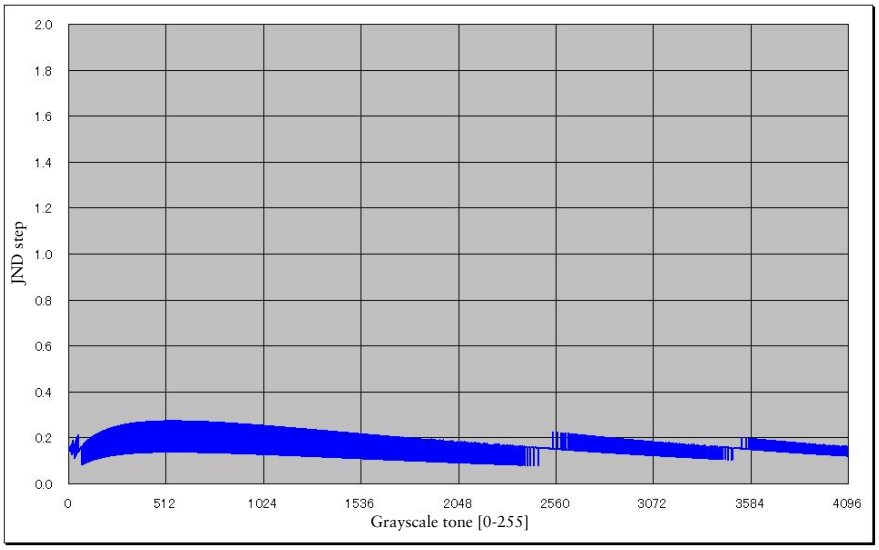


Fig. 18: JND Steps of a 12-13-12-bit Monitor System

4.2 Capability and Potential of an 11-bit / 12-bit Simultaneous Grayscale Display

The RadiForce G33 is the first to achieve 11-bit / 12-bit simultaneous grayscale display among RadiForce monitors which further ensures extremely smooth grayscale rendering. The human eye has the ability to perceive subtle brightness differences and observation ability varies between individuals. JND step 1 indicates the minimum brightness difference that the average human observer can just perceive. The estimated average JND steps of the RadiForce G33 are as small as 0.2, which means this monitor will be able to display an extremely smooth grayscale and even extremely sensitive observers would not be able to discern the steps of tones. Therefore, there is a possibility that medical professionals can perceive extremely subtle tone shadings within medical images such as chest X-ray images that might not been able to be perceived on current monitors due to the bandings and tonal jumps (Fig. 19).

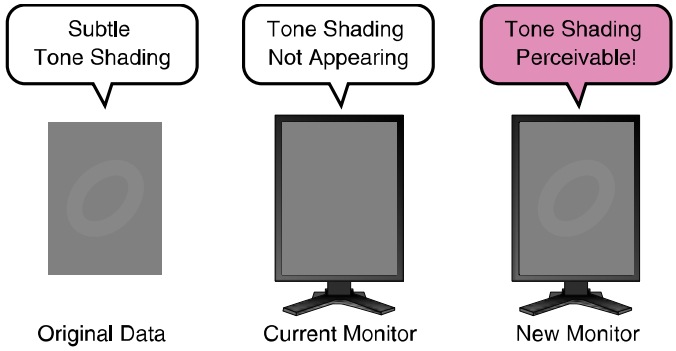


Fig. 19: Subtle Tone Shading Perceivable (Simulation Only)

Unfortunately, viewer software supporting 11-bit / 12-bit is yet being used today which gives a limited stage for the RadiForce G33. However, considering the increasing interest in 12-bit simultaneous grayscale display, demand for medical display monitors with the capability of displaying a higher number of grayscale will surely rise.

5 Benefit 3: Improvement of MTF Characteristics (Contrast Response Characteristics)

The third benefit of an aperture modulation LCD panel is the improvement of MTF Characteristics. MTF (Modulation Transfer Function), also known as CTF (Contrast Transfer Function), is a parameter to define the display sharpness and the resolution of a monitor panel. The MTF characteristics or the MTF curve is often indicated as a figure to objectively evaluate the monitor performance. The curve shows how the contrast decreases as onscreen black and white stripes become thinner.

Spatial Frequency refers to the number of line pairs per millimeter. The higher the spatial frequency is, the thinner the stripes are.

Spatial Frequency of RadiForce G31 and G33

- Pixel Pitch: 0.207mm
- Width of line pairs (Total width of a white line and a black line; One pixel pitch can either display one white line nor one black line): 0.207 x 2 = 0.412mm
- Spatial Frequency: 1 ÷ 0.412 = 2.427 line pairs / mm

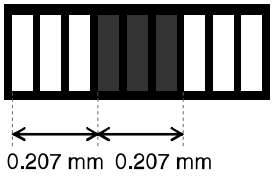


Fig. 20: Pixel Pitch of G31 and G33

Contrast refers to the value derived from the following equation.

- Lmax = Maximum brightness when displaying a white image
- Lmin = Minimum brightness when displaying a black image

$$\text{Contrast} = \frac{(\text{Lmax} - \text{Lmin})}{(\text{Lmax} + \text{Lmin})}$$

The monitor contrast decreases as the pairs of lines become thin, or in other words, as the spatial frequency increases. When comparing MTF curves, the monitor with the curve that keeps a higher contrast at a higher spatial frequency has superior sharpness and resolution. Fig. 21 compares the actual MTF curves of the RadiForce G31 and G33. The MTF curve of the G33 shows a higher contrast ratio at a higher special frequency, and accordingly has better MTF characteristics than that of the G31. In other words, the G33 is expected to display sharper and more detailed images, which is closer to the original image data than the G31.

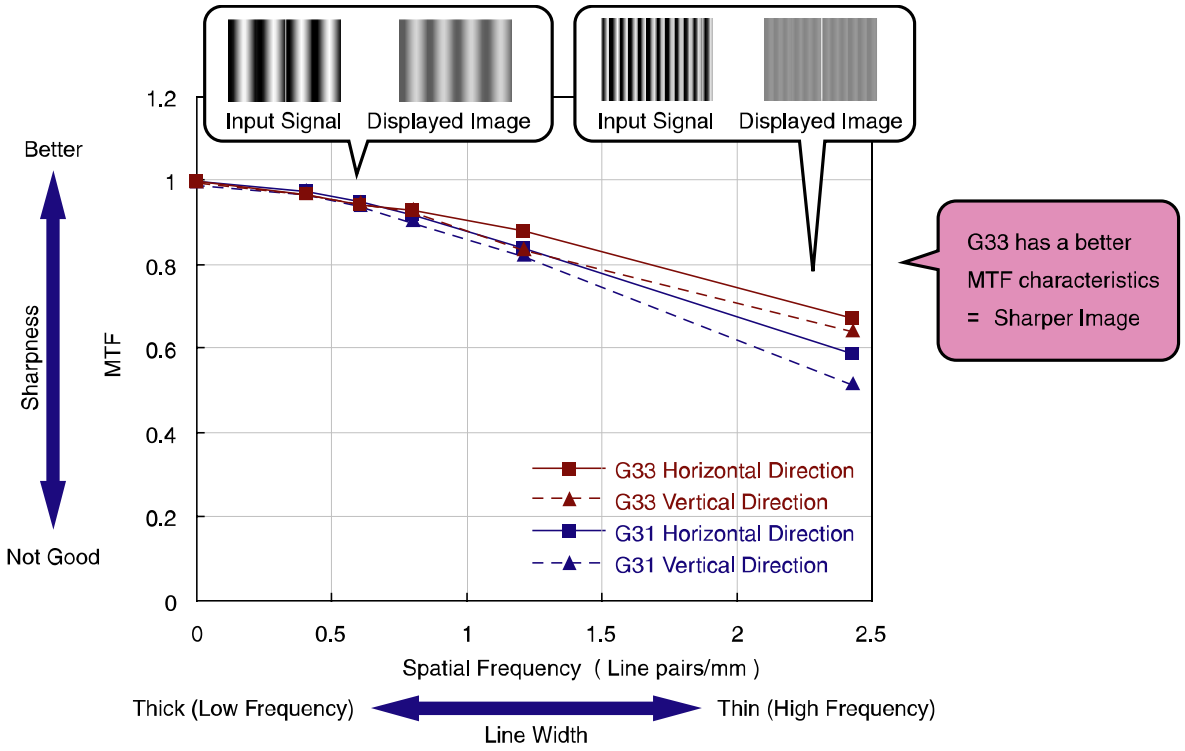


Fig. 21: Comparison of MTF Characteristics

The appearance of the pixel structure may have an influence upon the MTF characteristics. The pixels of a standard LCD panel give the appearance of a rectangular shape (Fig. 22), whereas the pixels of an aperture modulation LCD panel give the appearance of a dot shape due to the aperture ratio (Fig. 23). We will conduct further evaluation of how pixel appearances influence the monitor performance.

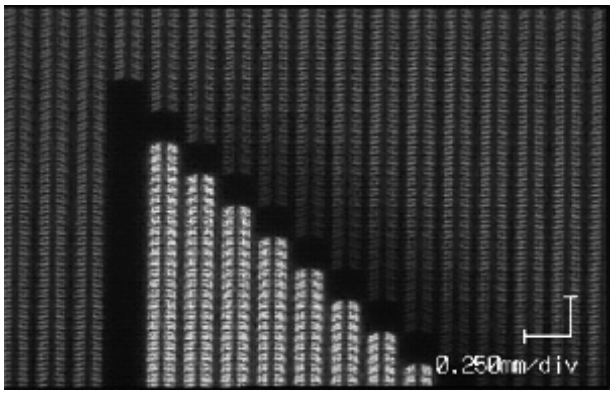


Fig. 22: Pixel Shape of a Standard Panel (x 100)

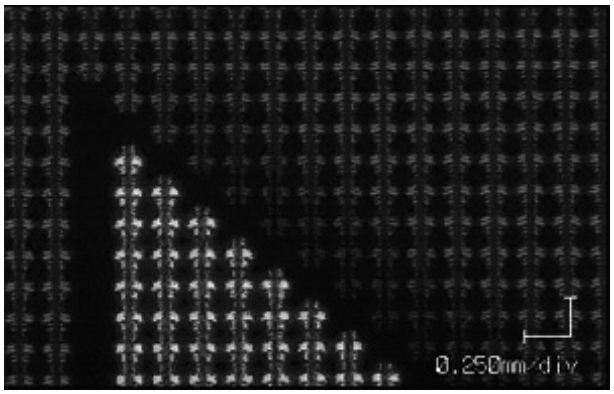


Fig. 23: Pixel Shape of an Aperture Modulation Panel (x 100)

6 Summary

EIZO's new medical display monitor, the RadiForce G33, employs an aperture modulation LCD panel. Aperture modulation is multi-grayscale technology that uses the combination of space modulation technology and frame rate control (FRC) technology and is applied to an aperture modulation LCD panel with the sub-pixel having a 2:4:1 aperture area ratio. With this multi-grayscale technology, G33 has achieved an 8,161 grayscale tone (13-bit) LUT.

For 8-bit or 10-bit display, the RadiForce G33 with a 13-bit (8,161 tones) LUT is expected to offer more accurate grayscale display than the current RadiForce monitors. This is because the monitor with a richer 13-bit LUT is allowed to select more ideal 8-bit grayscale tones than monitors with an 11.5-bit LUT.

In addition, having realized an 11-bit or 12-bit simultaneous grayscale display for the first time among the RadiForce monitors, the G33 offers extremely smooth grayscale rendering. As a result, it may become possible for medical professionals to perceive extremely subtle tone shadings within medical images such as chest X-ray images that may have not been able to be perceived on the current monitors due to banding and tonal jump.

Moreover, some evaluation results show that the new RadiForce G33 has better MTF characteristics than the current RadiForce G31. The pixels of the aperture modulation LCD panel give the appearance of a dot shape and not a rectangular shape due to the aperture ratio. We will conduct further evaluations of how pixel appearances influence the monitor performance.

Having the above-mentioned three benefits brought by aperture modulation technology, EIZO's new RadiForce G33 monitor can be described as the most accurate and ideal medical display monitor in the market today.