Contrast-Detail Characteristic Evaluations of Several Display Devices

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The contrast-detail characteristic of a display system is a powerful tool for evaluating displayed image quality. It takes into account the physical properties of the display, the psychophysical aspects of the observer, and the viewing conditions. It is a more sensitive measurement of the displayed image quality than a simple Society of Motion Picture and Television (SMPTE) pattern. Yet, it is relatively simple to measure and requires no special equipment or analysis tools. In this presentation, the results of the evaluation of several cathode ray tube (CRT) monitors and a digital projector will be presented. Contrast-detail characteristics of these display devices were measured under various gamma and display settings. The results show excellent intraobserver and interobserver variance (<1 step on the grayscale). Extraneous light, such as room lighting, affects the contrast threshold more severely at low background levels more than at high background. Gamma settings on graphics adapters affect the shapes of the contrast-detail curve for all display types. Gamma settings of approximately 2.0 result in a better contrast threshold for both high and low background brightness. The results show complex differences in contrast-detail characteristics for different display types. The digital projector display not only has significantly worse performance than CRT monitors, but also is affected more by extraneous light. High-brightness monitors with optimal monitor and graphics adapter settings have better performance than color or low-brightness monitors. However, under some settings, the performance of high-brightness monitors is not always better at all object sizes and background levels.

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UNDERSTANDING THE CAPABILITIES of a display device is required to effectively plan and maintain a picture archiving and communication system (PACS).¹ There are tradeoffs that must be made between the quality of a display system and its price to avoid having either inadequate or overly expensive devices. Moreover, a practical means is needed for acceptance testing

and for ongoing image quality-assurance and quality-control programs after the system is installed. Historically, the evaluation and quality control of cathode ray tube (CRT) displays for use in diagnostic radiology has been limited to either direct measurement of their physical characteristics or measurement of user's performance using static image patterns with limited spatial and contrast sensitivity under fixed background levels.¹⁻¹⁰ The effects of user perception and of the reading environment have not been thoroughly studied.⁶ In this study, a practical technique for the quantitative characterization of overall display performance using contrast-detail curves was applied. This method takes into account the physical properties of the display, the display environment, and visual perception response.

Several limitations of display hardware should be recognized to properly evaluate its performance. For all practical purposes, the display and the graphics adapter of computer systems must be treated as a matched pair. A poor graphics adapter that can not drive a display optimally can limit a good monitor. Similarly, a poor monitor will be unable to take advantage of the performance ability of a high-end graphics adapter. CRTs have a minimum activation level and a saturation level. Signal levels out of this range will produce no visible change. Thus, the output signal of the graphics adapter must be adjusted to the optimal operating range of the display. The adapter can in fact be the limiting factor for the quality of the displayed image. A computer-generated medical image can have a contrast range of 12 bits. This means that it can have up to 4,096 steps in intensity. However, most graphics adapters on the market today can only create 256 (8-bits) discrete voltage levels in their output signal. This means that the 4,096 steps must be compressed to 256 when displayed. This is less than the approximately 1,024 grayscale steps that the human eye can perceive for the luminance range from 0 to 4,000 cd/m².¹¹

The quality of a monitor as an independent component has often been determined using test patterns based on the Society of Motion Picture and Television Engineers (SMPTE) standards.¹ While a large number of test patterns are defined, the ones

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in widespread use generally contain the following test objects: vertical spatial resolution, horizontal spatial resolution, uniform white fields, uniform black fields, grayscale steps, and 5% and 95% contrast resolution. Spatial resolution is often tested at both the center and outer quadrants of the monitor. In analog video systems, the SMPTE pattern is introduced by breaking the video chain and replacing the camera source with an electronically generated pattern. In computer-based video systems, a digital pattern is presented to the graphics adapter and displayed. These patterns are most useful as a tool for gross adjustment of the brightness and contrast of a display for a set environment. The spatial resolution and contrast steps are usually too large to assess a display at the limiting specification.

Contrast-detail curves are a more sensitive alternative to SMPTE patterns for evaluating display performance. A contrast-detail curve indicates the smallest detectable contrast for objects of various sizes. This allows for testing a wider range of contrast and spatial resolution than a static pattern and provides more clinically relevant information.³

METHOD

A Silicon Graphics 320 computer running Microsoft NT (Microsoft, Redmond, WA), together with image processing software from IDL (Research System Inc, Boulder, CO), were used to generate digital test images used in this study. Several displays (two high-brightness monochrome monitors, one low-brightness monochrome monitor, one desktop color monitor, and one digital projector) were evaluated during our experiments. The computer system has its own internal graphics adapter that allows the user to set the display matrix size and gamma. The graphics adapter supports a 256-step grayscale. The matrix size of the graphics adapter was set to $1,280 \times 1,024$ for all displays.

The luminance outputs for a sampling of input pixel values were measured for all the displays except the digital projector were measure with a calibrated Photometer LX (Quantum Instruments Inc, Garden City, NY) for the gamma settings of 1 (the minimum), 2, 3, and 4 (the maximum). The measurements gave the effective look-up tables (LUT) for these displays. No additional LUT conversion was done at the software level. Consequently, all of the LUT conversions measured in our experiments are due to the graphic adapter and the monitors.

For all of the displays, the contrast thresholds were obtained by presenting the observer with test images and recording the minimum contrast level at which the object in the test image was detectable. Contrast was calculated by subtracting the pixel value for the background from that of the object. The test images were all grayscale images with 256 steps. In other words, the maximum brightness corresponded to a pixel value of 255 and the minimum brightness corresponded to a pixel value of 0.

In each of the test images, there was a single circular object

located on a uniform background. The test images had 800 pixels in both the horizontal and vertical directions. During the experiments, the observer was presented with a series of test images starting with a fixed background level and a fixed object size, both measured in pixel value. If the observer saw the circular object in the image, then he was presented with another test image with a decreased object contrast while keeping the fixed background and object size. The test continued until the observer no longer saw the object, at which time the last visible contrast level was recorded as the contrast threshold for that particular object size and background level. Then, test images with another fixed object size and background level were presented. This was continued until the contrast thresholds for a range of object sizes and background levels were obtained. The contrast threshold was plotted against object size to obtain the contrast-detail curves.

To study the effect of room lighting on the detection of object, the contrast thresholds for several displays were measured with and without the room light on. Room lighting was standard fluorescent at approximately 170 lux.

RESULTS

In Fig 1, the effective LUTs for the tested monitors are plotted for a fixed gamma of 2. Notice the differences in LUT and maximum luminance output obtained with identical graphics adapter gamma settings. As a result of this type of variation, the performance of monitors from different original equipment manufacturers may not match. In fact, the performance of identical monitors varies substantially depending on their settings. Additional flexibility in the application or interface software would be required to insure matching the visual appearance of images.

Figure 2 shows the different shapes of the

Fig 1. Plots of the look-up tables of the CRT monitors evaluated in the study for a gamma setting of 2. C_Hi_bright refers to a high-brightness monitor that was operated at 3 selected brightness levels (100, 200, and 300). I_Hi_bright and I_Low_bright were high- and a low-brightness monitors from another vendor. N_color was a SVGA color monitor.

Fig 2. Effect of gamma setting on the LUT. High gamma settings expand the luminance separations of the higher pixel values and compress the lower ones. Conversely, low gamma settings expand the luminance separations of the lower pixel values at the expense of the higher ones.

effective LUT obtained with different graphics adapter gamma settings for the same monitor. The maximum luminance setting was fixed. The effect of gamma, as implemented on the graphics adapter used in this test, is to expand different parts of the grayscale. At low gamma, the low pixel values are expanded in luminance range and the higher pixel values are compressed. Conversely, at higher gamma, the lower pixel values are presented in a compressed luminance range and the higher pixel values are expanded. On many PACS workstations, the monitor LUT is not readily accessible to the users. However, in some circumstances, the gamma setting on the adapter card can be adjusted. Consequently, monitors from the same vendor may not give the same appearance of images, even with the same graphics adapter, if different parameters have been selected.

The effect of room light on the contrast threshold as a function of gamma setting and background intensity is shown in Fig 3. In Fig 3, the contrast thresholds are plotted versus the background level for gamma settings of 2 and 4 with a fixed-size object. The dashed lines represent the thresholds measured with the room light on and the solid lines are the thresholds measured with room light off. Note that the effect of extraneous light (room lighting in our case) not only depends on the LUT (gamma setting), but also on the image background against which the object is viewed.

Figure 3 clearly shows that for gamma equals 4, extraneous light has little effect on objects on bright backgrounds, but can make a large difference for

Fig 3. Effect of extraneous light (room lighting) on the contrast threshold. Use of higher gamma worsens the contrast threshold performance at low luminance.

objects in darker areas. In the case of chest radiographs, this implies that extraneous light would have little effect on target detection in the mediastinum, but could affect the target detection in the lung fields. The effect of extraneous light is less severe for objects in the darker background for gamma equals 2 than for gamma equals 4. This is a result of the limited dynamic range of the display system and corresponds to being on the maximum-density shoulder of a high-contrast film.

Table 1 shows how the averaged contrast thresholds were affected by room lighting for the various displays evaluated. The contrast thresholds in Table 1 were obtained by averaging the contrast thresholds for all object sizes and for all background levels tested. For lower gamma settings, the effect

Table 1. Average Contrast Threshold for Various Monitor and Gamma Settings

	Average Contrast Threshold		
	Light Off	Light On	% Increase
Projector display	8.12	11.28	39%
C_Hi_bright 100			
gamma = 2	6.12	7.52	23%
C_Hi_bright 255			
gamma = 2	3.28	3.72	13%
C_Hi_bright 200			
gamma = 1	4.96	5.36	8%
C_Hi_bright 200			
gamma = 2	2.76	3.52	28%
C_Hi_bright 200			
gamma = 3	3.56	4.96	39%
C_Hi_bright 200			
gamma = 4	5.2	6.92	33%
I_Low_bright gamma = 1	3.9	4	3%
I_Low_bright gamma = 2	2.6	3	15%
I_Low_bright gamma = 3	2.5	3.5	40%
I_Low_bright gamma = 4	3.2	4.7	47%

Table 2. Intraobserver and Interobserver Variations in the Contrast-Detail Measurements

Background Levels	Standard Deviation of Contrast Threshold Measurement	
	Interobserver	Intraobserver
240	0.0	0.0
180	0.0	0.6
120	1.0	0.0
60	1.0	0.6
1	0.0	0.0

NOTE. Data acquired at gamma = 2. The intraobserver variations were obtained by averaging three trials for the same observer. The interobserver variations were the results of averaging a single trial for 4 observers.

of extraneous light is less severe. For gamma equals 2, the overall contrast threshold increased (or worsened) by approximately 20% for a typical office lighting conditions. For the projector display and the monitors with higher gamma settings, the averaged contrast threshold was increased by 30% to 40%.

In Table 2, the experimental results are presented to show that the interobserver and intraobserver

variance of contrast threshold measurements were within 1 pixel value. This means that the repeatability for a single observer and across observer variance in the contrast threshold were accurate to within 1 pixel value.

Figure 4 shows that the dependence of contrast threshold is a complex function of many factors, such as the type of display, background brightness level, object size, and so on. It shows the obvious inferiority of the digital projector display compared to the CRT-based display. However, the color monitor gives surprisingly similar contrast threshold to that of the high-brightness monochrome monitors for this particular gamma setting.

Table 3 shows the contrast threshold of different monitors, averaged over all object sizes and background levels. It can be seen that a gamma setting of 2 seems to give the best overall performance for most of the monitors. To optimize the performance in a given environment, it may be necessary to examine the effects of monitor brightness and gamma. For example, for monitor C, the lowest

Fig 4. Contrast-detail curves of several monitors, measured at the background levels of (A) 240, (B) 120, and (C) 60 pixel value.

Table 3. Overall Contrast Threshold for the Display Devices Evaluated

	C_Hi_Bright 100	C_Hi_Bright 200	C_Hi_Bright 255	I_Hi_Bright	I_Low_Bright	Color Monitor	Projector
Gamma = 1	3.60	4.96	5.48	4.72	4.88	3.72	Not tested
Gamma = 2	6.12	2.76	3.28	2.12	2.88	3.60	Not tested
Gamma = 3	6.28	3.56	3.36	3.32	3.52	4.84	7.48
Gamma = 4	9.56	5.20	4.92	5.08	4.96	6.67	8.12

NOTE. The first 3 columns are with the same monitor, but with different brightness settings. The fourth and fifth columns are the results for a low-brightness and a high-brightness monitor from the same vendor. The sixth column is for an SVGA color monitor, and the last column is for the digital projector.

contrast threshold can be obtained at a gamma of 2 and a brightness setting of 200. The projector display has the worst performance. The color monitor gives slightly worse performance than some low-brightness monochrome monitors, depending on the gamma settings.

DISCUSSION

The contrast threshold of an observer using a particular display device depends on many factors. The most obvious factor is probably the LUT, which itself is dependent on the gamma setting of the graphics adapter and other image processing parameters at the software level. Even with a fixed LUT, the contrast threshold is a complex function of object size and background luminance level at the object location. Therefore, there is no simple answer as to which display device is better. One has to look at the whole spectrum of factors to determine which display device is superior. Our experimental results have clearly shown such complexity. The measurements of the monitor's physical properties alone can not definitively establish the display quality under different circumstances. For example, the optimal LUT for identical monitors may not be the same in a bright viewing room as in a darker one. One needs a practical measure of the displayed image quality in the specific ambient environment in which the monitor will be used. We believe contrast threshold measurements are a practical means to access this quality.

One often encounters the problem of identical monitors looking different on different workstations. This may well be due to the difference in graphics adapter on these workstations or the gamma setting of the monitor itself. One needs access to a LUT adjustment mechanism to be able to match the "looks" of these monitors.

At higher gamma settings, the higher end of the LUT is extended so that there are more details visible at the brighter areas; however, the lower end of the LUT is compressed. Because there is a limit

on how low the minimum luminance level can go, compressing the lower end of LUT leads to loss of image quality in darker areas.

There is also a sensitivity issue for contrast threshold measurement. Our results have shown that at certain monitor settings, there is no significant difference between the specialty high brightness monitor and a typical desktop color monitor. Yet the measurements of the physical characteristics such as the brightness and the line-spread function clearly show a difference between a high brightness specialty monitor and a regular desktop color monitor. Why does the contrast threshold measurement not show a corresponding difference? We think it is due to the fact that the graphics adapter only can handle a limited number of grayscale steps (256 total), which is far less than human eyes are capable of resolving. In other words, the number of discreet grayscale steps a monitor can display is limited to 256 for the luminance range it spans (from the minimum brightness to the maximum). However, the number of just noticeable differences (JNDs) (ie, the number of grayscale steps of a human eye can resolve) contained within this luminance range is more than 256. Typically, from 0 to 100 cd/m², there are approximately 476 JNDs. Consequently, the precision of the contrast threshold determination is limited by the graphics adapter card, rather than the display device itself.

CONCLUSION

Contrast-detail evaluation of several display devices has shown that the display quality varies as a complex function of the object size, the image background level, the maximum and minimum brightness of the display, the type of display, and the viewing conditions. Contrast-detail measurements provide a practical measure of display quality under various settings for a monitor and graphics adapter.

In general, high brightness monitors yield lower

contrast thresholds and thus better object detection. However, higher brightness does not always result in significantly better observer performance for all monitors or all gamma settings. We think the problem is probably due to the limited number of gray steps the graphics adapter can display. With only 8 bits of graphics display, and at the level of luminance from 100 cd/m² to 300 cd/m², the performance difference measured by contrast threshold may be insignificant. Further research with a graphics adapter that can handle more than 8 bits is needed.

The gamma setting on the graphics adapter is very important, but is often overlooked during display evaluation. Our experiments show that the gamma setting has a significant effect on the contrast threshold, because it controls the final conversion of digital input to the luminance output onto the monitor. For most monitors evaluated in our study, a gamma setting of 2 seems to give the

best overall performance. Higher gamma may lead to decreased object detectability at low object and background brightness when viewed at high ambient lighting levels.

The digital projector evaluated in our study yielded poorer quality images than the CRT monitors. Extraneous light, such as room lighting, resulted in much worse image quality for the digital projector than for the CRT monitors.

Extraneous light increased the average contrast threshold by between 3% and 47%, depending on the display type and the monitor settings. Extraneous light affected the contrast threshold of object detection more in darker areas than the lighter areas on the monitor.

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