Characterization of Monochrome CRT Display Systems in the Field

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This article presents a review of image quality assessment methods for monochrome CRTs in the field as opposed to the laboratory. The review includes image quality programs at the University of Washington, the University of Texas at Houston, the University of Michigan, and the University of Arizona. CRT manufacturers and display-board suppliers also are concerned with image quality, particularly with respect to the life time of the CRT. The programs show that the need for image quality assessment for CRTs in the clinic is recognized. Although several experimental programs are in place, there is no universally accepted program. In fact, the clinical consequences of degraded monitor performance are not even well known and must be established. The existing programs mainly are based on the most comprehensive test pattern, the SMPTE pattern. The programs permit assessment of maximum luminance, display function, dynamic range, and contrast. They do not permit assessment of spatial resolution. There is no easy method to determine the spatial resolution in the field as precisely as desired simply because there are no visual aids (test patterns) to reliably determine loss of spatial resolution and signal-to-noise ratio using human observers. This report also presents initial and encouraging data obtained at the University of Arizona with a CCD camera. This CCD camera has the potential to be developed into an important tool for practical CRT evaluation for the clinic.

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THE DIAGNOSTIC RADIOLOGY department is at the beginning of a revolutionary change. Digital imaging sensors and displays are under development, designed to replace the traditional film-screen as imaging sensor and the film light box combination as display.¹⁻⁶ In the digital and filmless radiology department, images will be generated using digital detectors, and diagnosis

will be made using soft-copy display devices such as the CRT.⁷⁻⁹ This is because (despite its many shortcomings) the CRT is the most mature form of electronic display and will likely remain the display device of choice for the foreseeable future.

Of particular importance in this filmless radiology department is the workstation—the functional equivalent of the lightbox in a film-based operation. Wholesale replacement of lightboxes with workstations requires special consideration because of variation in cost, form factor, and performance characteristics. It is important to realize that, besides being limited by the inherent characteristics of the CRT and its electronic adjustments, the quality of diagnostic information provided by the CRT of a workstation is very much affected by its environment, the software tools used to present the data, and the precision at which the digital data are represented.

Thus, image quality control has an increasingly important role in the diagnostic radiology department. After all, it has been shown that a successful image quality control program can achieve three goals¹⁰: (1) reduce dose to the patient, (2) improve diagnosis, and (3) reduce costs. Now, after successful introduction of many digital imaging modalities, permitting many quantitative procedures, it is virtually impossible to run a radiology department without a credible image quality control program. For years, the American College of Radiology has offered guidelines for desirable image quality in several imaging areas including viewbox luminance and phantoms simulating early signs of cancer.^{11,12} Now there are groups such as Working Group 11 of the ACR-NEMA¹³ and the AAPM Task Group 18,¹⁴ which work on image quality guidelines for the age of soft-copy displays. Working Group 11, for instance, is developing the DICOM Display Standard,¹³ and the AAPM Task Group 18¹⁴ is working on a comprehensive set of image quality control procedures for display devices.

The goal of image quality control for the CRT is the optimal display of information to the human observer. This can be best accomplished if all monitors have similar maximum luminance, display function, black levels, and phosphor colors.

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Uniformity of luminance is desirable both within an individual monitor's field of view and among the different monitors in a workstation. To be practical, the protocol must be easy to perform and use inexpensive equipment. It also must be significant, meaning that correction for the measured changes have an effect on image quality and ultimately on the outcome of the diagnosis of disease; disease diagnosis should not be compromised by poor image quality.

Critical CRT parameters affecting the performance of the human observer include maximum luminance, the display function (characteristic curve), beam spot size or spatial resolution, noise, contrast, uniformity of luminance, geometric distortion, and signal-to-noise ratio.

This article reviews existing programs concerned with image quality control in the clinic and presents initial results involving a CCD camera, which easily could be adapted to quantitative image quality control in the clinic.

However, in reviewing the material presented, one must understand the following:

1. Because of the relatively low luminance level and limited spatial resolution of CRTs, the efficacy of soft-copy versus hardcopy diagnosis is still being challenged and many radiologists are still struggling with the new reading modality.
2. Because of limited experience with routine soft-copy diagnosis, the clinical consequences of degraded monitor performance have not been well established.
3. There is no universally accepted image quality program in place yet.

CHANGES IN IMAGE QUALITY PARAMETERS

CRT monitors have well-known systematic variations in performance, and there are many variations that are random. As a result, it is possible for critical parameters of the CRT to deviate from optimum values and thus prevent the radiologist from making the correct diagnosis. The following is a list of such changes.

1. Luminance nonuniformity can be caused by density deposited on the phosphor has reached a particular value. For a P-104 phosphor, the value is approximately 100 Coulombs/cm².¹⁵ Thus, if the beam current is 1 mA (corresponding to 6.24×10^{15} electrons/s or 10^{-3} Coulombs/s), the beam is on continuously, and the active area is 30 cm $\times$ 30 cm, the charge density of 100 Coulomb/cm² is achieved in 2.85 years. This means that in 2.85 years the luminance will have decreased by a factor of 2.
2. Luminance changes can be caused by processes at the thermionic cathode of the electron gun.
3. Changes in luminance as well as contrast can result from changes in the position of the contrast-brightness controls.
4. Changes in resolution or spot size can result from changes in beam current or from malfunctions of the electron optics in the CRT's electron gun.
5. Changes in CRT performance overall can result from changes in cabling (ie, a removal of the normally 75 Ω termination resistor) or from a malfunction of the display buffer, sending out the wrong composite video signal.
6. A common problem that occurs in image displays is yoke misalignment, which causes the image to be displayed at some deviation from perpendicular. In fact, there can be many ghost images, as shown in Fig 1.
7. Changes in the appearance of the images displayed on a CRT also can stem from changes in ambient room light. Therefore an image quality control program for CRTs must include monitoring of ambient illumination in the digital reading room.
8. Geometric distortion has many causes, including improper magnetic shimming, incorrect electronic adjustment or electronic malfunction, proximity to nearby magnetic devices, and static charge buildup on the screen.
9. Luminance nonuniformity can be caused by nonuniformity in the phosphor coating, by variation in glass thickness (affecting the transmission), and by dynamic focusing of the electron beam at the periphery of the monitor.
10. Local luminance nonuniformities also can exist as defects in the phosphor coating

Fig 1. Display of SMPTE pattern with ghosting caused by improper cabling at the CRT's input.

(scratches and flakes) resulting from the manufacturing process. Other enemies of uniformity include oil and dust. Many people use their fingers to point out features on displayed images. The resulting marks can reduce luminance by as much as 10%. Alcohol wipes leave a residue on glass, which also is undesirable; having glass cleaner and a soft cloth readily available to users can help minimize this problem.

DEPLOYMENT OF WORKSTATIONS

Because the diagnostic information provided by the CRT of a workstation also is affected by its environment, it seems appropriate to briefly review these influences. The primary consideration in selecting a particular environment is to determine the intended function of the workstation. Architectural and engineering design of workstations cannot be successful if divorced from the clinical scenario. What images are to be displayed and from which modalities? Who needs to view images at this workstation? Is the activity at this workstation diagnostic, clinical, consultative, or teaching? Because of the wide variation in cost and performance, the workstation should meet the needs of the user. Although a workstation with a single monitor may be adequate for incidental viewing of ordinary radiographs, for high-volume work involving simultaneous display of multiple views and historical images, two to four monitors are more

appropriate. Three-dimensional imaging imposes greater demands. The display of multiple signals from MRI is where the lightbox analogy fails, requiring sophisticated workstation tools for display and navigation. The current location of lightboxes and their usage is a clue to where workstations may be required.

Because of the low luminance levels of CRTs (compared with lightboxes), there is a predisposition to locate workstations in dark rooms. Unfortunately, this interferes with simultaneous reading of printed material, and with the operation of keyboards, telephones, and dictation systems. Some ambient illumination can be provided with minimal glare on the monitors by using "parabolic diffusers" with recessed fluorescent lights. These "diffusers" are reflective crosshatch grids that direct the light vertically. These are particularly valuable in areas where high ambient illumination is required, such as intensive care units, emergency rooms, and operating rooms. Lightboxes, often located in proximity to workstations for viewing of historical examinations, should be placed to minimize glare.

THE MOST COMMON TEST TOOL: THE SMPTE TEST PATTERN

All image quality programs reviewed below require use of the SMPTE pattern. We will begin by describing it briefly here, and more detailed information can be found in the Appendix. The pattern is shown in Fig 2.

Fig 2. SMPTE pattern.

The SMPTE pattern is the most comprehensive and widely used test pattern for image quality analysis. It allows for the proper setup, acceptance testing, and day-to-day operational checks and adjustments of focus, brightness, contrast, dynamic range, resolution response, midband streaking, uniformity, and linearity of viewing monitors. Figure 3 shows use of the SMPTE pattern and a spot photometer for the measurement of display function and dynamic range.

The pattern was developed in the early 1980s by members of the Subcommittee of the Society of Motion Picture and Television Engineers (SMPTE), and with the cooperation of other professional organizations from the medical field (clinicians as well as health physicists).¹⁶⁻¹⁸

Care must be taken with the SMPTE pattern if it was generated for the display format of a particular CRT display and then is to be displayed at a CRT with a different display format. The bar patterns for the tests of the spatial resolution may well have the wrong frequency because of interpolation from a 256×256 format to a 512×512 format (2 on/2 off rather than 1 on/1 off).

The SMPTE test pattern usually is available from manufacturers of medical imaging systems, but a computer program also can generate it. It can be generated for a square format or a rectangular format, in landscape or portrait orientation. The signal level is selected to match the contrast resolution of the display buffer used (eg, 8 bits, 10 bits, 12 bits).

Fig 3. Illustration of how the CRT's display function and dynamic range can be obtained with a spot photometer when the SMPTE pattern is displayed.

REVIEW OF ACTIVE IMAGE QUALITY PROGRAMS

There are several notable and encouraging beginnings; these programs are discussed below.

The University of Washington

One of the first studies on image quality control for CRTs was completed at the University of Washington.¹⁹ The purpose of the study was to gather preliminary data toward the eventual goal of developing a practical and significant quality control protocol for CRTs.

The only equipment used in the University of Washington study was the SMPTE test pattern and a calibrated photometer. Because the photometer cannot measure spatial resolution, the authors were constrained to using a qualitative measure for the resolution test. This measure was obtained from human observers, looking at the bar patterns in the corners and the center of the SMPTE test pattern, and judging whether the bars appeared blurry. Of course the results of this test were highly dependent on the observer, and were difficult to track week-to-week because the measurements were not repeatable. The set of measurements described can be performed in about 5 minutes per monitor each week.

The conclusions of this study were 4-fold.

1. In a clinical setting, large variations in the performance of a CRT can be caused by many factors including (but not limited to) mechanical failure, unauthorized adjustments, and replacement of the CRT by a technician. Without periodic checks, these large fluctuations can go unnoticed.

2. CRTs can exhibit small, steady changes that are imperceptible on a daily basis but can cause large changes over a long period. Quantitative tests are required to detect these changes.

3. Further studies are needed to monitor the changing characteristics of CRTs, and better equipment, such as a CCD camera, is needed to further quantify the results.

4. To decrease the amount of time required for future studies, a more efficient method of recording and analyzing the data is required.

Texas Children's Hospital

The program at Texas Children's Hospital was adapted from one developed at the University of Texas at Houston from experiences at filmless military hospitals. The hospital is a 456-bed institu-

tion, and its radiology department has about 50 CRTs. The original program was described by Willis et al.⁷

The tools required are the SMPTE pattern and a photometer such as the GO-352 Optometer with GO-265 CRT Detector Module (Graseby Optronics, Orlando, FL), the Digital Photometer J16 with J6523 Narrow Angle Luminance Probe (Tektronix; Wilsonville, OR), or the Luminance meter LS-110 and close-up lens (Minolta Corp, Ramsey, NJ).

In addition to the SMPTE pattern, at least three other images are available: (1) an all-black image for measuring black level (also important for setup procedures of a CRT), (2) an all-white image for measuring maximum luminance and uniformity, and (3) an image consisting of characters or symbols with small features (such as capital Es) to check focus.

When working with the SMPTE pattern, the authors pay much attention to the proper format of the pattern because "it does little good to test a $2K \times 2K$ monitor with a 256×256 pattern!"⁷

The authors also suggest incorporating the SMPTE test pattern in the log-on sequence to enable the operator to make a quick visual evaluation of monitor quality before each reading session. This approach provides the user with the ability to participate in the process of assuring that the workstation is providing images of adequate quality for clinical operations.

The authors have not yet determined the optimum frequency for performing image quality tests. They perform weekly quality control measurements with a minimal subset of tests, such as general appearance, maximum luminance, black level, visibility of 5% and 95% blocks, visibility of bar patterns, and absence of apparent geometric distortion. Quarterly tests measure uniformity, focus, and contrast. They also noticed that the rate of performance decay differs among individual monitors; thus, the frequency of measurements will be different.

The University of Michigan

E. Samei and M.J. Flynn of the University of Michigan devised an acceptance test program for CRTs for the Henry Ford Hospital in Detroit, MI, which also can serve as an image quality program.²⁰ This program is heavily oriented toward the essentials of the DICOM Standard, ie, perceptual linearization and the concept of just noticeable

differences (JND).^{13,21} Consequently, measurements of dynamic range, for instance, are expressed in numbers of JND!

The tests are performed with no frequency processing and application of a linear HD curve (to be selected in the display controller) so that the standard SMPTE pattern would map the entire dynamic range of the display. In addition, the ambient detectors, with which many CRTs are equipped nowadays, are deactivated. The tests are done in an area with a low level of ambient light. A dark, light-absorbing cloth can be placed over the display to block the ambient light.

The tools required are (1) the SMPTE pattern, (2) a spot photometer, (3) a metric measuring ruler, (4) a small uniform fluorescent light source, (5) a piece of dark, light-absorbing cloth, (6) a flashlight, (7) a tool to measure a 30° angle, and (8) a glare test pattern, ie, an image with a disk of 50 to perhaps 500 pixels diameter at 0% video signal in the center, and the remainder (the surround) at 100% video signal.

The SMPTE pattern and the spot photometer are used to determine the maximum and minimum luminances of the display function. The maximum and minimum luminance values are used to determine the corresponding JND values from the standard table for display perceptual linearization in the ACR/NEMA Task Group XI report. A spreadsheet then maps the range of pixel values to the range of JND values and plots the standard and measured luminances as a function of JND on a semilog plot. Usually there is general agreement between the measured and standard results.

Display artifacts are evaluated by examination of the vertical borders of the SMPTE pattern's bright/dark regions for low-frequency lag, high-frequency overshoot, and ghosting artifacts. The artifacts should be minimal considering the desired application for which the monitor is to be used.

Spatial resolution is evaluated by inspecting the high-contrast resolution patterns of the SMPTE pattern visually and grading the appearances on a point scale (0 = substantially degraded, 0.5 = equivocal, 1.0 = acceptable). Intermediate grades (0.25 and 0.75) also may be used. For a CRT, 0.5 is an appropriate compromise between resolution and raster/alias artifacts; 0.25 also may be acceptable depending on the desired quality (clinical versus diagnostic displays). However, all values should be above 0.0. In addition, the charac-

ter clarity over the display area is examined. Of course, attention also is paid to the proper display format of the pattern. The highest spatial frequency must be the monitor's Nyquist frequency, ie, 1 pixel on/1 pixel off.

Geometric distortions are evaluated with the aid of the basic grid of the SMPTE pattern and the metric ruler. The ruler is used to measure distance from the various grid lines to other grid lines in the vertical direction, the horizontal direction, and diagonally.

Veiling glare is evaluated by displaying the veiling glare image (black disk on a white background) and measuring the luminance in the center of the black disk as well as the luminance of the white background with the photometer. The ratio of the luminance L_{white} in the white surround to the luminance L_{dark} is called the glare-ratio ($G = L_{\text{white}}/L_{\text{dark}}$). Ambient light reflection is evaluated using the small fluorescent light source and the photometer. Placing the light source at $+30^\circ$ and the photometer at -30° with respect to the CRT's normal (the mirror location of the source), specular reflection of the CRT can be measured. By placing the light source at 0° and the photometer at -30° with respect to the CRT's normal, diffuse reflection of the CRT can be measured. The percentage of specular reflection and diffuse reflection are recorded.

Equalization also is of interest. Here, the brightness of SMPTE pattern's 20% and 90% steps is measured as the steps are displayed with surrounding of various brightness using the zoom and multiloading features of the display software. The absence of any equalization processes is determined by evaluating the deviations of the measured values from the mean. The deviations should be within 15%.

Noise is evaluated with using low-contrast resolution patterns within the SMPTE patterns.

At this time, no specific values of the objectively measured parameters can be considered "acceptable" because of lack of experience. More experience with the respective responses of different display monitors is needed for realistic acceptance criteria to be adopted.

In time, it is hoped that objective criteria will be established for acceptable spatial resolution and noise, perhaps based on the use of a sensor such as a CCD camera.

The University of Arizona

The University of Arizona has had an active CRT evaluation program for many years.²²⁻²⁷ Many procedures for evaluation of image quality have been evaluated. Initially, an apparatus was used, based on mechanically scanning a photomultiplier-slit-lens combination across the faceplate of a CRT. More recently, this mechanical scanning mechanism was replaced by a high-performance CCD camera, capable of imaging a small portion of the CRT under high optical magnification. However, the emphasis was always on laboratory evaluation, mainly because there was only limited use of CRTs in the clinic, and the procedures themselves were time-consuming. In addition, a fairly heavy platform was required for precise positioning of the imaging equipment.

Recently, a program was begun at the University of Arizona, which centered on clinical evaluation. The real breakthrough came when it was discovered that a commercially available CCD camera could be interfaced easily to a laptop computer via either the parallel port or a USB connector. (The camera is offered by Logitech under the tradename "QuickCam.Pro" and can be acquired in computer stores.) The CCD camera has a resolution of 640×480 pixels and many technical details that are not fully known to us (none of the agents reached on the company's help-line was able to provide us with technical details). Figure 4 shows the CCD

Fig 4. CCD camera used for preliminary experiments at the University of Arizona.

camera mounted on top of a laptop computer. It is used mainly for video conferencing.

Even though the camera was not designed for image quality assessment of CRTs, and clearly needs major technical modifications before it can be used for such, the initial results of this program are very encouraging and will be discussed.

The CCD camera came with a wide-angle lens. Before the experiments with this CCD camera started, we acquired a lens (a Hastings Triplet Achromat with a diameter of 8 mm and an effective focal length of 12.5 mm from Edmund Scientific), with a narrow field of view such that we could do 2 types of experiments:

1. Experiments with the camera very close to the CRT, almost touching the CRT surface, to allow clear analysis of the modulation of high contrast test patterns such as 1 line on/1 line off, and 2 lines on/2 lines off.
2. Experiments with the camera set up at a distances of 30 to 40 cm, appropriate for viewing of larger areas of a CRT such as that where the SMPTE pattern is displayed.

Figure 5 shows the CCD camera in the position for close-ups, held closely against the CRT by the experimenter.

Figure 6 shows the CCD camera in the position for large field or "wide-angle" viewing as in observing a scene. Here the CRT displays the SMPTE pattern, and the CCD images the CRT image of the SMPTE pattern. A shield (shroud) is employed to permit evaluation of the CRT image of the SMPTE pattern without interference of ambient

Fig 5. Demonstration how the CCD camera can be used in the close-up position for analysis of line profiles and modulation.

Fig 6. Demonstration of how the CCD camera can be used to image the SMPTE pattern for analysis of display function and dynamic range.

light. This arrangement is important for evaluation of CRT problems only. The shroud could be removed to allow evaluation of the effects of ambient light on the CRT image of the SMPTE pattern. We envision that in actual application, the shroud with the CCD camera could be held by an operator firmly against the CRT surface.

Before the start of experiments on the feasibility of using such a CCD camera in such an environment for CRT image evaluation in the field, it was necessary to operate the CCD camera in a linear mode. This is because the CCD camera inherently is not linear; it is AC-coupled. It turned out that, by judicious choice of the camera's many control parameters, it was possible to obtain a linear characteristic. The specific parameters were:

Brightness setting	B156
Contrast setting	C255
Exposure	E167
Sensitivity	S255

Figure 7 shows this operation for 2 brightness ranges: a high-brightness one (solid line) and a low-brightness one (dashed line).

Two types of experiments were conducted to evaluate the CCD camera's use for CRT evaluation.

1. *Experiment 1* was designed to determine how well the CCD camera could follow changes in CRT spatial resolution, expressed by changes in modulation. This was done with the CCD in the close-up mode, as shown in Fig 5.
2. *Experiment 2* was designed to determine how well the CCD could follow changes in CRT luminance, and the objective was to deter-

Fig 7. Demonstration of linear operation of the CCD camera.

mine changes in a CRT's display function. This was done with the CCD in the wide-angle mode and the display of the SMPTE pattern by the CRT, as shown in Fig 6.

Experiment 1: Evaluation of Changes in CRT Spatial Resolution

In the close-up mode, holding the CCD close to the CRT (as shown in Fig 5), one could clearly image the CRT's scanlines. They are shown in Fig 8A. Then, the CRT's focusing voltage was changed in order to change the CRT's modulation. Figure 8B shows the scanlines after defocusing at a particular voltage level, and indeed they are defocused. Figure 9 shows the measured modulation for approximately 8 different voltage levels and two different monitors.

The modulation was evaluated in the standard way by applying software to find a vertical profile across the scan lines and then to find the maxima and minima of these profiles. The modulation is found from these maxima and minima by the following equation: $M = (\max - \min)/(\max + \min)$. It is clear that the measured modulation follows the applied voltage. A CCD of the size used and held in such a position (as described) can be used to quantify changes in spatial resolution of the CRT.

Experiment 2: Evaluation of Changes in CRT Luminance and of Its Display Function

In the wide angle mode, with the CCD mounted at the end of the shroud, the CRT displayed the SMPTE pattern, and this pattern was imaged by the

Fig 8. CCD camera images of (A) well-focused CRT lines and (B) defocused CRT lines.

CCD. Figure 10 is the CCD image of the SMPTE pattern. Figure 11 is a plot of the mean CCD pixel values in the 10 grey steps of the image of the SMPTE pattern. Then the CRT's brightness control was decreased to simulate a loss of brightness by

Fig 9. CRT scan line modulation of 2 CRTs as a function of defocussing voltage.

Fig 10. CCD camera image of SMPTE pattern for evaluation of CRT display function and dynamic range.

the CRT. Again, an image of the displayed SMPTE pattern was taken by the CCD camera, and again the mean CCD pixel values were taken in the 10 grey steps of the SMPTE pattern. The new values also are plotted in Fig 11, identified by the dotted line. These values are lower than the earlier ones, as one would expect, because the CRT luminance had been reduced. Clearly, the CCD followed the changes in CRT luminance; it also essentially provided the data of the resulting two CRT display functions, as shown by the two curves in Fig 11.

It is clear that this particular CCD camera cannot be used immediately; much experimentation, devel-

Fig 11. Measurement of display function from a CCD camera image of the SMPTE pattern displayed at high and low brightness.

opment, and calibration must be completed before this approach to CRT evaluation can be turned into a practical system. However, the results are very encouraging and stand on their own. They demonstrate that a simple objective and quantitative tool for CRT image quality control in the clinic certainly can minimize unreliable visual inspection.

PROGRAMS OFFERED BY INDUSTRY

Manufacturers of display controllers (Dome Imaging Systems^{7,28} and BARCO Display Systems²⁹ [formerly Metheus Inc]) and CRTs (BARCO Display Systems, Clinton Electronics,³⁰ Image Systems Inc,³¹ Siemens AG,³² among others) have been concerned for some time with calibration and particularly with the most common problem of CRTs, ie, the decrease of luminance as function time.

The above manufacturers of display controllers offer photometers ("calibrators") attached to the display controllers; these allow precise calibration of the display function of the CRT. This calibration also includes selection of certain display functions, the most important of which is the Barten Curve.¹³ The software provided to perform the calibration is similar to that provided most recently on the Internet and is discussed below in the section entitled "Software for Image Quality Control of CRTs on the Internet."

One CRT manufacturer (Clinton Electronics) offers a photometer built "into" the CRT. This built-in photometer also permits estimation of ambient illumination.

Clinton Electronics

Clinton offers a package called "True Image."³⁰ Here, a photodiode with signal conditioning is mounted to the funnel of the CRT over a small clear area; there is no aquadag on the outside or aluminum on the inside of the funnel. The CRT faceplate acts as a collector for ambient light and is calibrated with a controlled light source and meter as a CRT. The electron gun is held at cutoff in the monitor while this measurement is obtained. The ambient reference value is used in setting the black level and peak white settings. Software factory values define target luminance levels of 0.3 and 80 ft-L as typical points. The sensor micro and display micro communicate internally without outside input. If the brightness and contrast user controls have been adjusted so that the unit is operating outside the target

values, the sensor micro will pass correction values to the display micro, which will overwrite the incorrect values. The result of a calibration cycle is reported to the PC-based program through the RS-232 port and is appended to a history file. The PC program GUI is displayed with the target and adjusted values. The RS-232 in the future will be a USB so that multihead workstations can be polled and identified from a common connection.

Luminance corrections via the calibration cycle can be initiated from software or manually. The True Image system provides a flexible interface so that calibration can be remotely controlled. The software has time-out clocks that prevent calibration cycles from being performed if the monitor is not warmed up. If the monitor has exhausted its available adjustment range with respect to the contrast and brightness, a failed calibration is reported. At this time, one will experience a loss of spatial resolution. Unfortunately, at this time it is not clear what the acceptable levels are for loss of resolution.

BARCO Display Systems

BARCO Display Systems also is concerned with display consistency over time, among devices, and even over the screen area.²⁹ The solutions are represented by different systems in the domain of hardware, firmware, and external software.

Efforts to achieve display consistency with hardware include cathode current stabilization circuitry, working on different current levels (lowlights and highlights) as well as video amplifier modulation capability to equalize luminance throughout the screen. A sensor is included in the hardware efforts to calibrate screen luminance anywhere on the screen and make the luminance uniform. Efforts in the domain of firmware include algorithms for luminance equalization and waveform calculation. And finally, in the domain of software, a quality assurance tool entitled MediCal is available for the hospital technician; it provides conformity calibration, consistency checks, quality figures, display installation, and alignment.

Image Systems Inc

Image Systems Inc has a system called "Remote Commander," which includes a photometer to permit measurement of the CRT's luminance.³¹ Software is provided to check the actual beam current and adjust it such that the loss of luminance

efficiency of the CRT is accounted for. Efforts also are underway to check for constancy of the beam current as a function of the electron gun voltages. Eventually this will help to correct for degradation of the electron gun's electron emission.

Siemens AG

Siemens AG is holding the maximum luminance constant by slowly increasing the beam current to compensate for the decrease in the phosphor's luminance.³² Furthermore, they know precisely the characteristic curve of the electron gun. These tests are performed and corrections done almost on a daily basis such that the luminance of the CRT is very constant during the lifetime of the CRT, over at least 20,000 hours.

Software for Image Quality Control of CRTs on the Internet

Software tools for ensuring consistent video display performance are becoming available on the Internet. For example, the web site www.image-smiths.com offers VeriLUM.³³ In the past, this type of software had been provided by video card vendors and the video monitor manufacturers. More recently, the responsibility for assuring the quality of soft copy display has been placed exactly where hard copy quality assurance resides: in the hands of the end user.

The goal is to make it easy and efficient to judge when a video display system is continuing to function normally or needs adjustment or replacement. VeriLUM can be used for acceptance testing of a video display system before the completion of procurement paperwork.

VeriLUM can be used to perform gamma correction in conformance with the DICOM Part 14 Greyscale Standard Display Function or a user-specified gamma model, or any other user-defined luminance response model. Loading a lookup table at system startup time is possible if a greyscale video board is used that has the facility for on-board gamma correction. Currently VeriLUM provides on-board gamma correction using BARCO Display Systems (Metheus) and DOME Imaging Systems greyscale video boards. If the operating system is Microsoft Windows 95 or 98 and if the color video card supports downloadable gamma ramps, then VeriLUM will use that capability.

A VeriLUM luminance pod must be connected to the PC each time the software is run. After initializa-

tion, other luminance pods can be attached and used for measurements.

VeriLUM software can be installed on as many workstations as desired; no additional licenses are required. That allows a VeriLUM luminance pod to be taken from workstation to workstation to perform measurements. The VeriLUM luminance pod uses a serial communications port on the PC, and thus a simple extension cable from the serial port to the front of the PC minimizes the aggravation of searching behind the PC for the proper connector.

In summary, VeriLUM provides a simple tool for performing calibration, tracking, acceptance testing, and visual verification of a video display system.

The system requirements are simple. VeriLUM requires an Intel PC; Microsoft Windows 95, 98, or NT 4.0 Operating System; and a video card capable of $1,024 \times 768$ pixels with a minimum of 256 colors or a greyscale video board (BARCO Display Systems or DOME Imaging Systems). Windows NT administrator privileges are required to install VeriLUM software in Windows NT 4.0.

VISUAL ASSESSMENT OF DISPLAY DEVICES

Although most of the above-described image quality tests are performed using a photometer, some also require a human observer to view a scene where a CRT displays an SMPTE pattern and grade the appearance on some scale. Such tests are called psychophysical or subjective. They are based on the human observer's ability to relatively accurately determine luminance differences between an object and a background. To this degree, the tests can be called objective. The luminance differences are called just noticeable differences, or JND (as described in reference 13), and they depend very much on the size and shape of the object to be viewed. Ultimately, it is the objective of the image evaluation task to find patterns that permit detection of image quality changes such as spatial resolution or changes in contrast.

There are patterns and methods other than the SMPTE test pattern to evaluate a CRT. In a recent report by Van Metter et al.,³⁴ 2 test patterns were compared for their use in CRT image quality assessment: the Briggs test target system and the 4-alternative forced choice (4-AFC) contrast detail assessment. Following is a description of the respective patterns and methods as well as a review of the article by Van Metter et al.

The Briggs Test Target System

The Briggs BTP No. 4 test target system is not well known in medical imaging. It was developed by S.J. Briggs of Boeing³⁵⁻³⁷ and has been used by the image evaluation community for assessing displays used for applications such as airborne and satellite reconnaissance. The anticipated uses for the BTP 4 system included the visual evaluation of display function and sharpness. In fact it has been commercialized by the National Display Laboratory as a quality control program for CRTs.³⁸

Figure 12 shows an enlarged and annotated image of a single Briggs target that contains 17 checkerboards arranged in order of decreasing size. The largest checkerboard is 3×3 checkers, with each checker being 25 pixels square. The smallest checkerboard is 2×2 checkers, with each checker being 1 pixel in size. The checkerboards of each target are embedded in a uniform background 128 pixels wide and 256 pixels high. Each checkerboard has an associated base score as indicated. Several targets form a target set, where each target is operated at a different digital drive level (ie, each one appears in the image at a different brightness level).

Fig 12. Briggs target.

A more complete description of the targets is provided by Van Metter and found in a manual that also describes the use of the test target system in detail.^{29,32} All targets within a test set have the same contrast (C), ie, contrast is defined as the difference between the grey level of the light checker (L) and the dark checker (D).

The 4-AFC Contrast Detail Assessment

A 4-AFC method for evaluating the overall quality of electronic displays was proposed in 1998 by Hangiandreou et al.³⁹ Test images consist of arrays of square targets that vary in size and contrast. The ability of observers to correctly determine the location of each target is used to compute the maximum threshold contrast (MTC) of the display. This corresponds to the contrast required to detect the smallest target (1-pixel) that can be presented.

In practice, an observer is presented with 3 sets of 8 test images. Each image consists of an 8×4 array of delimited areas each containing a target in 1 of 4 locations. Each image has targets of a fixed size (linear dimensions of 1, 2, 3, 4, 7, 11, 17, and 27 pixels). Each of the 8 rows in an image has targets of differing contrast (pixel value difference from the background of 1, 2, 3, 4, 7, 11, 17, and 27). An example is shown in Fig 13. The task is for the observer to record the location of each target.

Van Metter et al³⁴ conducted a study involving the 2 test methods in order to estimate the precision with which prospective users will be able to utilize 2 visual assessment methods for evaluating the sharpness of electronic displays. Film-based simulations were used, in which objective image quality metrics for sharpness and noise could be controlled precisely, to quantify the relationship between subjective visual measures of display performance and the underlying objective measures. This allows the experimenters to predict the sensitivity of the visual methods and assess their suitability for quality assurance use.

Assessments by the viewers were found to correlate with sharpness and noise. However, the sensitivity of both targets for single-stimulus assessment was found to be inadequate. The authors are disappointed about the inability of both methods to reliably distinguish display simulations in which the MTF bandwidth was changed substantially. The more objective 4-AFC method had been expected to outperform the purely subjective Briggs method.

Fig 13. 4-AFC contrast detail pattern.

It did, but not by a large margin. Neither method meets the present need to reliably assess the performance of displays for diagnostic imaging in a manner that is sensitive enough to detect changes before they become diagnostically significant.

CONCLUSION

Test patterns and test methods are available to permit accurate and precise CRT performance measurements in the research laboratory, using relatively sophisticated instrumentation. They are essential to the proper and optimal operation of the CRT. They are very time-consuming.

The need for image quality assessment for CRTs in the clinic is recognized. Several experimental programs are in place. They are based mainly on the most comprehensive test pattern, the SMPTE. The programs permit assessment of maximum luminance, display function, dynamic range, and contrast. They do not permit assessment of spatial resolution. There is no easy method to determine spatial resolution in the field as precisely as desired simply because there are no visual aids (test patterns) to reliably determine loss of spatial resolu-

tion and signal-to-noise ratio using human observers.

Instrumentation is necessary, and is under development, to permit quick and precise assessment of CRT image quality in the clinic. The clinical consequences of degraded monitor performance need to be established.

APPENDIX: DETAILS OF THE SMPTE PATTERN AND THE SETUP OF CRTS

Note: In this section we present details of the SMPTE pattern, which also can be found elsewhere, but which could be of benefit to readers who don't have easy access to all the reference material.

The pattern includes 11 different areas of intensity from black to white, identified as 0% video signal to 100% video signal. These fields are useful for determining the display function as well as the CRT's dynamic range, ie, the ratio of maximum to minimum luminance. Figure 3 demonstrates use of the SMPTE pattern and a spot photometer to measure display function and dynamic range.

There are high-contrast and low-contrast resolution patterns in the center, and in the 4 corners. The high-contrast ones have a contrast of 100% each, and their purpose is to check for spatial resolution. These patterns cover 3 spatial frequencies each, in horizontal and vertical resolution: 1 pixel on/1 pixel off (the Nyquist frequency f_{Ny}), 2 pixels on/2 pixels off, and 3 pixels on/3 pixels off. The low-contrast patterns have a constant spatial frequency of 3 pixels on/3 pixels off ($1/3$ the Nyquist frequency), but have modulations of 1%, 3%, and 5%. The purpose of these low-contrast patterns is to check for spatial or temporal noise. In addition, there is a grid that delineates the various fields. The grid can be used to check for geometric distortion.

Most important for the setup of the monitor are a 0% and a 100% video signal block that have

superimposed areas of 5% video signal and 95% video signal (see section setup procedure below). There also are 2 other areas that have a white rectangle superimposed on black, and black superimposed on white. Boundaries of these rectangles should be sharp without "bleeding" of white into black areas, indicating sufficient electrical bandwidth of the amplifier.

Every CRT has controls marked "brightness" and "contrast." The brightness control sets the beam current intensity and represents a means to provide brightness "offset." The contrast control adjusts the gain of the video amplifier of the CRT. Together they control output contrast in the fashion of window and level of digital display buffers.

In setting up a monitor, the contrast and brightness controls are adjusted until the 0% to 5% and the 95% to 100% objects of the SMPTE pattern are discernible by the observer. Specifically, without an image present (actually with an image of 0% video signal present), the brightness control is set such that one cannot see the video raster at the particular ambient illumination present ("optical cutoff"). Then, with the SMPTE pattern displayed, the contrast controller is set such that one can see both the 5% and the 95% video object. Then the dynamic range of the monitor is adjusted relatively well with respect to the human observer. After completion of this setup procedure, the contrast and brightness controls should be locked because readjustment of the controls (on purpose or inadvertently) is a common source of unexpected changes in monitor performance (maximum luminance and display function).

Any contrast enhancement should be done with the precise and repeatable window and level controls of the control console of the display station—not with the CRT's contrast and brightness controls.

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