Image Quality Degradation by Light Scattering in Display Devices

Michael J. Flynn and Aldo Badano

Veiling glare and ambient light reflection can significantly degrade the quality of an image on a display device. Veiling glare is primarily associated with the diffuse spread of image signal caused by multiple light scattering in the emissive structure of the device. The glare ratio associated with a test image with a 1-cm-diameter black spot is reported as 555 for film, 89 for a monochrome monitor, and 25 for a color monitor. Diffuse light reflection results from ambient light entering the display surface and returning at random emission angles. The diffuse reflection coefficient (luminance/illuminance, 1/sr) is reported as 0.026 for film, 0.058 for a monochrome monitor, and 0.025 for a color monitor with an antireflective surface coating. Both processes increase the luminance in black regions and cause contrast reduction. Specular reflections interfere with detail in the displayed scene. The specular reflection coefficient (luminance/luminance) is reported as 0.011 for film, 0.041 for a monochrome monitor, and 0.021 for a color monitor with an antireflective coating.

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RADIOGRAPHIC DISPLAYS are designed to convey the visual information in an image to an observer. To achieve this goal, light is generated or modulated in intensity within structures that may have multiple layers. Light photons have numerous opportunities for scattering when traveling through these layers to the human visual system receptors. In some cases, light scattering can improve image quality. For instance, in emissive electronic devices, multiple scattering of light within a phosphor layer produces a quasi-Lambertian angular emission distribution that makes the display brightness independent of the viewing angle. In other situations, scattering processes degrade image quality.

From the Department of Diagnostic Radiology, Henry Ford Health System, Detroit, MI, and the Nuclear Engineering and Radiological Sciences Department, University of Michigan, Ann Arbor, MI.

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Address reprint requests to Michael J. Flynn, PhD, Radiology Research (2F), Henry Ford Health System, 1 Ford Pl, Detroit, MI 48202.

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This article addresses the deleterious effects of light scattering in display devices with respect to veiling glare and to ambient light reflections. A review of the physics and characteristics of such effects is presented, and the differences between currently available medical imaging cathode-ray tubes (CRTs) and flat panel displays (FPDs) are noted.

Veiling glare is primarily associated with the diffuse spread of light caused by multiple scattering processes in display devices. For example, in CRTs, the thick faceplate of the vacuum bulb causes multiple internal reflections that result in unwanted veiling glare. The observed result is a low-frequency degradation of image quality perceived as a reduction in contrast. This phenomenon is present in all imaging systems and has been studied in detectors,¹⁻³ in lenses,⁴ and in the human eye.^{5,6}

Ambient reflections from room lights can contaminate the primary luminous signal of the display device. The display reflectance generally is considered as a superposition of specular and diffuse components. Specular reflections are mirror-like reflections that superimpose a highly structured pattern on the desired image. The diffuse component causes a uniform added background that affects the blackness of the device and reduces contrast. The luminous intensity in the room where radiographic display devices are used varies greatly, from the relatively dark radiology reading room to bright rooms associated with areas of patient care. Thus, the degradation of image quality from ambient lighting is a function of both the ambient illumination of the display device and the relative ambient reflection for both specular and diffuse components.

Minimizing the effect of light scattering on image quality is of particular importance in radiography because of the wide signal range and low noise inherent in the recorded image. Transilluminated radiographic film provides a display with a wide range of luminance and little deleterious light scattering. However, when radiographic images are displayed using electronic devices, the quality observed often is degraded owing to light scattering that contaminates dark regions of the image. Herein we report measured results for veiling glare and ambient reflection, which can be used to estimate

the potential for high-quality display. The results for several CRT devices are compared with measurements made using radiographic film.

VEILING GLARE

Radiographic images displayed using transilluminated film do not suffer significantly from degradation by veiling glare. Modulation of the luminance occurs within a very thin emulsion layer containing darkened grains. Although extensive scattering occurs, the small thickness prevents light photons from traveling laterally over distances that would degrade image quality.

In general, CRT display devices are not able to maintain veiling glare to the low levels associated with radiographic film. In CRTs, the emissive structure is designed to direct all light rays toward the viewer. This is achieved by placing a highly reflective backing in the vacuum side of the phosphor layer. Light generated in the phosphor grains must then travel through a thick faceplate where multiple scattering events occur before the light reaches the human eye. The limited absorption of light by the phosphor layer encourages multiple scattering of photons within the faceplate. Lateral light diffusion in CRT emissive structures causes luminance spread functions with tails that extend over the entire viewable area. This diffuse component over large areas degrades the maximum contrast capabilities of the device.

In addition to the optical scattering in emissive structures, veiling glare is caused by backscattering of electrons and from light leakage through aluminum-layer nonuniformities (cracks and holes). In color tubes, the black matrix that separates the phosphor dots contributes to color purity and reduces the lateral spread of light. As a consequence, the electronic contribution to veiling glare is known to be larger than the optical component, particularly for tubes with a shadow mask design.⁷⁻⁹ In general, the optical veiling glare of color CRT devices is less than that of monochrome devices, but the contributions from backscattered electrons are greater.

In FPD devices, the thin pixelated structures used to generate the image signal produce veiling glare effects that are significant only at short ranges and are not important at long distances from bright fields. For instance, in liquid crystal displays, light diffusion (referred to as optical cross-talk) is localized mostly to adjacent pixels and is associated

primarily with resolution loss.¹⁰ FPD devices typically have thin cover plates, which limit lateral spread from multiple internal scattering.¹¹

Characterization of Veiling Glare

The degradation of contrast resulting from veiling glare can be described by measuring the luminance level in the center of a dark spot caused by a bright ring with a given radius and with small radial thickness. The relative luminance at the center as a function of the radius of the ring can be defined as the ring response function. For shift-invariant systems, the ring response function is equivalent to the one-dimensional image point-spread function expressed as the number of photons that emerge toward the viewer at a given distance from the point source. The increase in luminance in dark regions of an image is associated with light originating at points within bright regions. For a large circular bright field with a dark circular region in the center (such as in Fig 1), the central luminance can be related to the integral of the veiling glare ring response function from the radius of the dark region to the radius of the bright region (Fig 2).

Using light transport Monte Carlo simulation techniques, the ring response function of display devices can be computed by tracking individual light photons coming from a point source. The number of photons that exit the emissive structure from within a ring area and within a specified solid angle is related to the total number of photons. Using this approach, the trade-offs between display brightness and veiling glare have been investigated.^{12,13} The predictions show that reduction of the ring response function tails can be achieved by increasing faceplate glass absorption or by using absorptive black matrix between monochrome phosphor dots.^{11,14}

The veiling glare ring response function of CRTs has extended tails and can have peaks associated with the geometric dimensions of the emissive structure. A computed ring response function is shown in Fig 2. By convolving a dark spot test pattern with a ring response function typical of conventional CRTs, the resulting degradation can be illustrated. The pattern on the right side of Fig 1 depicts the expected reduction in contrast. The diffuse component is observed clearly in the image data profiles shown below the image. This increase

Fig 1. Effect of veiling glare on test patterns with small dark regions. The curves depict a center data row from the above images. A diffuse background component is shown that reduces the ratio of the luminance in the bright region relative to the luminance in the dark spot, ie, the glare ratio defined as L_{max}/L_{min} .¹⁴

of luminance in the dark regions is associated with degradation of contrast.

Measurement of Veiling Glare

To date, no published standard defines experimental techniques to measure the veiling glare charac-

teristics of display devices. Generally, the ratio of maximum luminance to minimum luminance (contrast ratio) is measured for a specific test pattern.^{8,15} Investigators from the National Institute of Standards and Technology have reported results using black squares of varying size on a white back-

Fig 2. A typical ring response function for a monochrome CRT that has been computed using Monte Carlo simulation techniques. The integration over the ring area from 2 to 10 cm represents the contribution to the luminance of a 2-cm radius dark spot from a 10-cm bright region.

ground.¹⁶ Differences in the shape and relative size of dark and bright regions in the test pattern produce different results and prevent comparison of the veiling glare characteristics of display devices. In addition, especially for liquid crystal displays, the use of a contrast ratio can lead to confusion because often it is computed by measuring bright and dark luminance levels using uniform fields.

For experimental measurements of the veiling glare characteristics of a display device, a useful test pattern is a small black circular spot surrounded by a bright circular region. The glare ratio for this test pattern can be defined as the ratio of the luminance in the center, measured without the dark spot, to that measured with the dark spot present. However, the measured glare ratio will be different for test patterns with different radii for the dark and bright regions. If the glare ratio is measured for many different dark region radii, the ring response function can be obtained by differential analysis. Measurements with a single test pattern are more typically used to compare the veiling glare characteristics of different display devices.

Measurement of the low luminance signal in the dark region of a test pattern is difficult because light coming from the surrounding bright region can directly enter the probe. The human visual system is particularly good at viewing information in dark regions surrounded by bright fields. As such, the eye is an excellent detector, with little intrinsic veiling glare. The lack of veiling glare is in part attributable to a reduced directional sensitivity in the retina to obliquely incident light coming from

light scattered near the eye lens.^{5,6,17} Conventional camera systems with lenses have significant intrinsic veiling glare ($\sim 1\%$ to 2%), which is caused by light scattering in the optical components, particularly at lens interfaces and aperture edges.^{4,18} For camera lenses, the veiling glare often is referred to as flare.

We previously reported the performance characteristics of a luminance probe designed to measure the glare ratio of circular test patterns having very small black regions (Fig 3). A highly collimated probe with no lens is used to minimize contamination from bright surrounding regions. Using this probe, glare ratios greater than 1,000 can be measured reliably. The probe has been used to demonstrate the minimal veiling glare of transilluminated film using circular test patterns having a film density range of about 3. The results reported in this article were achieved using a probe similar in design to that used in our previous work¹⁹ but with additional collimation and a high gain detector (model SHD-033; International Light Inc, Newbury Port, MA).

AMBIENT LIGHT REFLECTIONS

Radiographic films have a coating on the emulsion layer that greatly reduces specular reflections. Because this coating is in contact with the emulsion layer, the optical characteristics of the image are not affected. The diffuse reflectance is relatively modest because the blackened grains in the emulsion layer will absorb a certain fraction of light. Although diagnostic interpretations are done in

Fig 3. Photometric probe for measuring veiling glare characteristics. A highly collimated probe is used, with a photodiode detector and light filter to measure the luminance in a black spot without signal contamination from the surrounding bright region.

rooms with specially arranged dim lighting, radiographic film still can be viewed relatively well in bright rooms, as often is required in areas of patient care such as the emergency room.

Because of the nature of CRT emissive structures, a large fraction of the light that illuminates the device is reflected either at the first surface or from multiple internal scattering. A rough surface coating cannot be used because it will blur the image detail owing to the thick glass faceplate. Light that enters the faceplate and strikes the phosphor layer encounters a structure that, by design, has high diffuse reflectance. The phosphor structure consists of small grains in a binder with a reflective backing. Similar to radiographic screens, this structure is designed for good light emission with little absorption. Thus, the monochrome CRT devices used for high-resolution radiographic display typically have very poor characteristics with respect to both specular and diffuse reflection of ambient light. This has forced the use of very dark rooms for diagnostic interpretation and has severely handicapped the deployment of electronic imaging systems in patient care areas.

To dampen specular reflections, antireflective (AR) structures can be used. AR coatings typically consist of several thin film layers designed to reduce the reflectance of the front surface by increasing the light transmission into the faceplate. Normally, AR coatings also include a conductive layer that dissipates the static generated at the front surface and helps maintain a dust-free surface.^{20,21} The reflections from AR coatings can have a color shift when illuminated with a broad-spectrum light source because of the wavelength dependency of the thin film response. However, by decreasing the reflection of incident light, AR coatings may increase diffuse reflections because more light enters the faceplate. The effectiveness of AR coatings is a compromise between the specular and diffuse components of ambient light reflection.

To reduce diffuse reflectance, CRTs may use an absorptive faceplate that will attenuate light that may scatter several times in the glass. For a faceplate with a transmittance of 1/2, the diffuse reflections will be reduced by at least a factor of 1/4 because the reflected light will travel through the glass twice. Typically, more reduction is found because of the oblique directions that the reflected light may travel and because of multiple internal scattering. However, this reduction comes at the

expense of a reduction in display brightness of 1/2. In color monitors, the black matrix material between phosphor cells is of considerable benefit in absorbing incident light without reducing brightness. Thus, the design of color monitors is advantageous from the standpoint of both veiling glare and ambient reflection. However, to date, black matrix phosphor technologies have not been used with high-brightness monochrome phosphors.

Ideally, a display device will have an AR coating and a design that specifically absorbs ambient light. New flat-panel display devices offer opportunities for the absorption of ambient light that are not possible with CRTs. New active matrix liquid crystal display devices are being designed to optimize the absorption of ambient light for use in sunlit applications such as for avionic devices.²² New devices may be able to achieve better ambient light reflection performance than is currently experienced with radiographic films.

Characterization of Display Reflections

The reflectance of display devices can be characterized by separate components involving specular and diffuse light scattering. Specular reflections produce distinct virtual images at the display surface that mirror luminous objects in the room. The reflected luminance L_s can be related to the source luminance L_s by $R_s = L_s/L_s$, where R_s is the dimensionless specular reflectance coefficient. Specular reflections can severely degrade image quality in specific regions by adding interfering structured signal to the image content and by causing localized regions of contrast reduction.

Ambient illumination of the display surface also will produce diffuse reflections with no detail and similar intensity over the entire screen. Typically, light photons will strike the display surface and emerge with a broad angular distribution caused by surface roughness and multiple scattering processes. Diffuse reflections can be characterized by a coefficient defined as $R_D(\theta, \phi) = L_D(\theta)/I(\phi)$, where $L_D(\theta)$ is the diffusely reflected luminance measured at the angle θ from the surface normal, and $I(\phi)$ is the illuminance at the surface from light impinging at an angle ϕ . Because of the units associated with measures of luminance (nit) and illuminance (lux), $R_D(\theta, \phi)$ has units of 1/sr. For an ideal Lambertian reflector, $L_D(\theta)$ is independent of θ and the reflection coefficient is only a function of the illumination angle, $R_D(\phi)$. If the illumination of the surface

is from many directions, as is the case in a room, the illuminance will have differential contributions from different directions, such that

$$I = \int_0^{90} I(\phi) d\phi,$$

where $I(\phi)d\phi$ is the differential illuminance averaged over all azimuthal angles. The diffuse reflection coefficient that is specific to a particular lighting condition can be defined as

$$R_D(\theta) = L_D(\theta)/I,$$

where $R_D(\theta)$ is a weighted average of $R_D(\theta, \phi)$, which depends on the angular distribution of illumination.

Measurement of Display Reflections

Methods for measuring reflection coefficients have been the focus of recent efforts.²³⁻²⁶ Although test methods have been proposed as part of an international standard,²⁷ the defined experimental techniques have been found to be not repeatable and unreliable because of variations in instrumentation response and light source geometry.²⁸ Kelley et al²⁹ and Becker²⁵ recently suggested that for FPD devices, difficulties can arise when reflections fall in the intermediate area between specular and diffuse. They propose using the bidirectional reflection distribution function (BRDF) to fully describe the performance in any ambient lighting condition. The BRDF is a function of both source and observer directions and is equivalent to $R_D(\theta, \phi)$.

For measurement of specular reflection, a small uniform source of light can be used to create a specularly reflected image on an otherwise black display surface located in a dark room. To minimize the diffuse component, the area of the light source should be as small as possible. We have used a small spot lamp with a white luminous area of about 5 cm in diameter. Using a spot photometer, the luminance of the reflected image is related to the luminance of the light source when directly viewed. We have used a Minolta (Ramsey, NJ) LS110 spot photometer, which measures luminance in a 1/3 degree spot. Typical values for the reflection angles include 15° and 30°, at distances ranging from 50 to 100 cm. Because most displays are viewed from a direction near the surface normal, we have made measurements with the light source and the spot photometer at 15° from the central point of the display.

The diffuse reflection from display devices is measured by illuminating the display device in an off condition with a diffuse source.* Others have used various lamps at different positions in a dark room.^{27,28} Inconsistent measures result in part from variations in illumination that come from the walls, objects, and persons in the room. We have used a 40 × 40 × 40-cm box with white reflective sides and two compact fluorescent lamps located at the back corners (Fig 4). Luminance is measured in a normal direction through a hole in the back of the box with a spot photometer. Illuminance is measured with a small illuminance probe placed on the surface of the display. The measured luminance per illuminance is reported as lumens/sr/m² (ie, cd/m² or nit) per lumens/m² (ie, lux), which has units of 1/sr. This test device creates, in effect, a reproducible white room that can be taken to different locations for comparison measurements. The angular distribution of illumination from this test device is representative of that found in patient care areas.

RESULTS

In this article, we describe experimental techniques for measuring the degradation in image quality caused by light scattering in display devices. A method for measuring the veiling glare ratio using circular test patterns and a specifically designed luminance probe is presented in the section on measuring veiling glare. Practical experimental techniques to measure specular and diffuse reflection coefficients are delineated in the section on measuring display reflections. In this section, we report experimental results for a monochrome CRT (24 in, model M24L; Image Systems, Minnetonka, MN) and a color CRT (19 in, model Super-Scan Elite 751; Hitachi, Monitor Division, Westwood, MA). The results are compared with data obtained for transilluminated radiographic film using the same experimental techniques.

Measurements of veiling glare were carried out using two dark-spot test patterns having a bright 32-cm circular field with 1-cm and 2-cm central dark spots. For measuring the glare characteristics of radiographic film, the test patterns were digitally printed on film using a laser printer (Kodak Ekt-

*For devices that rely on changes in transmission to modulate the luminance of the scene (ie, transilluminated film, liquid crystal displays), measurements of diffuse reflections with fields at different luminance levels are required.

Fig 4. Test device for measuring diffuse reflection coefficients consisting of a 40 × 40 × 40-cm box with white reflective sides and two compact fluorescent lamps located at the back corners. The front side of the box has been removed for illustration purposes. Luminance is measured in a normal direction through a hole in the back of the box with a spot photometer. Illuminance is measured with a small illuminance probe placed on the surface of the display.

scan Laser Printer, model XLP; Eastman Kodak Co, Rochester, NY). The optical density in the test pattern films was 2.84 in the dark spot and 0.08 in the bright region, producing relative luminance values of 575. The same test patterns were displayed in the CRTs as $1,024 \times 1,024$ images, with the monitor contrast control adjusted to maximum. The monitor brightness control was set to the minimum level and then increased until the luminance measured for a full dark field increased relative to the value observed with the unit turned off. The brightness was then slightly reduced from this point. The monitor full-field dark luminance was recorded and used to correct subsequent measurements. All veiling glare measurements were made with the entrance of the photopic probe less than 1 mm from the surface of the display. Table 1 shows the results on veiling glare ratio for both 1-cm and 2-cm dark-spot test patterns.

As discussed previously, the diffuse reflection

Table 1. Veiling Glare Ratios for Test Patterns Having 32-cm Bright Circular Fields and Dark-Spot Diameters of 1 and 2 cm

Dark Spot Diameter (cm)	Radiographic Film	Monochrome CRT	Color CRT
1	555 ± 2	89.0 ± 0.6	25.0 ± 0.1
2	546 ± 1	125.8 ± 0.6	44.0 ± 0.1

NOTE. For film, the measured values are near those expected from the film density of the black spot, ie, a glare ratio of 575. Error estimates are based on the standard deviation of 20 consecutive measurements. The 24-in monochrome monitor (Image Series M24L) demonstrates significant glare from optical scattering. The 19-in color monitor (Hitachi SuperScan Elite 751), with even more veiling glare, is typical of monitors used on modern graphic arts workstations.

coefficient is specific to the angular distribution of illumination associated with particular measurement conditions. When using the experimental technique described in this work, the obtained result corresponds to $R_D(0) = L_D(0)/I$, with I being the total illuminance at the display surface. The illuminance probe used records incident light with a broad angular response (International Light Inc, model SCL110). Table 2 shows the diffuse and specular coefficients for all three display types.

When measuring diffuse reflections from radiographic film, attention must be given to the optical density values in the image because they affect the light diffusion characteristics of the device. For instance, R_D measured for film with a typical chest radiograph was 0.026 1/sr. When using the same technique with a 1-cm dark-spot veiling glare test pattern, the result was 0.020 1/sr. The difference is associated with ambient light, which is transmitted to the view box and reflected back. This dependence of R_D with the image luminance pattern is not observed in CRTs, where measurements are performed with the display turned off.

Table 2. Specular and Diffuse Reflection Coefficients for Film and CRTs

Display	R_S	R_D (1/sr)
Radiographic film	0.011 ± 0.001	0.0264 ± 0.0002
Monochrome CRT	0.041 ± 0.001	0.0582 ± 0.0002
Color CRT	0.021 ± 0.001	0.0251 ± 0.0002

NOTE. The reflection properties of the color monitor are better because of an AR coating and the black matrix in the phosphor layer. Random errors are estimated from the standard deviation of 10 consecutive measurements.

Fig 5. (a) Standard display function curve shown as log-luminance versus image value in units of just noticeable visual differences (JNDs).^{31,32} A unit change in the JND variable causes a luminance change equal to the contrast threshold at the indicated luminance level. Curves b, c, and d depict the effect of adding a background luminance level of 1, 4, and 10 cd/m^2 . A significant reduction of contrast for small image values is indicated by the small slope of this curve for high background levels.

DISCUSSION

At high luminance, a function that maps an image value to brightness such that the logarithm of the luminance is linearly proportional to the image value will produce a uniform perception of contrast at all brightness levels. This occurs because the human vision system perceives contrast as a relative change in luminance ($\Delta L/L$) for sufficiently bright scenes. However, for many display systems, the dark regions of the scene occur at a luminance level so low that the contrast response of the human observer is poor.³⁰ To compensate for this, the relative contrast ($\Delta L/L$) at low luminance can be increased relative to that at high luminance. An industry standard display curve that maps image values to luminance can be used to obtain a uniform perception of brightness in both dark and bright regions of an image.^{31,32} This relationship is shown in Fig 5, where it can be seen that the slope of the curve relating log-luminance to image value is greater at low luminance. This standard display curve is based on psychovisual models of experiments that measure the threshold contrast of a small test pattern on a uniform background to establish the contrast for which the test pattern can just be detected. The luminance difference associated with this contrast threshold often is referred to as the just noticeable difference (JND) in luminance, and the standard display curve often is plotted in units of JNDs, which are taken to be proportional to display values.

Many systems will calibrate the display device luminance response curve such that it follows the display standard curve based on measurements

made with no ambient illumination. However, when such a system is used in a reading room, the ambient illumination will add a constant luminance to the display response owing to diffuse reflections. To illustrate the effect of diffuse reflections on image quality, we have plotted the expected curve when a background luminance of 1, 4, or 10 cd/m^2 is added to the normal display luminance (Fig 5). For the monochrome monitor tested for this work with a diffuse reflection coefficient of about 0.06 l/sr, an added luminance of 6 cd/m^2 results from an illuminance of 100 lux, which is typical of common office lighting. The significant reduction in the slope of the curves for low image values, which are at a luminance of 1 cd/m^2 for the monochrome monitor, is associated with a significant reduction in the perceived contrast. Ideally, the added luminance should not be greater than 20% of the minimum luminance of the display device. For example, a display with a luminance range of 3 to 300 cd/m^2 could be used in a room with 100-lux ambient illumination if $R_D \leq .006$ l/sr. For film viewed in a luminance range of 20 to 2000 cd/m^2 , no significant degradation occurs if $R_D \leq .04$ l/sr.

The image quality degradation associated with specular reflections is notably different from that associated with diffuse reflection or veiling glare. Although similar contrast reduction occurs where specular reflections contribute to display luminance, the detailed patterns of the specular reflection are more problematic. The specific pattern of a reflection may overlay complex structures in the image scene and reduce the conspicuity of diagnos-

tic features. Additionally, there is a belief that the presence of these added features in the image and the human observer's need to separate reflection artifacts from image information contribute to visual fatigue.

Veiling glare adds luminance in dark regions of an image in amounts that vary according to the spatial distribution of bright regions. This added luminance locally decreases contrast and can degrade the detection of low-contrast structures. The specific effect is different for each image. Particularly problematic are scenes such as the lateral chest view that can have very dark lung regions surrounded by a large bright field. In general, displays with a glare ratio greater than 200 when measured with a 1-cm circular dark-spot test patterns will have little contrast degradation from

veiling glare. A display with a glare ratio of less than 100 will have poor image quality for certain images.

To date, much attention has been paid to the resolution and brightness required of a display device for application in medical radiography. Herein we have described how veiling glare and ambient reflections associated with current CRT technology may seriously affect the quality of a displayed radiograph relative to the quality seen with transilluminated radiographs. Therefore, systems with very good resolution and brightness may not be suitable for diagnostic application because of these optical limitations. The serious problems relating to veiling glare and ambient reflections perhaps have not been adequately acknowledged to date.

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