Why and How Is Soft Copy Reading Possible in Clinical Practice?

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The properties of the human visual system (HVS) relevant to the diagnostic process are described after a brief introduction on the general problems and advantages of using soft copy for primary radiology interpretations. At various spatial and temporal frequencies the contrast sensitivity defines the spatial resolution of the eye-brain system and the sensitivity to flicker. The adaptation to the displayed radiological scene and the ambient illumination determine the dynamic range for the operation of the HVS. Although image display devices are determined mainly by state-of-the-art technology, analysis of the HVS may suggest technical characteristics for electronic displays that will help to optimize the display to the operation of the HVS. These include display size, spatial resolution, contrast resolution, luminance range, and noise, from which further consequences for the technical components of a monitor follow. It is emphasized that routine monitor quality control must be available in clinical practice. These image quality measures must be simple enough to be applied as part of the daily routine. These test instructions might also serve as elements of technical acceptance and constancy tests. Copyright © 1999 by W.B. Saunders Company

KEY WORDS: soft copy display, human visual system, contrast sensitivity, CRT, monitor, image quality, acceptance test, radiology, interpretation.

ONE HUNDRED YEARS after the invention of the cathode ray tube (CRT) in 1897 by the German physicist Karl Ferdinand Braun, CRT monitors are beginning to be used for primary diagnostic interpretation in radiological daily life. Meanwhile, there is no doubt that Picture Archiving and Communication Systems (PACS) will become widespread because networking of radiology departments and integration of information across remote sites are considered to increase radiologists' productivity. This is accompanied by an opportunity to reduce healthcare costs. The networking of radiologists' and physicians' information technology is also augmented by the rapidly increasing use of the Internet for the distribution of images and other information.

This trend has been preceded by the digitization of the imaging modalities, starting with the advent of computed tomography (CT) in the 1970s. At present, projection radiography, which is the modality of probably the highest information content demands per image, is switching to digital detectors. Therefore, it is obvious that the output media,

ie, the display of images, is going to be digitized. It is expected that soft copy reading will replace film interpretation in the near future. Thereby film costs will be saved. Hence, the question arises whether presently available monitors can meet the requirements of the radiological diagnostic process.

The section that follows presents some general problems and advantages of soft copy interpretation. The next section reviews some characteristics of the human visual system (HVS) and then the technical properties of monitors are addressed. Next, how all of this can be applied to practical test instructions for use in clinical practice with the goal of assuring image quality is discussed. This presentation concentrates on grayscale CRT monitors, as flat panel displays are not expected to be used for the radiological diagnostic task in the next few years.

PROPERTIES OF SOFT COPY INTERPRETATION

Because the data are provided in digital form by the imaging acquisition system, it is obvious that digital image processing methods can be applied directly to the images without first having to digitize them as would be the case with a film radiograph. Examples of such processing are contrast enhancement by the application of look-up tables and edge enhancement by filtering. The image display can be customized for the various applications under varying circumstances. It can be designed for a specific task, for a specific user, for a specific organ, or for specific ambient light conditions. Furthermore, electronic displays suited for visualizing data from three-dimensional methods are likely to become more important.

Replacing film by soft copy reading will also avoid the specific problems associated with film. These are environmental problems because of the

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chemistry, lost studies and incorrectly exposed films. Siegel¹ reported that the rate of lost examinations dropped more than by a factor of 10 and the image retake rate dropped from 5% to about 0.8% after the introduction of PACS. However, replacing film is only one part in the transition to the filmless hospital. The other part is the integration of all available information with the help of modern information technology.

Using soft copy interpretation presents a considerable potential for dose reduction. Soft copy readings are based on digital data. Hence, improperly exposed images can be corrected by postprocessing. Furthermore, it is possible to visualize a set of acquired data with different display parameters. Several exposures would be required to do that with analog film. Overall, this leads to considerable dose saving in radiology.

The most important advantage of PACS, however, is the simultaneous availability of images at different sites in a networked environment. This opens the door to a completely new working style for healthcare professionals, a style that can result in increased productivity by optimizing processes in the hospital and in the networking of physicians. For instance, images can be viewed simultaneously by several people. Not only images but also all of the pertinent information related to the patient will be integrated and made available for the healthcare process. These new kinds of diagnostic processes will be supported also by more and more widespread use of the Internet.

Because the handling of images on electronic displays is totally different from that of film radiographs, user interfaces for specific tasks have to be designed. Strategies for the handling of images, for the manner and order of presentation, and for the storage and buffering of images have to be developed. Finally the transfer of images in the networks must be fast enough to avoid time delays. The reading process must be sufficiently quick if soft copy interpretation is to be of value. Although these problems cannot be addressed in this contribution, they have to be solved for the acceptance of primary soft copy reading in radiology.

However, the crucial prerequisite for acceptance of soft copy diagnosis is image quality. Do CRT monitors provide the image quality needed to display all of the information necessary for a safe diagnosis? Which technical approaches should be applied in order to provide and secure the best

possible image quality in clinical practice? To answer these questions, the human visual system (HVS) must be analyzed.

THE HUMAN VISUAL SYSTEM

This section cannot describe the HVS in its full complexity. Rather, only some of the most important properties of the human visual system will be addressed. Because the HVS is in fact part of the imaging chain, it contributes to the overall performance of the display system. Ideally, the technical parameters of the system, which also include the surrounding conditions, should be adjusted to the characteristics of the eye-brain system of the observer (Fig 1).

Contrast Sensitivity and Spatial Resolution

Contrast sensitivity is usually determined by carrying out observer experiments.^{2,3} By this the luminance L of an object that is just noticeable in front of some background with luminance L_0 , is determined. The ratio

$$\Delta L/L_0 = (L - L_0)/L_0 \quad (1)$$

is called the threshold contrast. Its reciprocal value, the contrast sensitivity, is a measure of the probability that a standard observer can perceive this object. The problem of determining this quantity is that it is dependent on the test pattern, on its size, on its shape, and on its frequency content. The result also depends on the background, on noise, and even on noise structure.

However, Barten⁴ developed a model that fits most of the experimental data. With this model the contrast sensitivity can be calculated, particularly

Fig 1. The human visual system (HVS) is part of the imaging system. The arrows indicate the information flow. The bold arrow illustrates the adjustment of display system and HVS.

for a square of sinusoidal modulation in front of a uniform background.⁵

The contrast sensitivity for such objects with a diameter of 2 degrees, computed according to Barten's model⁴ is plotted in Fig 2. It can be seen that the contrast sensitivity of the HVS in the range between 1 cd/m² and 1000 cd/m² has its maximum for spatial frequencies between 3/degree and 6/degree. For a viewing distance of 0.4 m these values correspond to object sizes of 1.2 mm and 0.6 mm, respectively. The Weber-Fechner⁶ law pertains in that the contrast sensitivity in the region of medium to low spatial frequencies is almost independent of the luminance for medium to high luminance values (Weber range). With decreasing luminances below 1 cd/m², the contrast sensitivity decreases approximately according to $L^{1/2}$. This is called the deVries-Rose law.⁶ In this range the transition from photopic vision with cone receptors to scotopic vision with rods occurs, and visibility becomes impaired. For high spatial frequencies, say above 15/degree, the contrast sensitivity strongly decreases. The resolution limit is approached at about 30/degree. This is in agreement with the common statement that the HVS is able to resolve 1 arc minute.

Whereas the contrast sensitivity, as shown in Fig 2, is valid for adapted observers, the threshold contrast is usually elevated by not being adapted to a specific luminance, by masking effects,² and by irritating extra or reflected light.

Fig 2. Contrast sensitivity for the perception of an object of 2° diameter and sinusoidal modulation and its dependence on spatial frequency for different background luminances L , computed along the model of reference 4.

Contrast Sensitivity and Temporal Resolution

The contrast sensitivity can be equally well determined as a function of time or of frequency.² As a result the contrast sensitivity sharply drops above 50 Hz for all relevant luminance values. Farrell et al⁷ gave a formula for the critical flicker frequency as a function of viewing angle and luminance. From this it is concluded that for realistic viewing conditions the critical flicker frequency lies at about 70 Hz. Anticipating the technical requirements for monitors, the frame rate of radiological monitors must exceed this limit in order to be flicker free.

Dynamic Range

Human visual sensitivity covers an absolute range of more than six orders of magnitude,⁸ which means that the HVS is able to adapt to extremely different lighting situations. For the diagnostic process using medical images the important question is what dynamic range can be perceived within a complex radiological scene?

Bartleson et al⁸ found that perceived brightness as a function of the stimulus is nearly the same when the stimulus varies over several orders of magnitude. Normann et al⁹ measured the hyperpolarization potentials in vertebrate cone cells as a measure of the photoreceptor response. This response potential V in terms of some maximum $V_{\max}$ is fairly well described by the model function¹⁰

$$V/V_{\max} = L/(L + L_0), \quad (2)$$

where L_0 is related to the adaptation luminance, L_a , and can be approximated in the luminance range provided by the CRTs by¹⁰

$$L_0 = 12.6 L_a^{0.63} \quad (3)$$

where the luminances have to be in units of cd/m². These curves are plotted in Fig 3.

The curves for different background light are simply shifted. If the eye is adapted to a bright background, the sensitivity, ie, the output potential, for a small stimulus is reduced. This effect is called desensitization.

The perceivable contrast is further reduced by light coming from bright parts of the image scattered into adjacent receptor cells according to the MTF of the eye lens¹¹ and by small involuntary permanent eye movements, called microsaccades.¹⁰

Fig 3. Cone response as function of the stimulus luminance L for different adaptation luminances L_a , calculated according to equations 2 and 3 in the text.

These two effects lead to a reduced local contrast of the perceived image at the retina.

In short, the perceivable contrast ratio, ie, the ratio of maximum to minimum luminance in one image will be much lower than might be expected in a best-case situation for realistic complex scenes and will be in the order of magnitude of 100. The exact value will, of course, depend on the type of image, on the complexity of the scene, and on the adaptation process.¹²

The number of perceivable gray levels can be crucially influenced by the tone scale or display curve of a device. Here and in the following, a gray level is understood to be one among the luminance values displayed by a device corresponding to one of the digital input values. While in a complete dark surround, the HVS is able to discern luminance differences that correspond to about 500 gray levels in the luminance range of a typical light box. This is not true in realistic environments and in the presence of ambient light. However, the number of perceivable gray levels can be maximized by the application of a specific display curve. The display can be adjusted to the best brightness for perception.

The nonlinearity of the signal processing in the HVS requires that the tone scale is also a nonlinear function of the digital driving code value. Based on the Barten model or on other observer experiments a display curve can be found that perceptually linearizes the display,⁵ which means that small increments in digital code value cause the same increment in perceived brightness, irrespective of where in the input domain the stimulus is applied.

There are several display curves in this discussion¹³ because the results of observer experiments depend on test pattern, on noise, and so on, as discussed above. The one based on the Barten model is recommended by ACR/NEMA's working group XI.¹⁴ Another one is the modified cubic root law based on the CIE system.¹⁵ However, such a curve only specifies the relation of the luminance output to the digital input of a display device. It does not mean the optimization of the display, because the optimal look of an image depends not only on the acquisition modality, but also on the organ, on the purpose, and on the user. Beside the basic maximization of the dynamic range, the objective of perceptually linearizing a display is to provide a standardized look for soft copy images of different types and vendors, on different devices, or even of hard copy.¹⁴

TECHNICAL PROPERTIES OF MONITORS

The most important design specifications of monitors for image quality will be described now. Most of the physical parameters are mutually dependent on each other, which leads to trade-offs among the quantities as explained here.

Display Size

The standard film radiograph size is 14×17 (35 cm $\times$ 43 cm). Screens of common 21 in. CRT monitors are slightly smaller, namely 30 cm $\times$ 40 cm. Considering that bigger displays are also heavier in weight, larger in size, and have higher power consumption, the 21 in. screen size is considered to be a good compromise between desirable image size and technical considerations. This, however, would change with the introduction of acceptable flat panel displays, which do not suffer from bulkiness.

Spatial Resolution

Assuming that the function of contrast sensitivity given above is also relevant to medical image reading, one can draw some conclusions on the reasonable spatial resolution of a monitor. If the resolution limit of the HVS is set to 30/degree and if the monitor height is 300 mm (corresponding to a 21 in. landscape monitor), the minimum object size Δx that can be perceived from a given viewing distance d , and thus the number of television lines that make sense, are given in Table 1.

Accordingly, it should be possible to perceive

Table 1. Perceivable Object Size Δx and Number of TV Lines as Function of the Viewing Distance d

d/mm	$\Delta x/mm$	No. of TV Lines
300	0.087	3400
400	0.12	2600
500	0.15	2100

the smallest details that are displayed on a monitor (300 mm in height) with roughly 2000 to 3000 TV lines with a viewing distance between 300 and 500 mm. All this assumes that the user is optimally adapted and that the resolution of the monitor defined by the modulation transfer function corresponds approximately to one TV line. The latter is not a trivial requirement, because the beam spot size on the screen, and thus the MTF, is different in horizontal and in vertical directions. It depends on the electron optics, on the phosphor spreading of the light generated by the impinging electron beam, on halation effects in the glass faceplate, and additionally (in the horizontal direction) on the frequency response of the electronic circuitry. In Fig 4, we show simulated vertical lines, set to the maximum code value of 255 in front of a zero background to demonstrate the dependence on the maximum luminance for white. The simulations were carried out with the software ARGUS,¹⁶ which is well suited to simulate the influence of the technical parameters on image quality.¹⁷

Luminance, Contrast Ratio, and Veiling Glare

Because the beam spot gets broader for higher beam currents (see Fig 4), the maximum luminance of a CRT display has to be limited to maintain spatial resolution. Depending on the transmissivity of the glass faceplate and on the luminous efficiency of the phosphor, all presently available

medical CRT monitors have a maximum luminance L_{max} below 1000 cd/m². In most cases L_{max} is between 200 and 600 cd/m². If for the diagnostic task the highest spatial resolution is required, eg, for the primary diagnosis of digital radiographs, practical experience with common medical monitors shows that the luminance should not be set-up to values higher than about 300 cd/m².

On the other hand, it follows from the earlier discussion that the lowest luminance, L_{min} should not be too low. At around 1 cd/m² the scotopic region is approached where the vision deteriorates, the threshold contrast increases, and the detectability is reduced compared with the photopic region. In practice, depending on ambient light, L_{min} will take on much higher values.

There are several reasons that prevent L_{min} from becoming very low in practical circumstances. Applying realistic images, light traversing the faceplate is reflected at the interfaces and scattered inside the system consisting of glass, phosphor and aluminum layers. In this way, light originating from bright parts of the image is scattered into adjacent dark parts. A similar effect shows up because of the backscattering of electrons inside the tube.¹⁸ These effects lead to the phenomena of veiling glare and halation haze¹⁹ and increase the actual L_{min} depending on the image. The minimum luminance L_{min} is furthermore increased by ambient light reflected from the boundaries of the faceplate and scattered. Reducing these effects by employing darkened glass and antireflection coating unfortunately reduces the transmissivity of the glass faceplate. Therefore, higher beam currents have to be used to generate the same luminance, which in turn means higher demands to the engineering art and electron-optical design to keep the beam spot size small.

Fig 4. Simulated vertical lines for maximum luminance of 100 cd/m², 300 cd/m², and 590 cd/m² (from left to right). The image shown corresponds to a region of 10 × 10 pixels or 2.9 mm × 2.9 mm for this specific monitor.

Fortunately, modern state-of-the-art CRT monitors are equipped with these faceplates and high-performance electron tubes. Nevertheless, to achieve a high contrast ratio, the ambient light has to be rather low (say below 100 lx).

Measurements show, that the contrast ratio $L_{\max}/L_{\min}$ is usually lower than 300 in realistic and useful situations. Earlier it was shown that the usable contrast ratio is in the order of magnitude of 100; this value fits well to that which the HVS is able to process. For comparison, the nominal contrast ratio of a radiographic film in front of a light box can be given approximately as 1000, ie, the optical density (OD) covers the range from 0.2 to about 3.2, which gives 3.0 on a $\log_{10}$ luminance scale. But, the perceivable luminance range for viewing film radiographs is reduced by the effects discussed above and as reported by Muka et al.⁵ Moreover, the diagnostic valuable region of the film has to be considered to be somewhere between $OD = 0.5$ and $OD = 2.5$, which only gives 2 on the logarithmic scale, corresponding again to 100 for the contrast ratio.

Dynamic Range and Display Curve

Dynamic range is understood to mean the number of just noticeable gray levels. Although under ideal conditions the number of discernible gray levels in the considered luminance range is larger than about 500, in most viewing situations hardly smaller luminance differences than those corresponding to 256 gray levels are perceivable. Thus, at first glance a digital-to-analog converter operating with 8 bits seems to be sufficient.

However, the characteristic curve of a CRT monitor is given basically by the voltage-to-current relationship of the tube's electron gun, which crudely can be approximated by an exponential curve with exponent γ between 2 and 3. Such a curve is similar to a perceptually linearized display curve, but it cannot be expected that the intrinsic monitor curve provides exact perceptual linearization. Thus, the dynamic range has to be maximized by choosing a proper display curve to linearize it perceptually. In digital systems this can be done by applying a look-up table (LUT) to the digital code values. However, the application of a LUT may reduce the number of gray levels. This is illustrated in Fig 5, which shows measured and CIE display curves¹⁵ for two CRT monitors. CRT 1 has a display curve in good agreement with the CIE

Fig 5. Measured display curves and CIE standard display curves for two CRT monitors. The luminance was measured with a handheld photometer.

curve corresponding to $L_{\min}$ and $L_{\max}$. CRT 2 suffers from low contrast in the dark areas, which is remedied by a gamma correction applying a LUT. In the case of CRT 1, an 8-bit LUT gives 240 output gray values, whereas a 10-bit LUT gives 256 gray levels (after a final compression to 8 bits). In the extreme case of CRT 2 the 8-bit LUT reduces the number of output graylevels to 196, even the 10-bit LUT provides only 229 gray levels. Consequently, the application of LUTs has to take place in the component with the highest bit depth available to avoid losing dynamic range.

To provide optimal diagnostic capability of soft copy images the look of a soft copy display has to be optimized specifically to the task and to the user. In general, this can be regarded as a kind of dynamic range maximization in the luminance range considered, and may include spatial frequency processing, too. However, as long as film is used in parallel with soft copies, there will be the need for matching soft and hard copy, to make soft copies look like film images, and vice versa. If a perceptual display standard is applied also to hard copy radiographs, as proposed by Blume and Muka,^{14,23} this problem can be solved by the same method of applying a LUT, as described above. Hereby, it has to be considered that the optical density corresponds to the logarithm of luminance. For this task, it is appropriate to separate the application specific LUT (outlined in Fig 1 in the processing step indicated by the box "proc") from the application of the display LUT that provides the standard display curve. Such a perceptual standard display curve should secure the similarity of im-

ages,¹⁴ irrespective of their absolute luminance range.

Noise

The electronic circuitry of the DAC and video amplifier noise are the main contributors to temporal noise. The major source of spatial noise is the phosphor grain noise. Roehrig et al²¹ show that temporal noise of the display plays a role only for very low luminances. For higher luminance values the spatial noise dominates. The phosphor grain noise power spectrum (NPS) was estimated by measurements^{22,24} and also compared with film noise.²³ It is of high interest and importance, because it can mask small details and thus elevate the detection threshold. The NPS of two different, commonly used phosphor types have been measured.²⁴ The result was then used for simulating the images of corresponding, not yet existing monitors. These images were judged in an observer experiment to get some impression of the impact of the phosphor luminance noise on image quality and on other design parameters like the electron beam spot size. The interesting result was, that for 1K CRT monitors the choice of the phosphor may play a minor role; for 2K monitors, however, the sharpness and the detectability may be reduced by high phosphor luminance noise. Consequently, for the design and specification of high-resolution 2K monitors the use of a low-noise phosphor, like P45, is recommended to avoid compromising image quality, and, in particular, to achieve the expected high spatial resolution.²⁴

PRACTICAL ACCEPTANCE AND CONSTANCY TESTS

In Germany, a Deutsche Industrie-Norm (DIN) working group is currently elaborating a standard for acceptance testing of radiological image display devices with the goal of image quality assurance in radiological departments. It is the author's opinion that in standards like this the requirements to be met should not be too severe concerning the test procedures and measurement equipment. The tests must be simple enough to be accepted in clinical practice. The optimal procedure with regard to applicability would be a purely visual one. Furthermore, many vendors should be able to meet the requirements to keep costs reasonable. Because of the increasing use of information technology and the Internet, it is expected that medical images will

also be displayed on so called commercial-off-the-shelf monitors. Therefore, it is also important, to secure image quality on these standard devices, as well as on high-performance special-purpose medical monitors.

In agreement with insights presented above the proposed DIN standard addresses the following main items, and test instructions are prescribed or recommended. Although several test patterns will be allowed, almost all of the testing can be done with the SMPTE pattern,²⁰ which seems to be well suited for our purposes because of its versatility. The basic test instructions to be used are:

- Proper ambient light and surround conditions (to be tested against a still to be specified standard).
- Luminance measurements including the ambient light. This will also be part of the constancy test. The contrast ratio, C_0 , must be larger than 100 for reporting monitors, and larger than 40 for other monitors where $L_{\min}$ is determined with the monitor switched off. As a consequence, the ambient light has to be low enough to achieve these values.
- A display curve must be done that verifies the similarity between different output devices and that guarantees the visibility of the 5% and 95% spot of the SMPTE test pattern. This, as well as the similarity of perceived brightness steps of adjacent fields, eg, squares with 0%, 10%, . . . , 90% command level in the SMPTE pattern, need to be checked visually.
- For the spatial resolution the visibility of horizontal and vertical 1-pixel bar patterns modulated to 100% must be checked visually. This means, they have to be perceived and recognized clearly as bar patterns. Analogously, this has to be done with low-modulation bar patterns to check the contrast resolution.
- Attributes related to geometry (distortions), color (artifacts in grayscale images displayed on color monitors), uniformity across the screen, temporal stability (flicker, artifacts), and spatial artifacts also must be checked.

These relatively simple tests will be an important step towards image quality assurance in daily clinical routine. In addition to the clinical need, thorough, standard test methods and procedures for

use in research laboratories and by manufacturers should be developed.

CONCLUSION

Earlier a brief description of human visual system (HVS) properties relevant to soft copy reading of digital radiographs was presented. The most important characteristic of the HVS is the sensitivity to small image contrast that depends on spatial frequency and on luminance. This gives some hints on the favorable operational range of the HVS. The analysis of the adaptation process to complex scenes within radiographs leads to the dynamic range that can be comfortably processed by the HVS.

Some technical properties of modern monitors were also presented. The spatial resolution is given mainly by the addressability of rows and columns and by the properties of the scanning electron beam. Furthermore, luminance, contrast ratio, and veiling glare were investigated for typical viewing situations. Finally, the influence of the display curve on the dynamic range was explained and the impact of phosphor noise on the detectability of small details was addressed.

From all of this the author concludes that the overall characteristics of the HVS are well-suited to the visual tasks as viewed on present-day radiological CRT monitor displays. The spatial resolution as well as the contrast and dynamic range inherent in radiological scenes and presented on these displays is adjusted to the properties of the HVS.

These statements are valid in clinical practice, however, only if the monitor is properly set up and maintained according to the acceptance and constancy tests described above. The main points of

concern are controlling the ambient conditions, measuring luminance and the contrast ratio, establishing a display curve for maximum dynamic range, and visually testing spatial resolution, geometric properties, and for the presence of various artifacts.

The efficient control of ambient light is crucial for soft copy interpretation. The reading rooms have to be properly designed with the possibility to dim the lighting and to avoid extraneous light. Whether the loss in contrast ratio caused by external illumination and internal veiling glare can be satisfactorily compensated for by high frequency processing to increase the contrast in the dark parts of an image needs further research. Many receiver operating characteristic (ROC) studies indicate that this might indeed be the case.^{25,26} Because of the unfavorable influence of light glare, it is important to understand the mechanism of veiling glare in the monitor screen and to reduce it as much as possible.²⁷

Assuming that the image quality of soft copies is appropriate for primary diagnosis, the most severe problems that might hamper the wide acceptance and routine use of soft copy displays are due to user interface comfort and to network speed. Primary soft copy interpretation can be expected to succeed because of its many advantages compared with film radiographs.

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