Michael J. Flynn, PhD

Visual Requirements for High-Fidelity Display[1]

The digital radiographic process involves *(a)* the attenuation of x rays along rays forming an orthographic projection, *(b)* the detection of the radiation beam by a two-dimensional recording device, *(c)* the processing of detector signals to produce a digital image for presentation, and *(d)* the display of the digital image. The performance of the process is typically considered in terms of the ability to present anatomic structures of importance to the person interpreting the image. Any steps in the process that limit contrast, blur detail, or add noise can limit the interpretative process. Image information from the patient is potentially degraded by large focal spots that produce blur or by inappropriate peak kilovoltage that produces poor contrast. The recording of images is potentially degraded by detectors with poor modulation transfer characteristics or by detectors that add instrument noise to the x-ray signal. Display of the digital image can similarly add instrument noise to the signal and further restrict modulation transfer.

The image formation and radiographic recording processes are often capable of recording anatomic structures with very fine detail that produce very low contrast. If displayed with no further degradation, the detail and contrast in these signals can exceed the visual acuity limits of the human vision system. Interpretation in these circumstances requires some form of magnification, either geometric or produced by display processing.

The visual acuity of the human vision system is considered in this chapter. The maximum spatial frequency that the eye can detect is used to suggest the maximum spatial frequency that is needed for a display (ie, the minimum picture element size [pixel] and maximum display array size). The minimum contrast to detect standard test targets is used to explain how display devices should be calibrated to produce an effective gray-scale response. The nonlinear characteristics of the globally adapted eye are used to derive conditions to achieve an equivalent appearance of a digital image when it is displayed on different devices.

HUMAN VISION SYSTEM

The human visual system consists of an optic device similar to a camera (the eye), an image detector analogous to a charge-coupled device sensor (the retina), and a complex visual processing system capable of motion analysis and pattern recognition (the visual cortex). A typical distance for viewing medical images is 60 cm. At this distance, a 1° viewing angle from the eye sees an object with a size of about 1 cm in the image. The

Advances in Digital Radiography: RSNA Categorical Course in Diagnostic Radiology Physics 2003; pp 103–107.

[1]From Radiology Research, Henry Ford Health System, Suite 2F, 1 Ford Pl, Detroit, MI 48202 (e-mail: *mikef@rad.hfh.edu*).

lens of the eye replicates this object on the focal plane at the back of the eye with a size of about 288 μm (1). On the focal plane is a collection of cells responsible for the detection of light and generation of neural signals sent to the visual cortex. Certain receptive cells, termed cone cells, are primarily located in the center of the focal plane in a region known as the foveal structure. Different types of cone cells are sensitive to red, green, or blue light, depending on their type. Other types of light-sensitive cells, termed rod cells, are primarily located in the peripheral region of the focal plane. Rod cells are more sensitive to light than cone cells but do not respond differently to color.

In the center of the foveal structure is a small region with highly packed cone cells, no rod cells, and only a thin layer of neural cells that accumulate laterally on the surface. The rod-free region of the fovea corresponds to about 2° of visual angle, or 570 μm (2). An even smaller region of about 1°, or 250 μm, has a thinned retina with no cone pedicles (2). In the most central region of about 50 μm, the cones cells are hexagonally packed with a density of about 200,000 cells per square millimeter (3) and a spacing of about 2.0 μm. The fovea is responsible for detailed visual recognition of patterns in fields with high luminance. When interpreting medial images, the observer will typically search the image for detailed findings using the fovea region. The cognitive features of the visual difference and the difference between the central and peripheral region in the image interpretation process are not otherwise considered here.[2]

VISUAL ACUITY TESTS

The psychophysics of vision considers human visual performance for tasks involving various visual test signals. Parameters of interest include spatial detail, contrast, temporal change, temporal adaptation, and the perception of color, depth, shape, or motion. The spatial and contrast performance measures are of principal interest for digital radiography.

A variety of test patterns have been used to assess visual acuity. Common in clinical ophthalmologic practice are patterns involving the recognition of letters having varying size. Most psychovisual research has used patterns containing sinusoidal varying luminance characterized by spatial frequency, modulation amplitude, orientation, and pattern size (Fig 1), which are referred to as grating patterns. These patterns are usually placed on a uniform background with luminance equal to the average luminance of the grating pattern. The contrast *(C)* of the signal is defined as either *(a)* the light change (ΔL) between regions of maximum and minimum luminance relative to the average luminance (L_{avg}) value, that is, $C_t = \Delta L/L_{avg}$, where C_t is threshold contrast; or *(b)* the magnitude of the sinusoidal modulation, $C_{tm} = (\Delta L/2)L_{avg}$. The latter is known as the Michelson contrast (C_{tm}) (4) and is of classic importance. The former has been used in recent work, including the publications of the National Electrical Manufacturers Association on the digital imaging and communication in medicine (DICOM) standards.

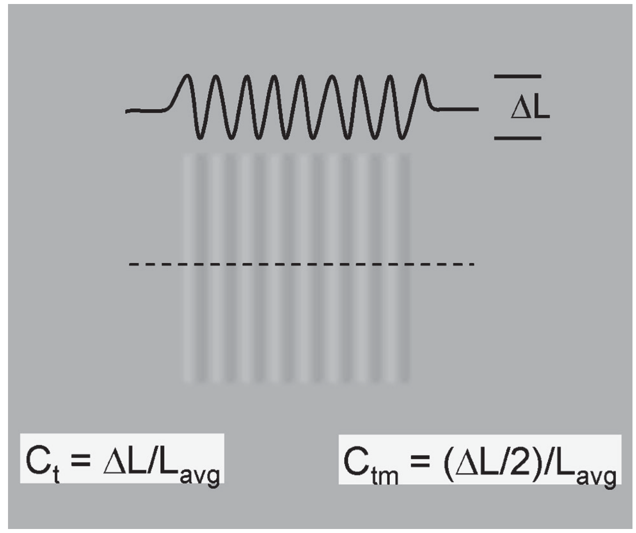

Figure 1. Standard test pattern of the type used for psychophysical visual experiments. Sinusoidally modulated grating pattern is placed on a uniform background. The peak-to-peak relative luminance change in the pattern is the contrast: $C_t = \Delta L/L_{avg}$. Alternatively, the Michelson contrast is defined as the relative amplitude of the sinusoidal modulation: $C_{tm} = (\Delta L/2)/L_{avg}$.

Most research on the perception of grating patterns has been directed at the contrast for which the test pattern is just visible, which is referred to as the threshold contrast (C_t or C_{tm}) (5). Often, the results are reported as the inverse of C_t and are described as contrast sensitivity, $C_s = 1/C_t$, or $C_{sm} = 1/C_{tm}$. For most studies, the images were generated *(a)* with optical devices for which the luminance of the grating pattern is added to a uniform luminance field by using an adjustable control (6), or *(b)* with highly specialized laboratory cathode-ray tube devices (7). Similar results have been shown for grating patterns that used either sine-wave modulation or square-wave modulation (6). Typically, the observer sets the contrast in a controlled manner to a level that is judged to be just noticeable. Alternatively, patterns are presented with various contrast levels in a two-alternative forced-choice experiment, and the relationship between the percentage correct and the contrast is used to deduce the contrast for a specified percentage correct. The latter is more time consuming but results in a value for C_t that is about two-thirds of the value measured in adjustable-contrast experiments (7).

[2]The Web teaching site of Kolb, Fernandez, and Nelson *(http://webvision.med.utah.edu)* is an excellent source of detailed information on the visual system.

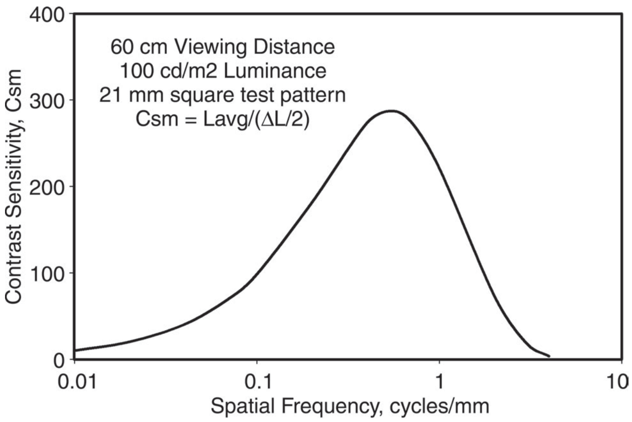

Figure 2. Contrast sensitivity (C_{sm}) based on the Michelson contrast, shown in relation to spatial frequency for a 21-mm grating test pattern image viewed at a 60-cm distance. The relationship is specific to an average luminance of 100 cd/m² and sinusoidal modulation. The relationship is based on the model of Barten (10) with the model parameters reported in the DICOM gray-scale standard (12).

Numerous variables influence contrast sensitivity, including spatial frequency, average luminance, orientation, pattern size, transient effects, flickering, adaptive effects, and retinal masking. Kelly (8) summarized early work in an invited paper presented at the National Eye Institute. More recently, several authors have deduced empiric models that best fit the experimental data in relation to multiple patterns (9–11). The empiric model of Barten (10) was used for the standards developed by the National Electrical Manufacturers Association for the calibration of display devices (12).

CONTRAST SENSITIVITY VERSUS SPATIAL FREQUENCY

Figure 2 illustrates the relationship of contrast sensitivity to spatial frequency (10) for test conditions that are near optimum for the human vision system. The curve shape follows the form of $C_s \sim f^2 e^{-f}$, where f is the spatial frequency of the grating pattern (8). At a viewing distance of 60 cm, a spatial frequency of 0.5 cycle per millimeter maximizes C_s at a value of about 140 (C_{sm} = 280), C_t = 0.007 (C_{tm} = 0.0035) for 80-cd/m² average luminance, 1° target size, and sinusoidal modulation. The shape of this relationship suggests that the eye acts as a bandpass filter with a spatial kernel associated with the impulse response of the retinal field (8), as determined by the ganglion-cone connections in the fovea.

The contrast sensitivity drops rapidly above its maximum, such that the sensitivity is reduced by more than a factor of 10 at two cycles per millimeter. Thus, display devices with a pixel pitch smaller than 0.250 mm do not noticeably degrade resolution at this viewing distance. Monochrome liquid crystal display monitors with 3 million pixels, sold by numerous companies, have a pixel pitch of 0.207 mm, which makes them effective at this viewing distance. If a display is used for close inspection of images with a viewing distance of 30 cm, a pixel pitch of 0.125 mm should be used. Modern picture archiving and communication system workstations provide the ability to magnify and pan an image and avoid the need for close-inspection viewing.

The poor contrast sensitivity at low spatial frequencies is also notable. C_s is reduced by a factor of 10 from the maximum at a spatial frequency of 0.06–0.07 cycle per millimeter (60-cm viewing distance) or one cycle over a distance of 1.4–1.7 cm. This can seriously affect the interpretation of large low-contrast objects in a digital radiograph, particularly if the image is displayed with magnification. In some specialties, such as chest imaging and mammography, many recommend that a minified view be examined as part of an interpretation, so that large structures are reduced in size and better matched to the visual response characteristics.

Although empiric models of the typical adult contrast sensitivity are used for gray-scale standards and for the optimization of radiographic display processing, it is important to understand that considerable variation in contrast sensitivity and its dependence on spatial frequency will occur among individuals. This can involve an overall reduction in contrast sensitivity, such as occurs with patients having cataracts, or a selective loss of high-frequency response, such as occurs with mild refractive error or mild amblyopia (13). Little is known about the variations that might occur among a population of radiologists who are considered to have normal vision.

CONTRAST THRESHOLD VERSUS BRIGHTNESS

In general, the contrast threshold increases and the contrast sensitivity decreases as the average luminance of the image is decreased. Figure 3 illustrates the peak-to-peak contrast threshold (C_t) as a function of image luminance over a range relevant to digital radiography. The illustration is derived directly from the tables in DICOM part 3.14 (12), which were derived from the Barten model for a 2° square target with modulation of four cycles per degree. From a luminance of 3,000 cd/m² down to 10 cd/m², the peak-to-peak contrast threshold varies slowly from 0.0065 to 0.011. At luminance values less than 10 cd/m², C_t increases more rapidly, with the value at 1 cd/m² being about 0.026.

If a series of test images having increasing average image values and a small grating pattern are displayed such that the image values are proportional to the log of the displayed luminance, the appearance of grating contrast will be similar for bright images. For dark images with a luminance less than 10 cd/m², the grating will appear with reduced contrast because of the reduced contrast sensitivity. A log luminance display response does result for transilluminated films that have been printed with film density proportional to image value. To compensate for this, the slope of the log luminance versus image value response can be increased at low brightness to compensate for the visual deficit. The DICOM gray-scale display function suggests a specific relationship to provide this compensation. Devices calibrated according to this response curve (Fig 4) are said to be "perceptually linear" in response.

CONTRAST PERCEPTION WITH GLOBAL ADAPTATION

The contrast threshold is specifically measured under conditions where the observer is able to adapt to the luminance of the test image. C_t in relation to luminance is thus measured under conditions where the observer is variably adapted for each luminance at which C_t is measured. If one changes the background luminance and keeps the average luminance of the grating pattern the same, adaptation causes a reduction in contrast sensitivity and an increase in contrast threshold. Figure 5 illustrates the altered contrast threshold for an observer who is adapted to a brightness of 100 cd/m^2 but observed grating test patterns with varying average luminance. The relationship is based on the biologic contrast response for the human vision system (14) derived from an analytic relationship for adapted photoreceptor response (15–17).

The concept of global adaptation is important for understanding the conditions necessary for an image to appear the same with respect to contrast on two different display systems. If both display systems are calibrated by using the DICOM gray-scale standard, perceptually equivalent contrast is obtained in relation to luminance only for a series of images for which the luminance varies. When looking at one image with different regions having high and low brightness, the observer globally adapts and responds optimally only in those regions where brightness is at the adaptation luminance. In the brighter and darker regions, the contrast response is suboptimal. If the two displays also are calibrated to have the same luminance ratio (ie, the ratio of the maximum luminance to the minimum luminance), then the contrast response degradation in the bright and dark regions will be the same. The conditions for equivalent contrast appearance when using multiple displays thus require that all devices be calibrated to the DICOM standard and that all devices be set up with the same luminance ratio.

The globally adapted contrast threshold is also useful for establishing criteria with respect to the luminance ratio used to set up multiple display devices. A ratio of 250–350 is appropriate to maintain the response of the display within the range where the human visual system can perceive reasonable contrast (14). This corresponds to a film density range of 0.1–2.5 for a ratio of 250 or 0.1–2.65 for a ratio of 350. Most radiologists will readily agree that visualization of contrast at densities greater than about 2.5 for a general radiograph is not possible without a bright spot illuminator.

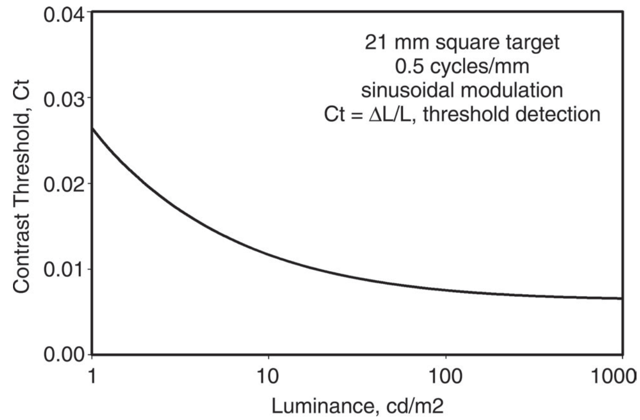

Figure 3. Peak-to-peak contrast threshold (C_t) for a grating test pattern, shown in relation to image luminance. The relationship is specific to a 21-mm square target with a spatial frequency of 0.5 cycle per millimeter that is viewed at 60 cm. The test pattern corresponds to the DICOM standard test conditions. The contrast sensitivity of the human visual system is poorer as the scene luminance is lowered, causing the threshold contrast to increase. The relationship is based on the model of Barten (10) with the model parameters reported in the DICOM gray-scale standard (12).

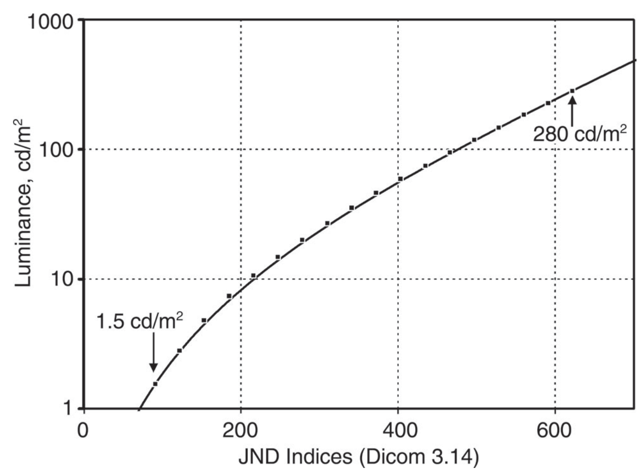

Figure 4. DICOM gray-scale display standard illustrated as luminance in relation to an index proportional to image value. An index value change of 1 produces a relative luminance change equal to the peak-to-peak contrast threshold. For this reason, the index values are referred to as just-noticeable-difference *(JND)* indices. The experimental data points illustrate the actual luminance response of a display device that has been calibrated to closely follow the standard curve.

INFLUENCE OF AMBIENT LIGHT ON CONTRAST

For a display device that is turned off, the surface of the display will have a low brightness that is termed

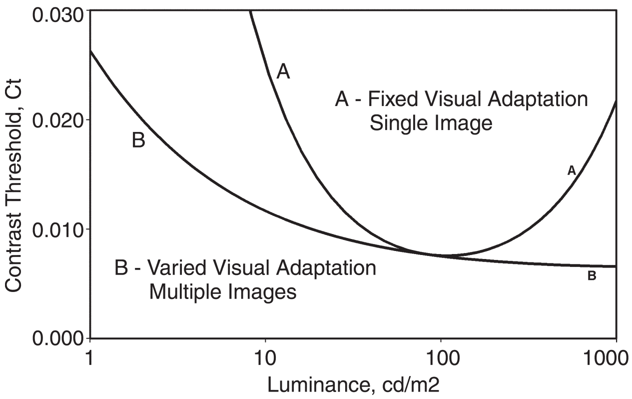

Figure 5. Contrast threshold predicted for conditions where the observer is globally adapted at 100 cd/m^2 to a single image (curve *A*). This response is compared to the contrast threshold for an observer who is variably adapted to a series of images with different luminances (curve *B*). The conditions are based on the grating pattern used for the DICOM gray-scale display standard, which defines a luminance calibration standard based on variable adaptation.

the ambient luminance. This comes mostly from the diffuse reflection of ambient light from the surface of a monitor. Display calibration methods account for this luminance when generating the lookup tables that control luminance response (Fig 4). If the room lighting conditions change, the minimum luminance of the display will change, and contrast can be markedly altered in the dark regions. For this reason, it is recommended that the ambient luminance not exceed one-third of the minimum luminance (18). This keeps the changes in contrast associated with normal variation in room light levels from excessively altering contrast.

Most display devices will also reflect a mirror image of bright objects. Standard test methods are recommended to determine the specular reflection coefficient of monitor surfaces (18) and then to set a limit on the ambient illumination coming from room lighting. Alternatively, an effective and simple test to establish that specular reflections are not degrading the appearance of images is to view the monitor with typical room illumination and the display device turned off. No object reflection should be visible. If ceiling lights or lamps are visible, the monitor should be moved or the lights turned off. If white objects such as medical coats are visible, the room lighting should be reduced.

DISCUSSION

A general understanding of the psychophysical performance of the human visual system, particularly with respect to visual acuity and the threshold detection of grating patterns, has been used to suggest the performance required of a high-fidelity display device. With respect to resolution, devices with 0.250-mm pixels are shown to be well matched to visual performance when used at a 60-cm viewing distance. The basis for the calibration of the gray-scale response of a monitor has been related to visual contrast threshold. An important criterion for equivalent appearance, the luminance ratio, has been explained in terms of global adaptation and its influence on contrast response in relation to brightness. Finally, limits for ambient illumination have been suggested, based on criteria that minimize the alteration of the contrast calibration in the dark portions of an image. The reader is referred to an earlier publication for further details and a detailed chart of display requirements (14).

References

1. Drasdo N, Fowler CW. Non-linear projection of the retinal image in a wide-angle schematic eye. Br J Ophthalmol 1974; 58:709–714.
2. Yamada E. Some structural features of the fovea centralis in the human retina. Arch Ophthalmol 1969; 82:151–159.
3. Ahnelt PK, Kolb H, Pflug R. Identification of a subtype of cone photoreceptor, likely to be blue sensitive, in the human retina. J Comp Neurol 1987; 255:18–34.
4. Michelson AA. Studies in optics. Chicago, Ill: University of Chicago Press, 1962.
5. Blackwell HR. Contrast threshold of the human eye. J Opt Soc Am 1946; 36:624–643.
6. DePalma JJ, Lowry EM. Sine-wave response of the visual system. II. Sine-wave and square-wave contrast sensitivity. J Opt Soc Am 1962; 52:328–335.
7. Legge GE. A power law for contrast discrimination. Vision Res 1980; 21:457–467.
8. Kelly DH. Visual contrast sensitivity. Opt Acta 1977; 24:107–129.
9. Rogers JG, Carel WL. Development of design criteria for sensor display devices. Technical report HAC C6619. Culver City, Calif: Hughes Aircraft Co, 1973.
10. Barten PG. Physical model for the contrast sensitivity of the human eye. Proc SPIE 1992; 1666:57–72.
11. Daly S. The visible difference predictor: an algorithm for the assessment of image fidelity. In: Watson AB, ed. Digital images and human vision. Cambridge, Mass: MIT Press, 1993; 179–206.
12. National Electrical Manufacturers Association. Digital imaging and communications in medicine (DICOM) part 14: grayscale standard display function. Publication no. NEMA-PS3.14. Rosslyn, Va: National Electrical Manufacturers Association, 2003.
13. Arden GB. The importance of measuring contrast sensitivity in cases of visual disturbances. Br J Ophthalmol 1978; 65:198–209.
14. Flynn MJ, Kanicki J, Badano A, Eyler WR. High-fidelity electronic display of digital radiographs. RadioGraphics 1999; 19:1653–1669.
15. Hecht S, Hsia Y. Relation between visual acuity and illumination. J Gen Physiol 1928; 11:255–281.
16. Baylor DA, Fuortes MGF. Electrical responses of single cones in the retina of the turtle. J Physiol 1970; 207:77–92.
17. Glantz RM. Visual adaptation: a case of nonlinear summation. Vision Res 1972; 12:103–109.
18. Samei E, Badano A, Chakraborty DP, et al. Assessment of display performance for medical imaging systems: final draft (version 9). College Park, Md: American Association of Physicists in Medicine Task Group 18, 2003.