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Display for Medical Imaging and DICOM Grayscale Standard Display Function Fundamentals

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Display for Medical Imaging and DICOM Grayscale Standard Display Function Fundamentals

Wei-Chung Cheng and Aldo Badano

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64.1 Medical Display

The term “medical display” is widely used while lacking a clear definition. In this chapter, we limit the scope of medical display to the following definition:

An optoelectronic instrument that presents a two-/three-dimensional array of medical data with corresponding monochrome or color pixels/voxels arranged in the original geometrical order for the human user to visually perceive the structured information.

This definition covers medical displays used in various modalities including computed tomography (CT), magnetic resonance (MR), positron emission tomography (PET), ultrasonography (US), digital radiography (DX), mammography (MG), digital angiography (XA), nuclear medicine (NM), and so on (see Section IV, Chapter 59). The scope of medical display in this chapter is slightly narrower than other regulatory or marketing definitions such as “display devices for diagnostic radiology” (U.S. Department of Health and Human Services Food and Drug Administration 2016a), “soft-copy presentation of medical images” (Samei et al. 2005; U.S. Department of Health and Human Services Food and Drug Administration 2008), and interface to a picture archiving and communication system (PACS) (Behlen et al. 2000). The relationship between the three-dimensional object and the two-dimensional image in an imaging system is thoroughly treated in Barrett and Myers (2013).

According to the abovementioned definition, the input to a medical display is an image that represents the medical data. Therefore, a driving computer is required in a medical display to handle the image and drive the display device. A medical display system is defined in the next section, followed by a summary of the essential measurable characteristics of a color display. The concept of perceptual linearity is quantified as the foundation of any display function. The derivation of Barten’s contrast sensitivity model is elaborated, as well as the simplified model, which was derived by the Digital Imaging and Communications in Medicine (DICOM) PS 3.14. The calibration and assessment
A typical medical display system consists of the driving computer, display interface, and display device. The driving computer hosts the hardware and software components that are required to execute the image viewer software programs. The hardware components include not only the essential computer parts such as CPU, memory, and storage, but also the graphics card or graphics processor. The software components include the operating system, graphics libraries, device drivers, color manager, and color profiles.

The display device, frequently called the monitor or screen, is an optoelectronic device such as a liquid crystal display (LCD) or cathode ray tube (CRT) monitor (Badano et al. 2004) that converts digital information into optical signals. The display device is driven by the driving computer via the display interface, such as the Digital Visual Interface (DVI) or the DisplayPort.

In a desktop computer-based medical display system, each of the computer hardware, computer software, display interface, and display device is an individual unit that is interchangeable and can be swapped by the user after shipment from the manufacturer. The benefits of such an open architecture are lower manufacturing cost and better controllability, because most parts are commercial off-the-shelf and the end user has access to individual parts. On the other hand, an open architecture is prone to the end user’s inappropriate manipulation, which was not envisioned by the manufacturer. For example, the luminance response of a professionally calibrated display system can be easily distorted if the end user incidentally alters brightness and contrast settings of the display device. In contrast, a closed architecture integrates the driving computer and display components in a monolithic device such as a mobile phone, tablet, all-in-one computer, or smart TV. The Apple iPhone is an example of closed architecture, in which every hardware/software block purchased.

Besides being a closed system, the other major differences in mobile displays are the reduced display size, higher pixel density, and shortened viewing distance. These factors impact on the spatial resolution properties, and are studied in Yamazaki et al. (2013b).

A display is a complex optoelectronic device. A color display has millions of pixels, and each of them can show millions of color shades independently, which makes characterizing a display a non-trivial task (Lueder 2001; Green et al. 2002; Marcu 2002; Balasubramanian 2003; Lee 2005; Badano 2011; Kagadis 2013). The AAPM Task Group 18 (TG18) recommends a set of essential optical characteristics of a medical display that should be rigorously assessed (Samei et al. 2005). These characteristics are grouped by their physical properties in Table 64.1. Many of the characteristics can be considered as the minimal/microscopic or maximal/macrosopic measures of the same physical property, while some represent the transition between the two ends. Each of the physical properties is discussed in the following.

The luminance response is the relationship between the digital input (p-value) and the luminance output. For a medical display, both the minimum luminance ($L_{\text{min}}$) and the maximum luminance ($L_{\text{max}}$) are critical specifications. The transition (or curve) from the minimum to the maximum luminance is the display function, which is the main topic of this chapter.

The reflectance response is the relationship between the incident ambient light and the reflected light from the display surface. The reflectance response is important for determining the impact of the ambient light on the perceivable minimum luminance. The reflectance response has two components—specular reflectance and diffuse reflectance.
The chromaticity response is the relationship between the p-value and the chromaticity of the output light. The chromaticity of the gray shade at the maximum p-value is the white point, which can be represented by a standard illuminant or color temperature (e.g., CIE D65 or 6500 K). The chromaticity at the minimum luminance is not as important, so it is usually not reported. The chromatic transition from the white point to the black point is gray tracking. The chromaticity responses of the primary colors (i.e., red, green, and blue) are important because they determine the color gamut of a color display. The chromatic transition of each primary color from the maximum p-value to the minimum p-value is color tracking.

The spatial response is the relationship between the pixel on/off state and the output lighting pattern. At the microscopic level, each pixel (or subpixel) can be described by the pixel size and aperture ratio. The modulation transfer function (MTF) is a standard method for measuring the spatial resolution. At the macroscopic level, the pixel size and pixel pitch together determine the effective display area. Considering the transition from a single pixel to the whole display area, geometrical distortion-free is a basic requirement that all pixels must be aligned straight and square.

Spatial uniformity is the relationship between sources of noise and their distributions. At the microscopic level, a dead pixel (or subpixel) stuck at the on/off state creates a strong, high frequency local noise. On the other hand, Mura is a weak, low frequency type of noises across a large area of the display. In between, the noise power spectrum (NPS) is a standard method for measuring the small fluctuation in luminance across the whole display area.

The temporal response describes the characteristics of the transition time of the output light. The gray-to-gray transition time is the rising or falling time required to change the luminance from one gray level to another. After reaching the target gray level, the luminance may either hold, like in a hold-type display technology such as LCD, or decay, like in a pulse-type display technology such as CRT. Frame rate describes how fast the image can be updated with respect to the input data. Refresh rate describes how often each pixel is re-scanned.

The spectral response is the relationship between each sub-pixel and its output spectrum. At the microscopic level, each of the red, green, and blue subpixels is associated with a specific spectrum, which is determined by the combination of the backlight and the color filter array, as well as the digital driving level (DDL) in the case of the LCD technology. At the macroscopic level, the spectrum of each color channel can be individually measured to determine the primary colors and color tracking. For the purpose of color correction, a single color channel may drive more than one subpixel, so the spectra of subpixels may differ from those of primary colors.

Finally, the angular response is the relationship between the viewing angle and the luminance/chromaticity response. Angular response should not be considered as a standalone display characteristic, but an additional dimension associated with the luminance and chromaticity responses. All of the abovementioned physical properties (luminance, reflectance, chromaticity, spatial, spatial uniformity, temporal, and spectral) are measured perpendicularly only. The angular luminance response is important for displays that exhibit strong viewing angle dependency such as LCD. Many display manufacturers use the luminance ratio, defined as the maximum luminance divided by the minimum luminance, with a very loose constraint, for example \( \geq 10 \), to report the maximum viewing angle, for example \( \pm 170^\circ \), which is rarely informative and often misleading. A better method is to use a polar chart to show contours of luminance or contrast at various angles.

Further discussion and measurement methods of the essential characteristics for color medical displays can be found in Samei et al. (2005), and International Committee for Display Metrology (ICDM) (2012).

### 64.4 Perceptual Linearity

The main objective of a medical display is to stimulate the user to evoke a visual sensation that is linearly correlated with the source data. For monochrome medical displays, the only optical property that can be modulated to represent the source data is luminance, which stimulates the visual sensation of brightness (Fairchild 2013). For color medical displays, the source data can
be represented by luminance and/or the other attributes such as hue and chroma. For example, the transition of hue in a rainbow color map can be used to present the source data in a pseudocolor fashion, which is used in perfusion MR and color-fused multimodal imaging. Ideally, the perceived visual sensation should linearly correlate with the source data. This property is often desirable and referred as perceptual linearity. Perceptual linearity is one of the key features that qualify a medical display. Achieving perceptual linearity involves accurate display calibration and a well-controlled viewing environment.

For monochrome displays, perceptual linearity is the relationship between the input data, \( p \), and the perceived brightness, \( J \), conforming to a linear equation:

\[
J = a \cdot p + b \quad (64.1)
\]

where \( a \) is a positive number, \( b \) is a finite number, and \( p \) is the input \( p \)-value.

The perceived brightness, \( J \), is a perceptual measure that needs to be determined by psychophysical experiments, which are usually costly to conduct. Alternatively, measuring the difference in perceived brightness, \( \Delta J \), is easier to determine with the following equation:

\[
\Delta J = a \cdot \Delta p + b \quad (64.2)
\]

Equation 64.2 is a more practical form of utilizing the concept of perceptual linearity. It determines how much increase in the \( p \)-value is required to evoke a certain amount of perceptual difference in brightness, and vice-versa. Due to the limitations of the human visual system, the minimum perceivable \( \Delta J \) is bounded by the just-noticeable difference (JND). Thus, the concept of the JND is also embedded in Equation 64.2.

### 64.5 Barten’s Contrast Sensitivity Model

The human visual system is known to be extremely complex (Palmer 1999). Although human vision researchers have been working on an accurate mathematical model for more than a century, due to the overwhelming amount of variables that can affect the human visual system, to date there is not an accurate yet universal model for predicting visual perception.

In 1992, Peter Barten published a contrast sensitivity model for the human eye (Barten 1992). The model is expressed as a function in Equation 64.3.

\[
S(u) = \frac{1}{m(u)} = \frac{M_{opt}(u)/k}{\sqrt{1 + \frac{1}{X_0^2} + \frac{u^2}{X_{max}^2}} \left\{ \frac{1}{\eta p \left( \frac{\pi}{4} d^2 L \right)} + \frac{\Phi_o}{1 - e^{-u/\sigma^2}} \right\} - \frac{\Phi_o}{1 - e^{-u/\sigma^2}}} \quad (64.3)
\]

\[
M_{opt}(u) = e^{-2\sigma^2u^2}, \quad \sigma = \sqrt{\frac{\sigma_0^2 + (C_{opt}d\sigma)^2}{2}} \quad (64.4)
\]

\[
d = 4.6 - 2.8 \cdot \tanh(0.4 \cdot \log_{10}(0.625 \cdot L)) \quad (64.5)
\]

The model mainly predicts the relationship between the contrast sensitivity, \( S \), and the spatial frequency, \( u \), under a certain viewing condition that is specified by 11 parameters. The contrast sensitivity, \( S \), is the inverse of the threshold, \( m \), which is measured with a visual psychophysical experiment. \( M_{opt} \), as defined in Equation 64.4, is the optical modulation transfer function (MTF) of the human eye. The pupil size, \( d \), is modeled as a function of \( L \), the object luminance, as defined in Equation 64.5. The rest of the parameters define the viewing conditions of the visual experiments, as listed in Table 64.2.

Barten’s model predicts the contrast sensitivity function under the following conditions. The subject looks at a vertically oriented grating pattern with both eyes. The spatial frequency of the grating pattern, \( u \), is adjusted by the subject. The task for the subject is to determine the threshold of the spatial frequency, \( m \), at which the grating pattern is visually discernable.

The parameters in Equation 64.3 and Table 64.2 can be classified into the following three groups.

1. Target-dependent parameters:
   - The angular size of the grating pattern in a square shape is \( X_o \) deg \( \times X_o \) deg.
   - The spatial frequency of the grating pattern is \( u \) cycle/deg.
   - The average luminance of the grating pattern is \( L \) cd/m².
   - The photon conversion factor, \( p \), is determined by the spectrum of the light source.

2. Subject-dependent parameters:
   - \( k \) is the signal-to-noise ratio of the subject’s eye.
   - \( \eta \) is the quantum efficiency of the subject’s eye.
   - \( \sigma_0 \) is a constant for determining the standard deviation of the line-spread function, \( \sigma \), in Equation 64.4.

3. Constants related to the human visual system:
   - \( X_{max} \) is the maximum angular size that can be integrated by the human eye.
   - \( N_{max} \) is the maximum number of cycles that can be integrated by the human eye.
   - \( C_{opt} \) is another constant for determining the standard deviation of the line-spread function \( \sigma \) in Equation 64.4.
   - \( T \) is the integration time of the human eye for static images.
   - \( \Phi_o \) is the spectral density of the neural noise.

The pupil size, \( d \), is an important factor of the model. Figure 64.2 shows the relationship between the pupil size, \( d \), and logarithm of the object luminance, \( \log(L) \). The pupil size is about 7 mm in the dark and decreases hyperbolically with \( \log(L) \). The pupil size affects two terms in Equation 64.3—\( M_{opt} \) and \((1/((\eta p((\pi/4) d L)))\).
Mathematically, Barten’s model can be comprehended by analyzing the three components in Equation 64.3 as follows.

The first component is the optical MTF, \( M_{\text{opt}} \). Figure 64.3 shows the relationship between the optical MTF, \( M_{\text{opt}} \), and the spatial frequency, \( u \), at three object luminance levels (\( L = 100, 1, \) and 0.01 cd/m\(^2\)). The MTF curve remains constant until the spatial frequency exceeds a certain point. The knee of each curve is controlled by the \( \sigma_0 \) constant. The MTF curves decrease when the object luminance is reduced from 100 to 1 and then 0.01 cd/m\(^2\).

The second component of Equation 64.3 represents the internal noise as

\[
\frac{1}{\eta p \pi d^2 L} \left( \frac{1}{\frac{u}{u_o}} + 1 - e^{-\left(\frac{u}{u_o}\right)^2} \right)
\]

(64.6)

Figure 64.4 plots Equation 64.6, the internal noise as a function of the spatial frequency, \( u \), for three object sizes (\( X_o = 6^\circ, 10^\circ, \) and \( 15^\circ \)). The internal noise decreases as the spatial frequency increases. The internal noise is higher when the object size \( X_o \) is larger. The internal noise is independent of the object luminance, \( L \).

The third component of Equation 64.3 is the combination of the neural noise and lateral inhibition modeled as

\[
\frac{1}{\eta p \pi d^2 L} \left( \frac{1}{\frac{u}{u_o}} + 1 - e^{-\left(\frac{u}{u_o}\right)^2} \right)
\]

(64.7)

TABLE 64.2

<table>
<thead>
<tr>
<th>Unit</th>
<th>Meaning</th>
<th>Barten (1992)</th>
<th>DICOM PS-3.14</th>
</tr>
</thead>
<tbody>
<tr>
<td>( u )</td>
<td>Spatial frequency</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>( L ) cd/m(^2)</td>
<td>Luminance of the object</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( X_o ) Deg</td>
<td>Angular size of the object</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>( p ) Photon/(Td<em>Sec</em>Deg)</td>
<td>Photon conversion factor</td>
<td>357</td>
<td></td>
</tr>
<tr>
<td>( k ) –</td>
<td>Signal to noise ratio</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td>( \eta ) %</td>
<td>Quantum efficiency of the eye</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>( \sigma_0 ) Deg</td>
<td>Resolvable spatial frequency</td>
<td>0.5</td>
<td>0.0133</td>
</tr>
<tr>
<td>( u_o ) Cycle/deg</td>
<td>Spatial frequency above which the lateral inhibition ceases</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>( X_o_{\text{max}} ) Deg</td>
<td>Maximum angular size of the integration area</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>( N_o_{\text{max}} ) Cycle</td>
<td>Maximum number of cycles over which the eye can integrate</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>( C_{\text{rel}} ) Deg/mm(^3)</td>
<td>Increase of the line-spread function with pupil size</td>
<td>0.0001</td>
<td>0.0001</td>
</tr>
<tr>
<td>( T ) Sec</td>
<td>Integration time</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>( \Phi_o ) Sec * deg(^2)</td>
<td>Spectral density of neural noise</td>
<td>( 3 \times 10^{-4} )</td>
<td>( 3 \times 10^{-4} )</td>
</tr>
</tbody>
</table>

FIGURE 64.2  The relationship between pupil size and luminance modeled by Equation 64.5.

FIGURE 64.3  The relationship between \( M_{\text{opt}} \) and \( u \) at three object luminance levels modeled by Equation 64.4.
Figure 64.5 shows the relationship between the combination of the neural noise and lateral inhibition and the spatial frequency at three luminance levels modeled by Equation 64.7. Overall, the contrast sensitivity decreases as the luminance decreases.

The curves in Figure 64.6 depict how contrast sensitivity is affected by spatial frequency for a certain object luminance. Given the curves, the relationship between contrast sensitivity and object luminance, which is of our interest, can be retrieved indirectly. For example, in Figure 64.6, the dashed vertical line, \( u = 4 \), intersects with the three curves at three points, which can be used to determine the relationship between the contrast sensitivity and object luminance. However, replacing \( u = 4 \) with another vertical line, for example \( u = 8 \), will obviously result in a completely different relationship. Therefore, such an approach is highly dependent on the chosen spatial frequency, \( u \).

Barten’s model was fitted and compared with the empirical data from eight previous studies (Barten 1999). In all of the eight studies, the main objective was to establish the relationship between contrast sensitivity and spatial frequency. Only three of the eight studies conducted experiments at various object luminance levels. Since the relationship between contrast sensitivity and object luminance was not the main objective of these studies, it is understandable if Barten’s model fails to predict it accurately.

Another consideration when using Barten’s model is the surrounding condition. Surround is defined as the field outside the stimulus, and can be considered as the entire room or environment (Fairchild 2013). The surround impacts on the overall image contrast effects (Bartleson and Breneman 1967; Fairchild 1995), and is included in other visual perception models (Luo and Hunt 1998; Moroney et al. 2002). In the eight studies, the visual experiments were conducted in a dark environment, which differs from the common use case of a radiology reading room. The lack of consideration of the surround effects in Barten’s model may also reduce its prediction accuracy in practice.

### 64.6 Barten’s Simplified Model

A simplified version of Barten’s model was adopted by DICOM PS 3.14 when deriving the grayscale standard display...
function in 2003 (NEMA 2011). The model was simplified by fixing 12 of the 13 parameters in Table 64.2, including the spatial frequency, \( u \), leaving the object luminance, \( L \), the only variable.

Equation 64.3 can be rearranged as

\[
S(u) = \frac{1}{k} \sqrt{\frac{T}{2}} \cdot M_{opt}(u) \sqrt{\frac{1}{X_0^2} + \frac{1}{X_{max}^2} + \frac{u^2}{N_{max}^2}} \cdot \frac{4}{\pi \eta \rho} \cdot \frac{1}{d^2 L} + \frac{\Phi_u}{1 - e^{-(\pi u) / \eta}} 
\]

(64.8)

\[
= \frac{q_1 \cdot M_{opt}(u)}{d^2 L + q_3} 
\]

(64.9)

where the substituting variables \( q_1, q_2, \) and \( q_3 \) are

\[
q_1 = \frac{1}{k} \sqrt{\frac{T}{2}} \sqrt{\frac{1}{X_0^2} + \frac{1}{X_{max}^2} + \frac{u^2}{N_{max}^2}} \quad \text{Eq. (64.10)}
\]

\[
q_2 = \frac{4}{\pi \eta \rho} \quad \text{Eq. (64.11)}
\]

\[
q_3 = \frac{\Phi_u}{1 - e^{-(\pi u) / \eta}} \quad \text{Eq. (64.12)}
\]

After plugging in the 12 parameters listed in the rightmost column of Table 64.2, the substituting variables can be calculated as

\[
q_1 = 0.1183034375
\]

\[
q_2 = 3.962774805 \cdot 10^{-5}
\]

\[
q_3 = 1.356243499 \cdot 10^{-7}
\]

Since the object luminance \( L \) is the only remaining variable, Equation 64.9 becomes a univariate function of the object luminance. To distinguish Barten’s simplified model from the original one, a different symbol \( S' \) is used

\[
S'(L) = \frac{q_1 \cdot M_{opt}(L)}{d^2 L + q_3} 
\]

(64.13)

In Equation 64.13, \( M_{opt} \) and \( d \) cannot be simplified further because both are functions of \( L \) (cf. Equations 64.4 and 64.5).

Based on the 12 parameters used in DICOM PS 3.14, the following experiment conditions can be inferred. The object size is \( 2^\circ \times 2^\circ (X_0 = 2) \), which is equivalent to a 8.7 mm \( \times \) 8.7 mm square placed 250 mm away from the subject. The spatial frequency of the grating pattern is 4 cycles/deg \( (u = 4) \), so the grating frequency is 0.92 line-pair/mm. The color temperature of the illumination is 2850 K \( (\rho = 357) \), the same as the orange-tinted light from a halogen lamp used (DePalma and Lowry 1962). The three subject-dependent parameters, \( k = 3.3, \eta = 2.5, \) and \( \sigma_0 = 0.0133 \), were suggested by Barten in Barten (1999), because they were calculated from the geometrical means of the parameters used in the previous eight studies (DePalma and Lowry 1962; Patel 1966; Van Nes and Bouman 1967; Campbell and Robson 1968; Watanabe et al. 1968; Van Meeteren and Vos 1972; Virsu and Rovamo 1979; Carlson 1982. The remaining seven parameters are the same as those used in Barten (1999).

The relationship between the logarithm of the contrast sensitivity and the logarithm of the object luminance, modeled by Equation 64.13, is shown in Figure 64.7.

Notice that the maximum luminance tested in Barten (1999) was 1028 cd/m\(^2\). In DICOM PS 3.14, Equation 64.13 is applied to the luminance range between 0.05 and 4000 cd/m\(^2\), which covers the black point of a typical CRT display (0.05 cd/m\(^2\)) and a radiology lightbox for reading X-ray film (4000 cd/m\(^2\)). Therefore, gray levels above 1030 cd/m\(^2\) (at DDL 815) were extrapolated from Barten’s model and may need experimental verification.

### 64.7 Grayscale Standard Display Function

Based on Barten’s simplified model, the grayscale standard display function was derived by DICOM PS 3.14. The main goal of the GSDF is to standardize a one-to-one mapping between the object luminance and the perceived brightness with reasonable perceptual linearity. DICOM PS 3.14 uses the term

![Figure 64.7](image-url)
“just-noticeable difference (JND) index,” annotated by \( j \), to quantify the perceived brightness. The GSDF was derived based on the idea that the contrast of two adjacent JND indices should be inversely proportional to the contrast sensitivity function. The contrast is defined in Michaelson’s contrast formula

\[
\frac{L_{j+1} - L_j}{L_{j+1} + L_j} = \frac{1}{S'(L_j)} \tag{64.14}
\]

where \( j \) and \( j + 1 \) are adjacent JND indices, \( L_j \) is the object luminance at JND index \( j \), and \( S' \) is the contrast sensitivity calculated from Equation 64.13, Barten’s simplified model.

Thus, the object luminance of each JND index, \( j + 1 \), can be calculated from \( L_j \):

\[
L_{j+1} = \frac{S'(L_j) + 1}{S'(L_j) - 1} L_j, \quad 1 < j \leq 1023
\]

\[
L_1 = 0.05
\]

The unit of \( L \) is cd/m\(^2\). The boundary condition, \( L_1 \), is meant to be the minimum luminance of the display. \( L_1 = 0.05 \) was chosen by DICOM PS 3.14 to represent the black point of a typical CRT display. Also, a ratio of 1 was chosen to formulate the proportionality in Equation 64.14.

The recursively defined Equation 64.15 can be rewritten as

\[
L_j = 0.05 \prod_{k=2}^{j} \frac{S'(L_k) + 1}{S'(L_k) - 1} \tag{64.16}
\]

Figure 64.8 shows the relationship between the object luminance and JND index, as modeled by Equation 64.16.

In DICOM PS 3.14, the GSDF was further simplified by fitting the curve in Figure 64.8 with the following equation

\[
\log_{10} L_j = \frac{a + c \cdot 
\log(L_j) + e \cdot (\log(L_j))^2 + g \cdot (\log(L_j))^3}{1 + b \cdot \log(L_j) + d \cdot (\log(L_j))^2 + f \cdot (\log(L_j))^3 + h \cdot (\log(L_j))^4 + k \cdot (\log(L_j))^5} \tag{64.17}
\]

where

\[
\begin{align*}
a &= -1.3011877, \\
b &= -2.5840191 \times 10^{-2}, \\
c &= 8.0242636 \times 10^{-2}, \\
d &= -1.0320229 \times 10^{-1}, \\
e &= 1.3646699 \times 10^{-1}, \\
f &= 2.8745420 \times 10^{-3}, \\
g &= -2.5468404 \times 10^{-3}, \\
h &= -3.1978977 \times 10^{-3}, \\
k &= -1.2992634 \times 10^{-4}, \\
m &= 1.3635334 \times 10^{-3}.
\end{align*}
\]

Equation 64.17 defines the mapping from the object luminance, \( L \), in cd/m\(^2\) to the JND index, \( j \). \( \log_{10} \) stands for the natural logarithm, while \( \log_{10} \) stands for base-10 logarithm.

The inverse of the GSDF was also provided in DICOM PS 3.14 as

\[
j(L) = A + B \cdot \log_{10}(L) + C \cdot (\log_{10}(L))^2 + D \cdot (\log_{10}(L))^3 + E \cdot (\log_{10}(L))^4 + F \cdot (\log_{10}(L))^5 + G \cdot (\log_{10}(L))^6 + H \cdot (\log_{10}(L))^7 + I \cdot (\log_{10}(L))^8 \tag{64.18}
\]

where

\[
\begin{align*}
A &= 71.498068, \\
B &= 94.593053, \\
C &= 41.912053, \\
D &= 9.8247004, \\
E &= 0.28175407, \\
F &= -1.1878455, \\
G &= -0.18014349, \\
H &= 0.14710899, \\
I &= -0.017046845.
\end{align*}
\]

Equation 64.18 defines the mapping from the JND index, \( j \), to the luminance, \( L \), in cd/m\(^2\).
where \( p \) is the \( p \)-value, and \( L_p \) is the target display luminance with respect to \( p \). The term \( a \cdot p + b \) is a JND index, and \( L \) is the JND index-to-Luminance function, as defined in Equation 64.17.

The idea of the GSDF calibration is that the display luminance range must be identical to a certain interval of the GSDF curve, whose JND index is positively proportional to the \( p \)-value. In order to utilize the full luminance range of the display, AAPM TG18 recommends the following method for mapping the \( p \)-value to JND index.

\[
p_{\text{to-JND}}(p) = \frac{J(L_{p,\text{max}}) - J(L_{p,\text{min}})}{255} p + J(L_{p,\text{min}}) \quad (64.20)
\]

In Equation 64.20, \( L_{p,\text{max}} \) and \( L_{p,\text{min}} \) are the maximum and minimum luminance of the display, respectively (e.g., 255 and 0 for an 8-bit display). \( J \) is the luminance-to-JND index function defined in Equation 64.18. The idea behind Equation 64.20 is to distribute the DDL values evenly across the available JND index range.

The calibration flow is illustrated in Figure 64.9 and laid out as follows. Figure 64.9 consists of three charts. The left chart shows the relationship between luminance and DDL, which is decomposed into two charts (luminance versus JND index and DDL versus JND index) on the right.

1. Measure the minimum and maximum luminance to obtain \( L_{p,\text{min}} \) and \( L_{p,\text{max}} \), (cf. the left chart).
2. Use Equation 64.18 to find the JND indices \( J(L_{p,\text{min}}) \) and \( J(L_{p,\text{max}}) \) corresponding to \( L_{p,\text{min}} \) and \( L_{p,\text{max}} \) on the GSDF curve (cf. the top right chart).
3. Use \( J(L_{p,\text{min}}) \) and \( J(L_{p,\text{max}}) \) to derive the \( p \)-to-JND function, as defined by Equation 64.20 (cf. the bottom right chart).
4. For each \( p \), adjust the display luminance to match the target luminance, \( L(p\text{-to-JND}(p)) \).

### 64.8.2 Evaluating the GSDF Conformance of a Medical Display

AAPM TG18 defined a metric for evaluating the conformance with the DICOM GSDF based on the method recommended in Annex C of DICOM PS 3.14. The metric is called observed contrast, which applies to both the measured luminance curve and the GSDF curve.

The measured observed contrast is defined as

\[
\delta_k = \frac{\Delta L}{\Delta J} = \frac{L_{k+q} - L_k}{J_{k+q} - J_k} = \frac{L_k + L_{k+q}}{2} \quad (64.21)
\]

Figure 64.10 illustrates the definition of the observed contrast on the luminance versus JND index curve. Two data points are required to calculate the observed contrast, which means that, for two DDLs, \( p_k \) and \( p_{k+q} \), their luminance levels, \( L_k \) and \( L_{k+q} \), and their JND indices, \( J_k \) and \( J_{k+q} \), are required. \( \Delta L/\Delta J \) is the slope of the curve between these two points and represents “how much luminance increase is required to be noticeable.” According to Weber’s law, the required luminance increase, \( \Delta L/\Delta J \), is
proportional to the luminance level, \( L \). Therefore, theoretically, if the luminance versus JND curve follows Weber’s law, dividing \( \Delta L / \Delta J \) by \( L \) should result in a constant. Equation 64.21 uses the mean luminance of the two points as \( L \).

The DICOM reference observed contrast is defined as

\[
\delta_k^q = \frac{L_k^{q+1} - L_k^q}{L_k^{q+1} + L_k^q} = \frac{L(J_k) - L(J_{k+1})}{L(J_k^{q+1}) + L(J_k^q)} \quad (64.22)
\]

Compared with Equation 64.21, the difference is that the measured luminance in Equation 64.22 is replaced by the JND index-to-luminance function, \( L \), as defined in Equation 64.17.

The error between the measured luminance and the DICOM reference luminance is defined by AAPM TG18 as the difference between the measured observed contrast and the DICOM reference observed contrast.

\[
\delta_k = \delta_k^q = \frac{2}{J_k^{q+1} - J_k^q} \left( \frac{L_k^{q+1} - L_k^q}{L_k^{q+1} + L_k^q} - \frac{L(J_k^q) - L(J_k^{q+1})}{L(J_k^{q+1}) + L(J_k^q)} \right) \quad (64.23)
\]

Equation 64.23 is indeed the per-JND difference in Michelson’s contrast between the measured and DICOM reference data.

Finally, the GSDF conformance is evaluated with the maximum absolute difference in the observed contrast.

\[
\max |\delta_k - \delta_k^q|, \quad k = \{0, q, 2q, \ldots\} \quad (64.24)
\]

In Equation 64.24, \( q \) is the space between the evenly spaced \( p \)-values \( k = \{0, q, 2q, \ldots\} \). If 18 points are to be measured in an 8-bit display, the DDL values will be \( \{0, 15, 30, 45, 60, 75, 90, 105, 120, 135, 150, 165, 180, 195, 210, 225, 240, 255\} \).

In AAPM TG18, the recommended tolerance of GSDF conformance is 10% for primary medical displays, and 20% for secondary medical displays. Figure 64.11 shows the relationship between logarithm of the observed contrast and JND index defined in Equation 64.22.

Figure 64.12 illustrates the workflow in three charts for calculating \( \delta_k \) and \( \delta_k^q \) as follows.

1. Measure the display luminance at evenly spaced \( p \)-values to obtain \( L_p, p = \{0, q, 2q, \ldots\} \) (cf. left chart).
2. Use Equation 64.18 to find the JND indices \( J(L_{p, \min}) \) and \( J(L_{p, \max}) \) corresponding to \( L_{p, \min} \) and \( L_{p, \max} \) on the GSDF curve (cf. top right chart).
3. Use \( J(L_{p, \min}) \) and \( J(L_{p, \max}) \) to derive the \( p \)-to-JND function, as defined by Equation 64.20 (cf. bottom right chart).
4. For each DDL \( p \), calculate the corresponding DICOM reference luminance with Equations 64.18 and 64.20, \( L(p \text{-to-JND}(p)) \) (cf. top right chart).
5. Calculate \( \delta_k \), based on the data from Step (1) and Step (3) with Equation 64.21.
6. Calculate \( \delta_k^q \), based on the data from Step (4) and Step (3) with Equation 64.22.
7. Plot \( \delta_k \) on the observed contrast versus JND index chart, as shown in Figure 64.11 for visual analysis.
8. Calculate \( \max |\delta_k - \delta_k^q| \) and determine whether the display passes the DICOM GSDF conformance test.

Using the observed contrast defined in Equation 64.22 might be considered counterintuitive because, after all, the GSDF is based on a different contrast metric derived by Barten’s model. Therefore, the observed contrast curve in Figure 64.11 is not a constant, but a curve rising rapidly in the low JND region. Nevertheless, the 10% or 20% tolerance of GSDF conformance is still sufficient for the purpose of evaluation. Figure 64.13 shows the corresponding luminance error in JND for 10% and 20% tolerance of the GSDF conformance. The data were calculated by converting the observed contrast difference in Figure 64.11 into corresponding JND difference. It shows that the 10% and 20% tolerance is equivalent to a 0.1 and 0.2 JND difference, respectively.

Although 0.1~0.2 JND is a tight constraint for evaluating the luminance error, the ordering of the gray levels is not considered in the AAPM TG18 evaluation method. It is possible for a display to have reversed gray levels, for example, \( L_p > L_{p+1} \), especially in the low luminance region, while still passing the GSDF conformance check.
Comparing GSDF with sRGB and CIELAB

sRGB and CIELAB are two very common color spaces used in non-medical applications (Wyszecki and Stiles 1982; Lee 2005). sRGB is a color space for calibrating imaging devices including displays, scanners, and cameras (IEC 1999). The relationship between the normalized $p$-value and luminance is defined in Equation 64.25. The chromaticity of the white point is CIE Illuminant D65.

$$
\hat{L}_{\text{RGB}} = \begin{cases} 
12.92 \cdot \hat{p} & \text{if } \hat{p} \leq 0.04045 \\
1.055 \cdot \hat{p}^{2.4} - 0.055 & \text{otherwise}
\end{cases} \quad (64.25)
$$

where $\hat{p}$ is the normalized $p$-value, and $\hat{L}_{\text{RGB}}$ is the normalized luminance between 0 and 1.

CIELAB is a simple color perception model for predicting perceptual brightness and chromaticity (Fairchild 1995). Unlike GSDF and sRGB, the calculation of CIELAB requires two stimuli—the target color and the reference white. The reference white is required to account for the visual adaptation phenomena. The relationship between the normalized $p$-value and luminance is defined as follows.

$$
\hat{L}_{\text{CIELAB}} = f_{\text{CIELAB}} \left( \frac{1}{1.16} (\hat{p} + 0.16) \right) \quad (64.26)
$$

$$
f_{\text{CIELAB}}(t) = \begin{cases} 
t^3 & \text{if } t > \frac{6}{29} \\
3 \left( \frac{6}{29} \right)^2 \left( t - \frac{4}{29} \right) & \text{otherwise}
\end{cases} \quad (64.27)
$$

Graphs showing how to evaluate the GSDF conformance of a display and corresponding luminance error in JND for 10% and 20% tolerance of the GSDF conformance.
The luminance versus p-value curves of displays calibrated to sRGB, CIELAB L*, and GSDF at three maximum luminance levels are shown in Figure 64.14. Since sRGB and CIELAB do not consider the absolute luminance level, both have a single curve for arbitrary Lmax. The three GSDF-calibrated displays have the same luminance ratio, 10,000, but different luminance ranges—0.008 to 80, 0.05 to 500, and 0.4 to 4000 cd/m². These parameters were chosen to simulate an LCD monitor with a constant contrast ratio for the liquid crystal panel, while the backlight luminance can be adjusted. For the three GSDF curves, the curve is lowered as the luminance range increases. Therefore, a GSDF display needs to be recalibrated if the display luminance is altered by the user.

### Luminance Response in Mobile Displays

The luminance response is usually not adjustable in a mobile display as a close system. Furthermore, it is seldom clearly documented which color space the mobile display is calibrated to. Nevertheless, the measurement results of many high-end mobile displays show similarity in luminance response to that of the sRGB color space. In the study conducted in Yamazaki et al. (2013a), three mobile phones and five tablets were measured for their luminance responses. Two of the mobile phone displays were based on the organic light-emitting devices (OLED) technology, while the other six devices were based on the LCD technology. According to the experimental results obtained from the DICOM PS 3.14 assessment method (cf. Equation 64.24), none of the eight mobile displays was DICOM GSDF-compliant. This finding is not surprising if the mobile displays are meant to be sRGB-compliant.

The DICOM GSDF is a successful standard that has been widely used in monochrome medical displays. Recognition of the standard by regulatory bodies also facilitated its adaptation and spreading (U.S. Department of Health and Human Services Food and Drug Administration 2008; U.S. Department of Health and Human Services Food and Drug Administration 2016a,b). Unfortunately, the DICOM GSDF does not work for color medical displays, because the underlying contrast sensitivity model of Barten does not take color stimuli into account. Therefore, a counterpart of DICOM GSDF for calibrating color displays has been longed for by the color medical imaging community for years.

Before discussing any calibration standard, the concept of perceptual linearity in a color display must first be established. Earlier in this chapter, the perceptual linearity in a monochrome display was defined by Equation 64.2—\[ \Delta J = a \cdot \Delta p + b, \] where \( \Delta J \) is the JND index difference and \( \Delta p \) is the p-value difference. The p-value in a calibrated monochrome display can be considered as the intended brightness, because it maps to the JND index space, which is assumed to be linear in the perceptual domain. As shown in Figure 64.15, the p-value can be converted by hardware or software into the DDL, which is the final value driving the display device, for calibration purposes. The introduction of the p-value is to encapsulate the display system and provide an abstract, device-independent layer. However, professional-grade medical displays have built-in look-up tables for adjusting the gamma curve. The DICOM GSDF calibration can be done within the display, so that the DDL can be used as the
FIGURE 64.16 Difference in using monochrome and color displays.

$p$-value directly without conversion. Therefore, when controlling a DICOM GSDF-calibrated medical display with DDL data, we are actually dealing with the intended brightness data.

In the case of a color display, each pixel is controlled by three DDL values for the red, green, and blue channels, \((r,g,b)\). For backward compatibility, usually the gray shades \((k,k,k)\) of a color display are calibrated in the same way as those in a monochrome display \((k)\). To preserve the constant chromaticity of the gray shades, the primary red, green, and blue shades \((k,0,0), (0,k,0),\) and \((0,0,k)\) must be calibrated in the same way. So \((k,k,k), (k,0,0), (0,k,0),\) and \((0,0,k)\) all have the same gamma curves. Therefore, DDL \((r,0,0), (0,g,0),\) and \((0,0,b)\) can be considered as the intended brightness of the red, green, and blue channel, respectively.

To generalize \(\Delta J = a \cdot \Delta p + b\) from the one-dimensional monochrome space to the three-dimensional color space, both \(\Delta J\) and \(\Delta p\) need to be expanded to three dimensions. Expanding \(\Delta J\) is straightforward, because the perceptual difference between two colors is well defined in color science (Fairchild 2013). For example, CIEDE2000 can be used to calculate the difference between two colors specified in the CIELAB color space \((L^*,a^*,b^*)\). However, expanding the \(p\)-value is not trivial. The reason is as follows.

Recall that a color space is three-dimensional, and can be decomposed into one-dimensional brightness and two-dimensional chromaticity. Such decomposition is ubiquitously used in perceptually uniform color spaces (CIELAB and CIELUV), video encoding (YCbCr), image processing (hue-saturation level [HSL] or hue-saturation value [HSV]), and so on. DDL \((r,0,0), (0,g,0),\) and \((0,0,b)\) in a color display are not suitable to be used as the \(p\)-values, because all of the three parameters indicate the brightness dimension, while the two-dimensional chromaticity information is not represented and needs to be retrieved from the ratio between \(r, g,\) and \(b\). In other words, creating a perceptually linear calibration method in the \((r,g,b)\) space is virtually impossible.

Currently, the common practice for achieving perceptual linearity in color displays is to use the color management framework (Kriss 2010). Instead of requiring every DICOM GSDF-calibrated display to behave identically, the color management framework uses a color manager and a color profile to separate the device-independent \(p\)-value space and the device-dependent DDL space. The device-independent \(p\)-value space can be a perceptually uniform color space such as CIELAB. The user (application software, the image viewer) handles data in the perceptually linear color space, and the color manager will convert the data into DDL based on the transformation specified in the color profile. Thus, the user needs not and should not directly handle the DDL data for a color display (Figure 64.16).

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**REFERENCES**


