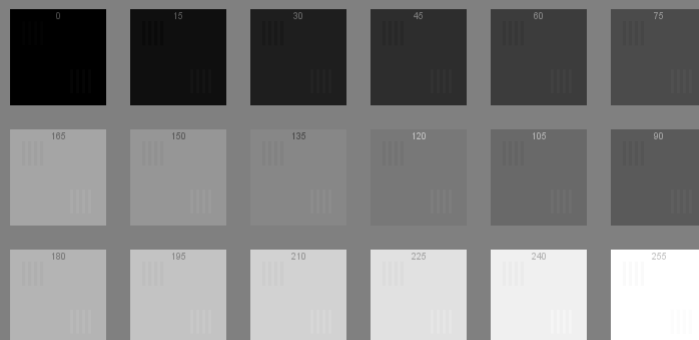
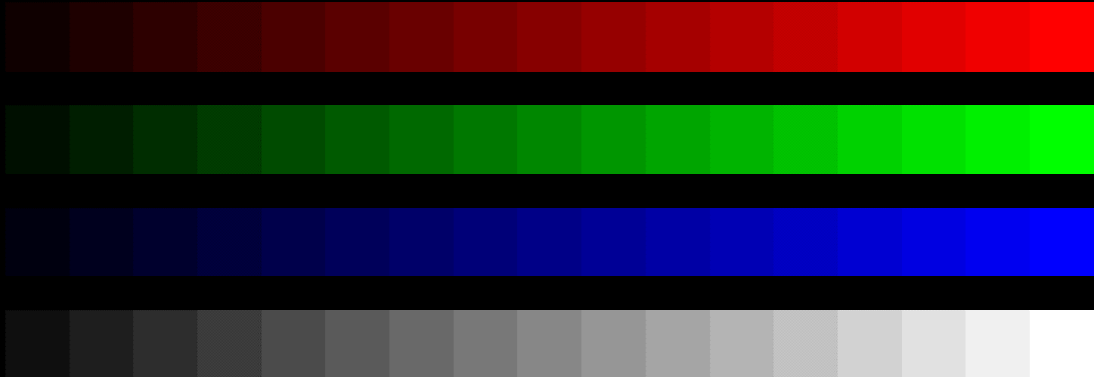


# Considerations for Evaluating Color Displays

Nicholas B. Bevins, Ph.D., DABR  
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## Outline

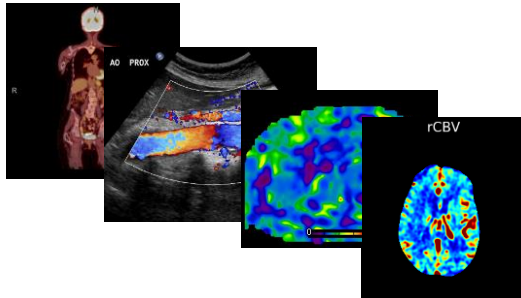
- Defining Color
  - Pseudo vs. True Color
  - Photometry → Colorimetry
  - Chromaticity
  - Color Spaces
- Gray Tracking
  - AAPM TG270
  - AAPM TG196
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- Ongoing Efforts

# Color in Medical Imaging



## Pseudo Color Images

Nuclear Medicine Fused Images  
 Ultrasound Doppler Images  
 MRI Elastography Images  
 CT Perfusion Images  
 ...



## True Color Images

Digital Pathology Images  
 Ophthalmologic Images  
 Dermatologic Images  
 ...



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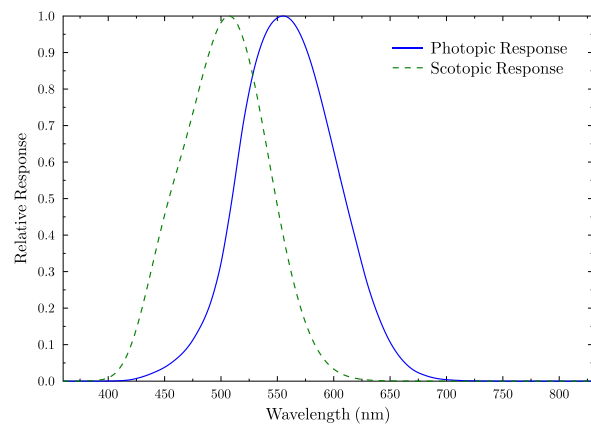
image source: Wikipedia

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# Photometry



- Science of measuring light as it is perceived by the human visual system
- Luminosity weighting functions for radiant power as a function of wavelength
- Different weighting for different visual responses (luminance dependent)



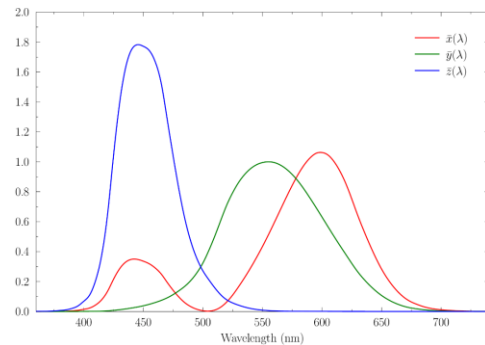
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# Colorimetry



- Extending to colors, spectral weighting functions defined by CIE
  - 1931 Standard Colorimetric Observer
- Based on human observer studies looking at perceptible differences between colors



$$X = \int_{\lambda} L_{e,\Omega,\lambda}(\lambda) \bar{x}(\lambda) d\lambda$$

$$Y = \int_{\lambda} L_{e,\Omega,\lambda}(\lambda) \bar{y}(\lambda) d\lambda$$

$$Z = \int_{\lambda} L_{e,\Omega,\lambda}(\lambda) \bar{z}(\lambda) d\lambda$$

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# Chromaticity

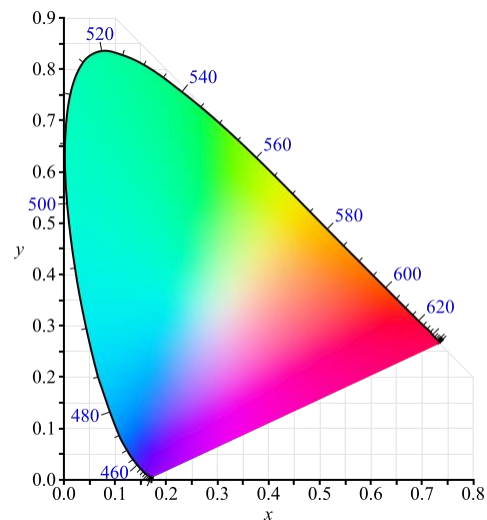


- Separating color into brightness and chromaticity
  - “Quality” of color

$$x = \frac{X}{X + Y + Z}$$

$$y = \frac{Y}{X + Y + Z}$$

$$z = \frac{Z}{X + Y + Z} = 1 - x - y$$



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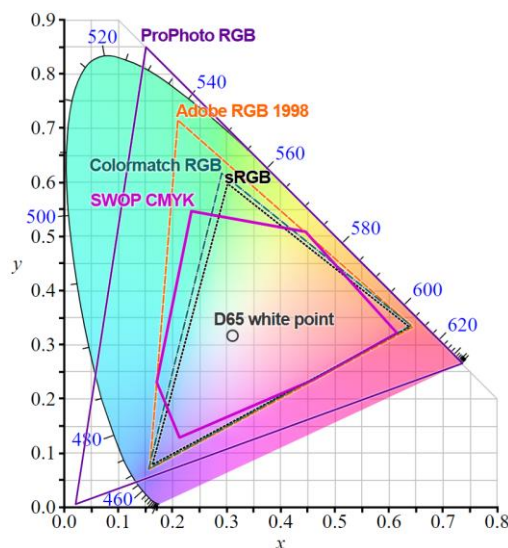
image source: Wikipedia

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## Color Spaces



- Perceptible colors and displayable colors are not equal for most systems
- Color spaces define representable colors from all chromaticities
- RGB color models are most common
  - sRGB
  - Adobe RGB



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image source: Wikipedia

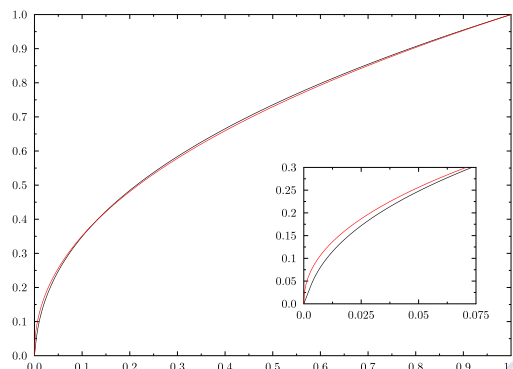
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## Color Spaces



- The sRGB color space is likely the most common color space
  - “Default” for most display systems
- Defined by three chromaticity coordinates (R, G, B) and a white point
- Also defined by specific luminance response and viewing conditions
  - Pseudo gamma 2.2
  - Not GSDF

Chromaticity	Red	Green	Blue	White
x	0.6400	0.3000	0.1500	0.3127
y	0.3300	0.6000	0.0600	0.3290
Y	0.2126	0.7152	0.0722	1.000



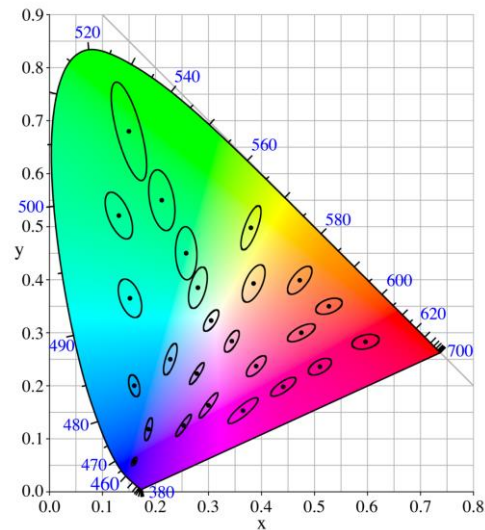
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## Color Differences



- Describing the quantitative difference between colors
- CIE 1931 color diagram is not perceptually uniform
  - MacAdam ellipses
  - All colors within ellipse are indistinguishable
  - Based on human observer studies
- Efforts to transform for perceptual uniformity
  - CIE 1960 UCS
  - CIE 1976 UCS

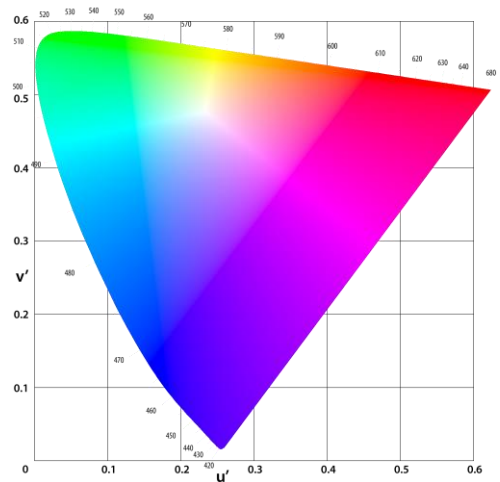
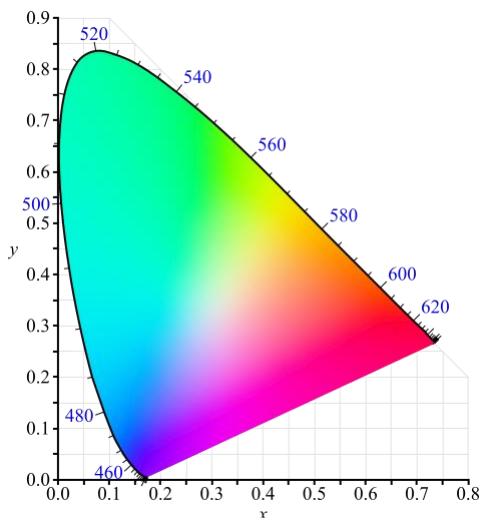


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image source: Wikipedia

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## Color Differences



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image source: Wikipedia

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## Color Difference



- Color difference has been through many iterations
- General improvements to overall linearity for perceptual changes
- Increasingly complicated formula for higher precision
- For small differences,  $\Delta(u', v')$  is relatively accurate

$$\Delta(u', v') = \sqrt{(u'_1 - u'_2)^2 + (v'_1 - v'_2)^2}$$

$$\Delta E_{ab}^* = \sqrt{(L_2^* - L_1^*)^2 + (a_2^* - a_1^*)^2 + (b_2^* - b_1^*)^2}$$

$$\Delta E_{94}^* = \sqrt{\left(\frac{\Delta L^*}{k_L S_L}\right)^2 + \left(\frac{\Delta C_{ab}^*}{k_C S_C}\right)^2 + \left(\frac{\Delta H_{ab}^*}{k_H S_H}\right)^2}$$

$$\Delta E_{00}^* = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2} + R_T \frac{\Delta C'}{k_C S_C} \frac{\Delta H'}{k_H S_H}$$

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## Gray Tracking and White Point



- Color of the light output by the display throughout the grayscale
- Evaluate by measuring the color difference

$$\Delta = \sqrt{(u'_1 - u'_2)^2 + (v'_1 - v'_2)^2}$$

- Compared against
  - Other display
  - Standard illuminant (e.g., D65)
  - Full brightness (TG196 methodology)

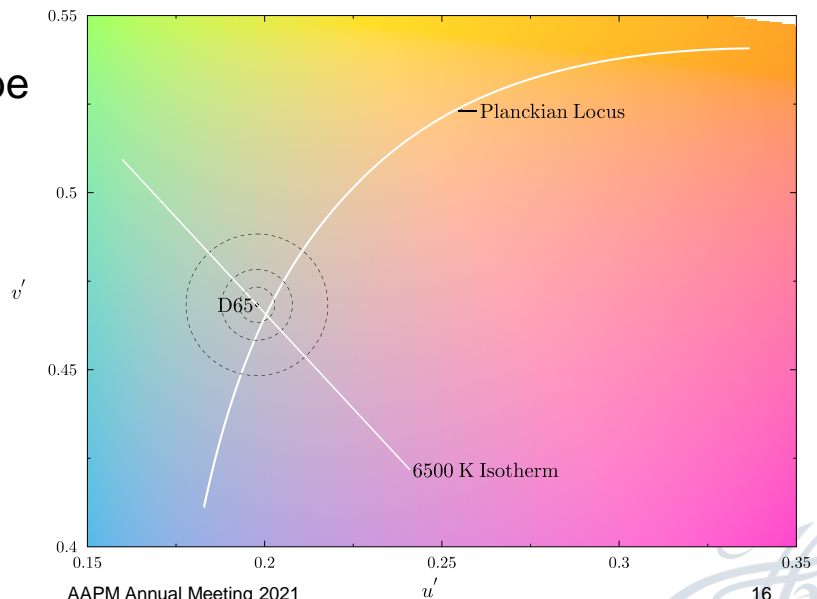
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## Standard Illuminants



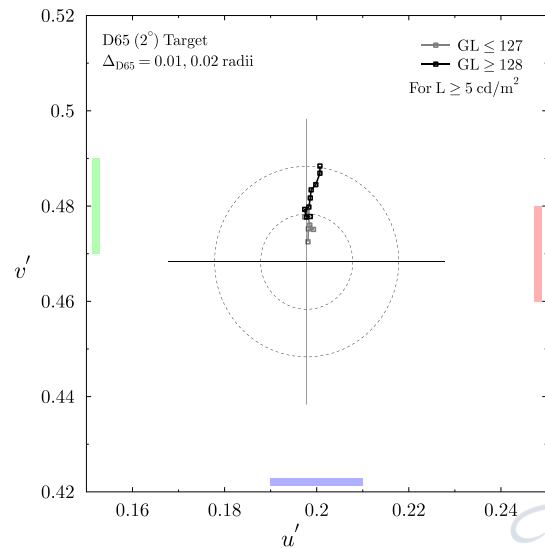
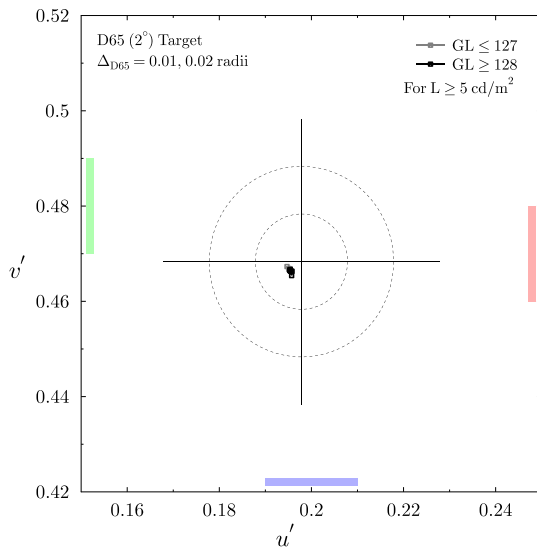
- Standard illuminant (e.g., D65) should be used instead of correlated color temperature (CCT)
  - CCT is defined as multiple points in color space
  - The maximum difference between the points is large



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# Gray Tracking



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# Gray Tracking (TG270 Methodology)



## ■ Comparing two displays

	Optimal Limit	Acceptable Limit
Same Workstation	$\Delta(u', v') \leq 0.005$	$\Delta(u', v') \leq 0.01$
Same Image Review Chain	$\Delta(u', v') \leq 0.01$	$\Delta(u', v') \leq 0.02$

## ■ Comparing display to standard illuminant

	Optimal Limit	Acceptable Limit
Diagnostic Display	$\Delta_{D65}(u', v') \leq 0.005$	$\Delta_{D65}(u', v') \leq 0.01$
Modality, EHR, CS	$\Delta_{D65}(u', v') \leq 0.01$	$\Delta_{D65}(u', v') \leq 0.02$

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## Gray Tracking (TG196 Methodology)



### ■ AAPM TG196 Gray Tracking

#### ■ Four metrics:

$$\tau_1, \tau_2, \tau_{1,\max}, \tau_{2,\max}$$

$$\tau_n = \frac{1}{N-1} \sum_{j=17-N+1}^{17} \Delta_n(u', v')$$

- $\tau_1$  defines color difference from maximum luminance chromaticity

$$\tau_{n,\max} = \max(\Delta_n(u', v')_k)$$

$$\Delta_1(u', v') = \sqrt{(u'_j - u'_{18})^2 + (v'_j - v'_{18})^2}$$

- $\tau_2$  defines color difference from neighboring luminance chromaticity

$$\Delta_2(u', v') = \sqrt{(u'_j - u'_{j-1})^2 + (v'_j - v'_{j-1})^2}$$

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## Gray Tracking (TG196 Methodology)



### ■ Good Tracking

$$\tau_1 = 0.0013$$

$$\tau_{1,\max} = 0.0021$$

$$\tau_2 = 0.0003$$

$$\tau_{2,\max} = 0.0009$$

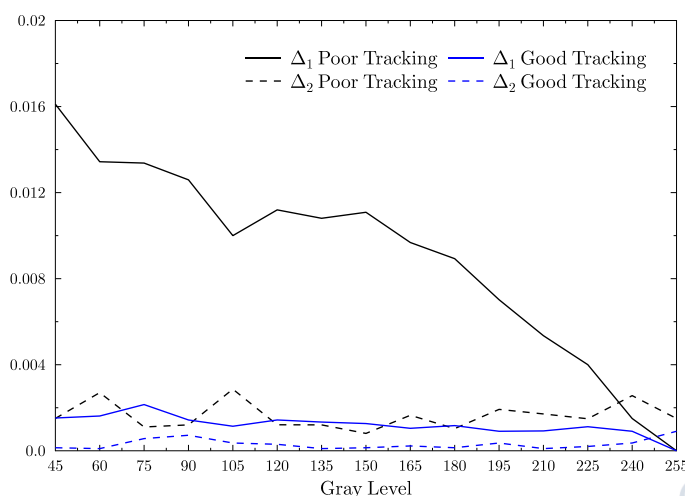
### ■ Poor Tracking

$$\tau_1 = 0.0096$$

$$\tau_{1,\max} = 0.0161$$

$$\tau_2 = 0.0016$$

$$\tau_{2,\max} = 0.0029$$



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## Devices



- Colorimeters
  - Determines chromaticity by use of filters
  - May also report luminance or illuminance
- Spectroradiometers
  - Measures amplitude of light as a function of wavelength
  - Results combined with color matching functions

	Colorimeters	Spectroradiometers
Output	Chromaticity Coordinates	Spectral power by wavelength
Accuracy	Modest (generally a function of cost)	High
Cost	Low-modest (\$200-\$1,000)	High (\$5,000-\$50,000+)

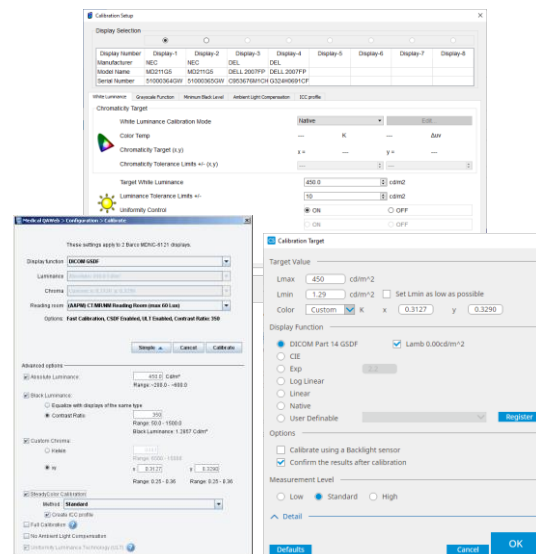
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## Software



- Vendors of medical displays often provide software for calibration and conformance testing
  - Color displays may allow for specified white point (based on CCT or chromaticity coordinate)
- Significant deviation from “native” may result in other issues



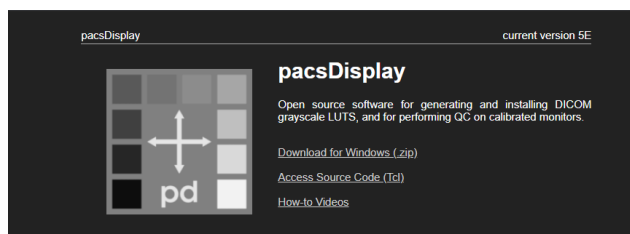
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## Software



- Third-party software for verification and QC
- pacsDisplay
  - Developed at HFHS
  - Calibrate displays to GSDF
  - QC for displays
  - Free and open source
  - pacsdisplay.org



### Background

The applications in this software package include programs for generating and installing DICOM grayscale look up tables (LUTs), a program to display a grayscale quality control test pattern, and features to perform QC evaluations of calibrated monitors. The present package release supports Microsoft Windows XP (32 bit), Windows 7 (32 and 64 bit), and Windows 10.

For monitor calibration, look up tables (LUTs) intended for the make and model of monitors used on your workstation need to be specified. The package distribution includes a LUT-Library with generic LUTs for various monitor models. This library is commonly searched to retrieve the required LUT. For monitor models that are not in the library, a gray palette needs to be obtained using one of the supported photometers. A LUT is then generated from the measured palette and a configuration file is edited.

For QC measures, the essential tools are distributed in a folder that does not require installation on a workstation. Typically this folder will be accessed from a USB memory device where a menu application is executed to select the desired application.

### OS Support

Package Release 5D now provides support for installation and use on Microsoft Windows 10 operating

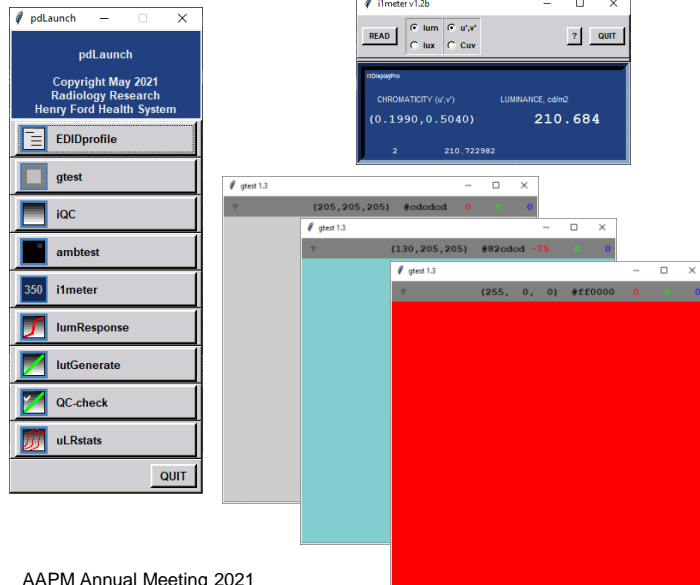
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## Software: pacsDisplay



- pdQC suite
  - Palette tool to “dial-in” any RGB level for evaluation
  - Meter tool to measure both luminance and chromaticity coordinates



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## AAPM Efforts



- 2005 TG18 report
  - Limited to  $\Delta(u',v')$  for the white point
- 2016 TG196 report
  - Defined gray tracking metrics
  - Compared accuracy between reference and field colorimeters
- 2019 TG270 report
  - Described both white point difference and TG196 metrics
  - Promoted gray tracking as part of routine QC
- TG322
  - Continuation of TG196 efforts
  - Currently stalled, may defer to ongoing IEC development

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## IEC Efforts



- Currently under a new work item proposal (NWIP-62635-3)
  - Part of TC 62/SC 62B/WG 51
  - Basic color accuracy evaluation methods
  - Limited scope
- Future work (62635-4?) would define more rigid limits, expectations

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## Conclusion



- Color displays are widely used throughout medical applications
  - Used to display both color and grayscale images
- Color display evaluation for medical applications still a work in progress
- Basic measurement of color values as part of routine QC as a first step

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Thank you

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