Considerations for Evaluating Color Displays

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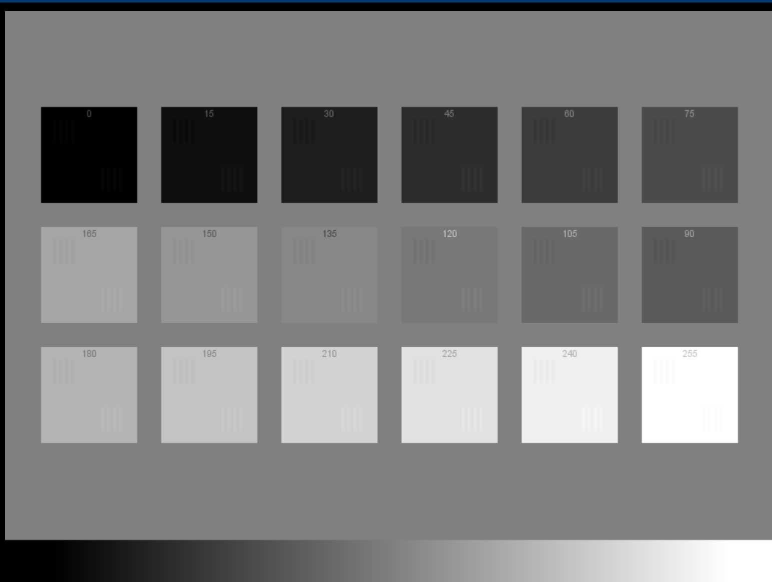
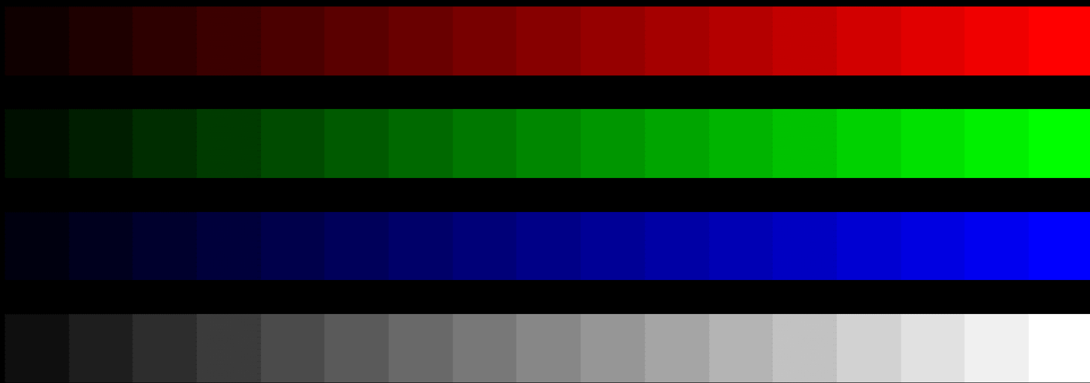
AAPM Annual Meeting 2021



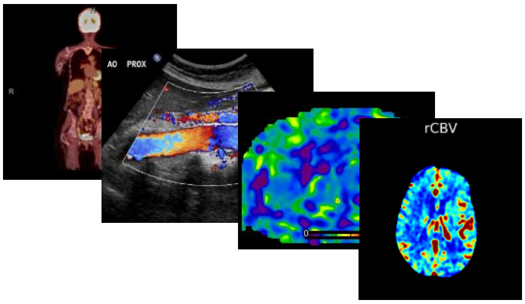


Outline

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

Color in Medical Imaging

Pseudo Color Images	True Color Images
Nuclear Medicine Fused Images	Digital Pathology Images
Ultrasound Doppler Images	Ophthalmologic Images
MRI Elastography Images	Dermatologic Images
CT Perfusion Images	…
…	



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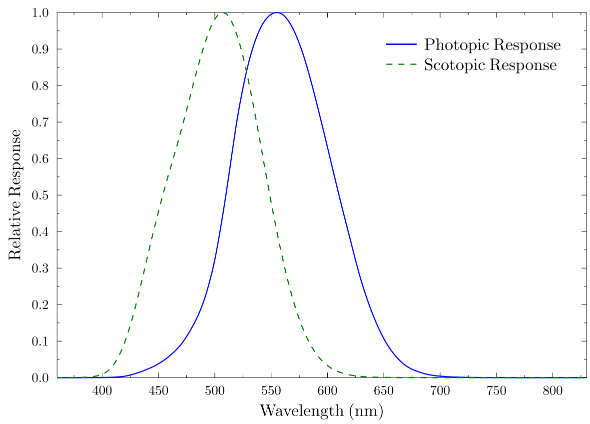
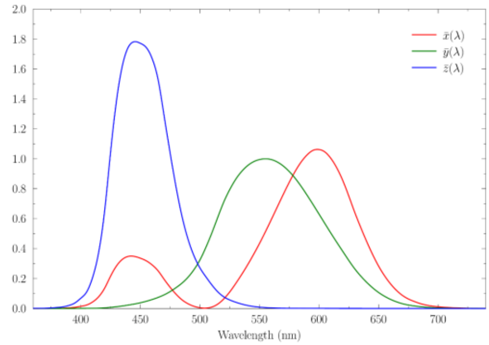
Photometry

- 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)



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



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

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

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

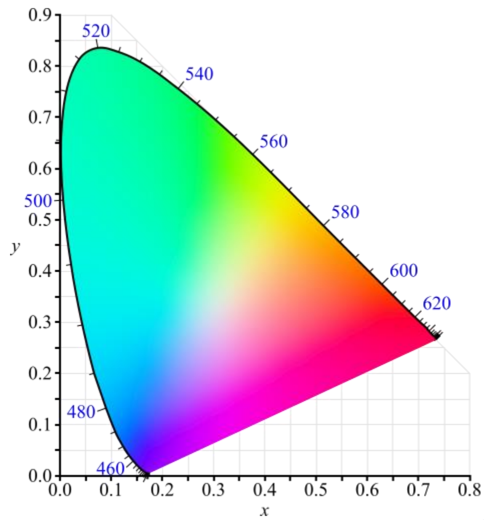
Chromaticity

- 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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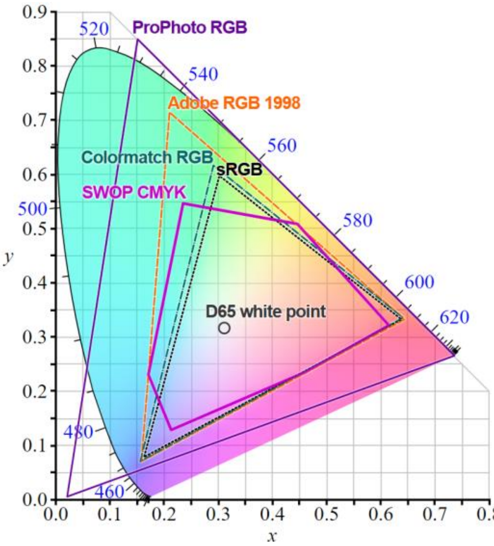
Color Spaces

- 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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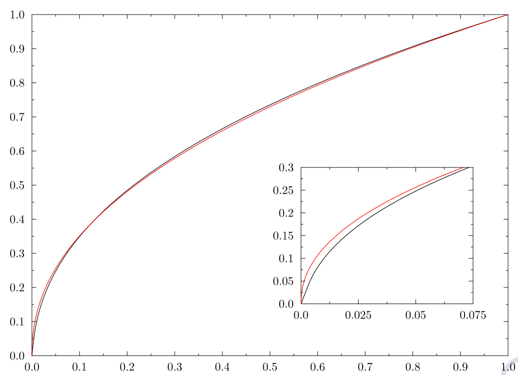
Color Spaces

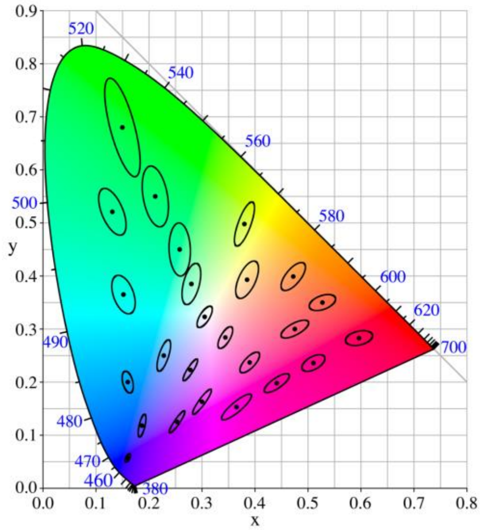
- The sRGB color space is likely the most common color space
  - "Default" for most display systems
- Defined by three chromaticity coordinates (R, G, B) and a white point
- Also defined by specific luminance response and viewing conditions
  - Pseudo gamma 2.2
  - Not GSDF

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



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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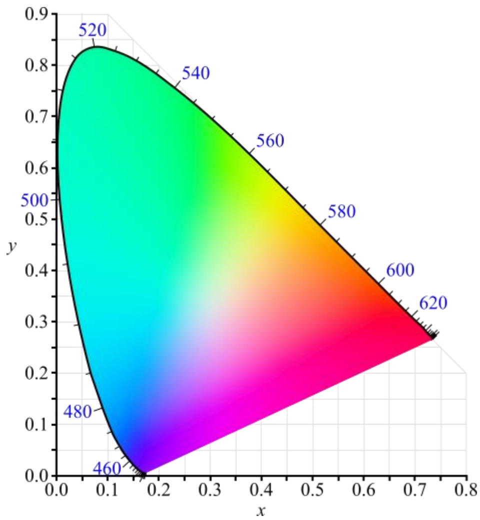
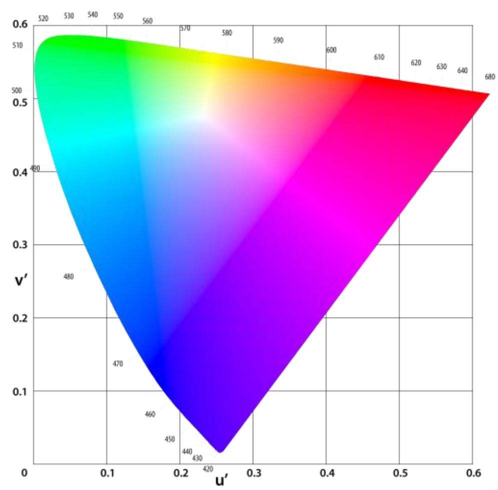
Color Differences





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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

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

$$\Delta E^*_{ab} = \sqrt{(L^*_2 - L^*_1) + (a^*_2 - a^*_1) + (b^*_2 - b^*_1)}$$

$$\Delta E^*_{94} = \sqrt{\left(\frac{\Delta L^*}{k_L S_L}\right)^2 + \left(\frac{\Delta C^*_{ab}}{k_C S_C}\right)^2 + \left(\frac{\Delta H^*_{ab}}{k_H S_H}\right)^2}$$

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

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Gray Tracking and White Point

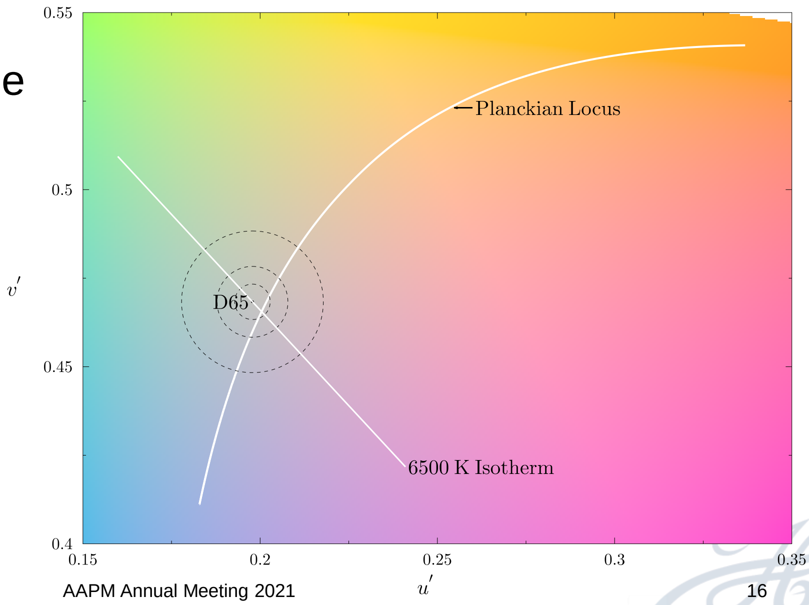
- Color of the light output by the display throughout the grayscale
- Evaluate by measuring the color difference

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

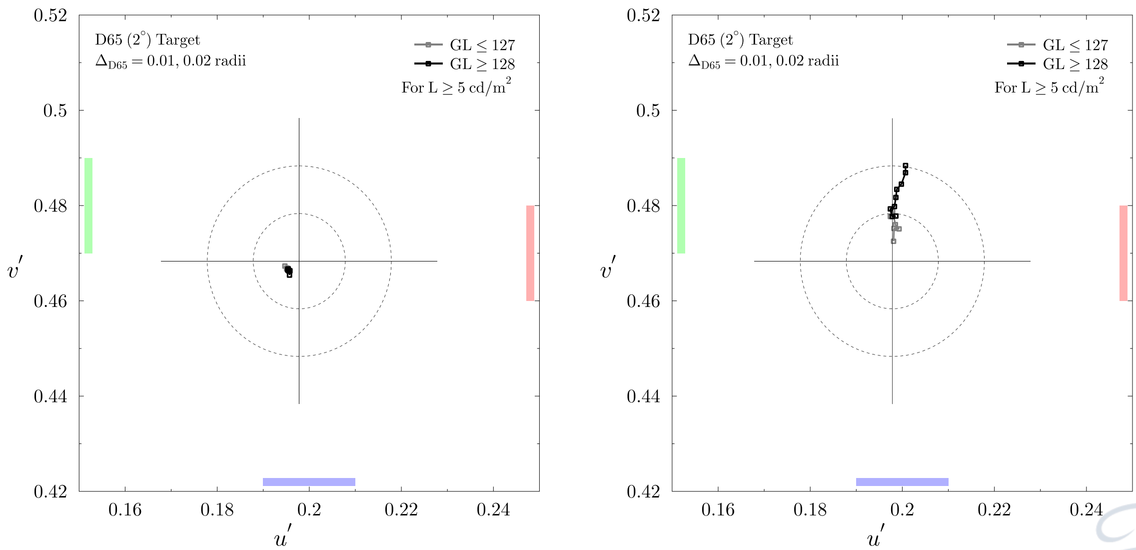
- Compared against
  - Other display
  - Standard illuminant (e.g., D65)
  - Full brightness (TG196 methodology)

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



Gray Tracking



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Gray Tracking (TG270 Methodology)

- Comparing two displays

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

- Comparing display to standard illuminant

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

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Gray Tracking (TG196 Methodology)

- AAPM TG196 Gray Tracking
  - Four metrics:

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

- τ_1 defines color difference from maximum luminance chromaticity
- τ_2 defines color difference from neighboring luminance chromaticity

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

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

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

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

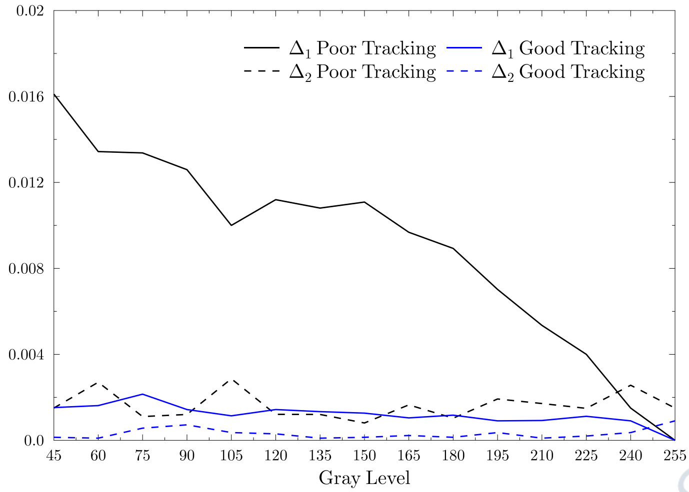
Gray Tracking (TG196 Methodology)

- 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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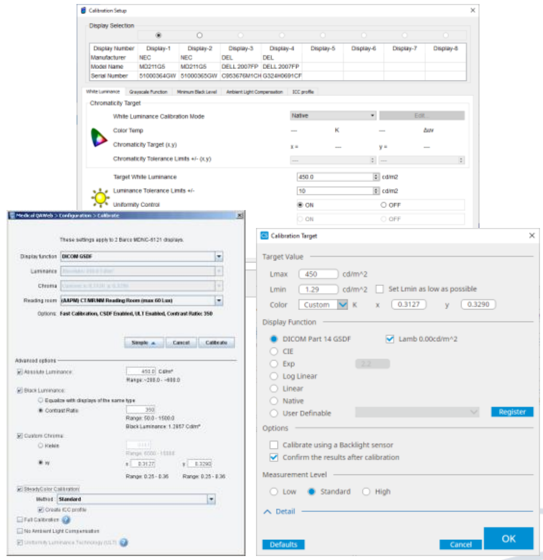
Devices

- 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+)

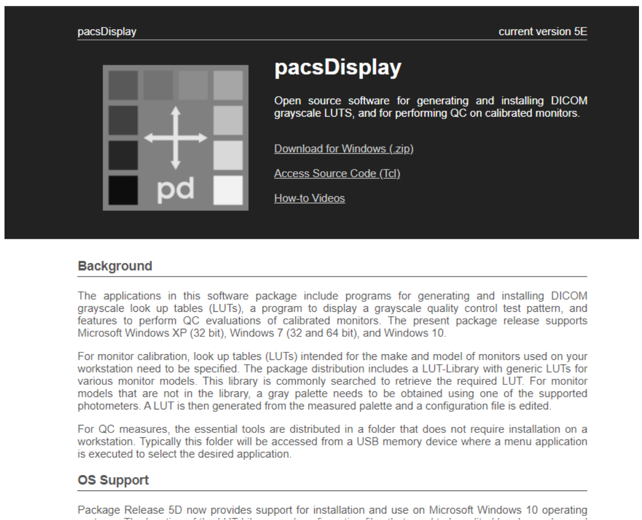
Software

- 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



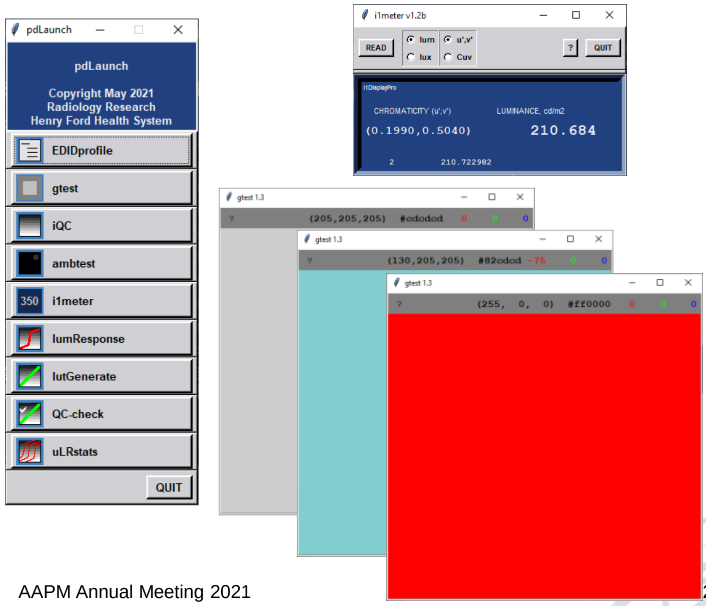
Software

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



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

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

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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