Display QC

AAPM 2018

SAM Imaging Education Course MO-GH-205-3

QC Measures for Color Displays

a) Color coordinate systems (5)
b) Devices for measuring color coordinates (11)
c) White point and gray tracking (3)
d) Defined color spaces (6)
e) QC assessments: gray tracking & color space (3)

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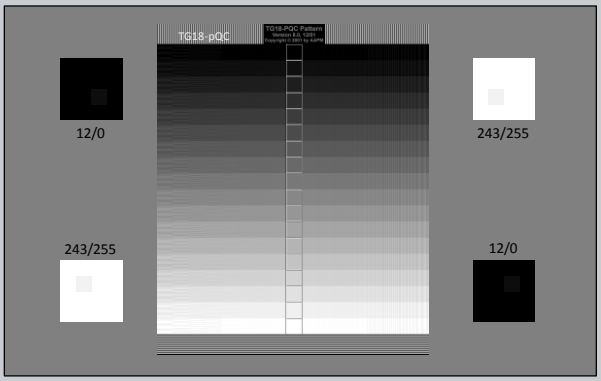
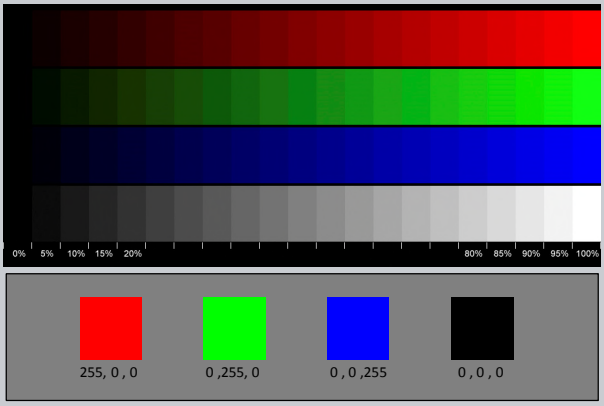
Display Quality Test Image



Display Quality Test Image



Photometric Standards

PHOTOMETRIC STANDARDS

Photometry is the science of the measurement of light, in terms of its perceived brightness to the human eye.
(Wikipedia)

Photometric Units

Radiometric light units relate to the energy of photons (watts).
Photometric light units relate to the visibility of photons (lumens)

Radiant flux

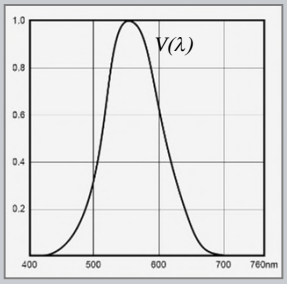
$Q_e(\lambda) = E_\lambda N_{(\lambda)}$ *joules*

$\Phi_e(\lambda) = dQ_e(\lambda)/dt$ *watts*

Luminous flux *lumens*

$\Phi_e = k_m \int \Phi_e(\lambda) v(\lambda) d\lambda$

k_m = *683 lumens/watt*



The sensitivity of the human eye is defined in terms of the lumens per watt as a function of wavelength.

Colorimetric Standards

COLORIMETRIC STANDARDS

Colorimetry is the science and technology used to quantify and describe physically the human color perception.
(Wikipedia, from Ohno2000)

Colorimetric Standards

International Commission on Illumination
Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

The CIE is a technical, scientific and cultural non-profit organization whose objectives include the development of standards, reports and other publications concerned with the science and technology of light and lighting.

CIE 15:2004, Colorimetry, 3rd edition

http://www.cie.co.at/

CIE Central Bureau, Vienna, AUSTRIA

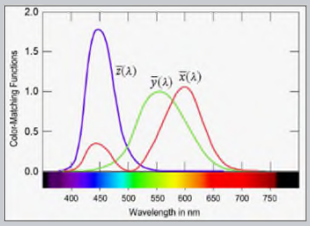
a) Color coordinate systems: CIE

a) Color coordinate systems defined by CIE (5 pgs.)

a) Color coordinate systems: CIE X,Y,Z

The CIE standard defines Tristimulus Values X, Y, Z as integrals of the spectral relative power $P(\lambda)$.

$$X = \int_0^\infty P(\lambda)\bar{x}(\lambda)\mathrm{d}\lambda,$$
$$Y = \int_0^\infty P(\lambda)\bar{y}(\lambda)\mathrm{d}\lambda,$$
$$Z = \int_0^\infty P(\lambda)\bar{z}(\lambda)\mathrm{d}\lambda.$$

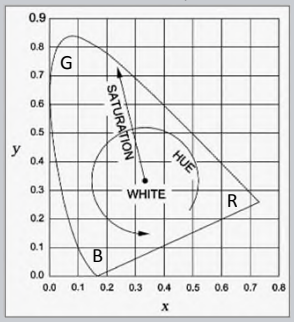


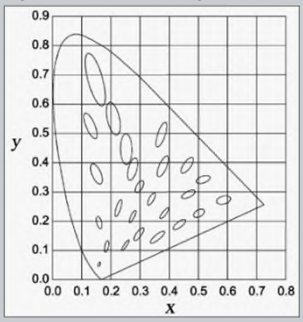
The Luminance in given only by the Y tristimulus value

The color matching functions used to weight the power spectrum come from human visual experiments. They reflect the different response of the cones in the retina.

a) Hue, saturation & color difference in the x,y coordinate system

X,Y,Z tristimulus values are transformed to x,y chromaticity coordinates and the luminosity Y (CIE 1931, 2 degree field, CIE 1964 10 degree field)





- Hue – direction from white
- Saturation – distance from white

McAdam ellipses (10x) represent equally noticeable color difference perceptions

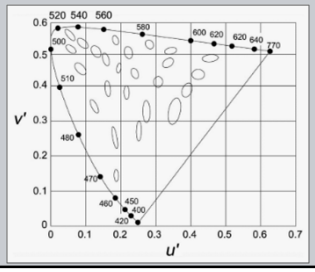
a) Color coordinate systems: CIE u',v'

CIE 1960:
u,v uniform chromaticity

$$u = \frac{4X}{X+15Y+3Z} = \frac{4x}{-2x+12y+3},$$
$$v = \frac{6Y}{X+15Y+3Z} = \frac{6y}{-2x+12y+3},$$

CIE 1976:
u',v' improved uniformity

$$u' = u$$
$$v' = 1.5\,v$$

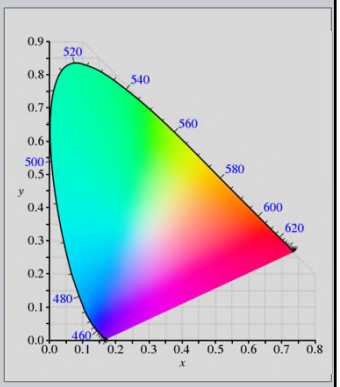


- McAdam ellipses (10x) represent equally noticeable color difference perceptions.
- The 1976 u',v' chromaticity coordinates are significantly more uniform with respect to the perception of color difference relative to the 1931 x,y coordinates.

a) Color coordinate systems: CIE x,y

- CIE defines chromaticity as,

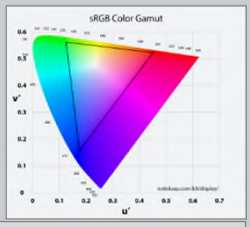
$$x = X / (X + Y + Z)$$
$$y = Y / (X + Y + Z)$$
$$z = Z / (X + Y + Z)$$



- Because $x + y + z = 0$, it suffices to quote only x,y.
- The diagram using the chromaticity coordinates is referred to as the CIE 1931 chromaticity diagram (2°).

a) Color coordinate systems: CIE u',v'

- The 1976 u'v' chromaticity coordinates can be easily computed from measurements of the spectral power, $P(\lambda)$.
- With improved color difference characteristics, they are the preferred units for describing the white point and color coordinates of monitors.



- The color space of a monitor is typically defined by the u',v' coordinates of the white point and the R, G, and B points.
- sRGB is a common color space standard for display devices.

CIE has defined color spaces describing both luminance, L, and chromaticity which have further improvements in uniformity (L*u*v*, L*a*b*). Their complex dependence on luminance makes them inappropriate for monitor metrology.

b) Color measurement devices

b) Devices for measuring color coordinates (11 pgs.)

b) Color measurement devices

Radiometers:

- A radiometer is a device for measuring the radiant flux (power) of electromagnetic radiation.
- For example, solar irradiance is measure of the power per unit area (watts/m^2) from sunlight incident on a surface.

Photometers:

- A photometer is a device to measure the apparent brightness of light to a 'nominal' human observer.
- The light power is weighted as a function of wavelength according to the standardized sensitivity of the eye (slide 5).
- Luminance is a photometric measure of the light emitted from the surface of a display device reported in units of candelas per square meter (cd/m^2).

Radiometers and Photometers are NOT used for color measures

b) Color measurement devices: spectroradiometers

Spectroradiometers:

- Spectroradiometers are devices designed to measure the spectral power distribution of a light source. From the spectral power distribution, the photometric and colorimetric quantities of light can be determined.
- Spectroradiometers typically take measurements of spectral radiance and calculate CIE tristimulus values through numeric integration. CIE chromaticity coordinates and luminosity can then be deduced.
- Also known as: Spectrophotometer or spectrocolorimeter

Spectroradiometers are the most accurate type of measurement device for assessing display color using a defined color coordinate system.

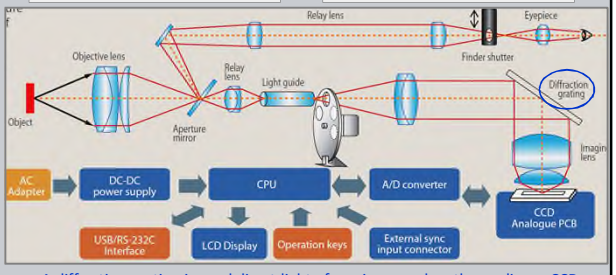
However, spectroradiometers are expensive ($10K to $30K)

TOPCON SR-3AR *Konica-Minolta CS-2000a*

b) Color measurement devices: spectroradiometers

TOPCON
SR 3AR

Konica
Minolta
CS2000A

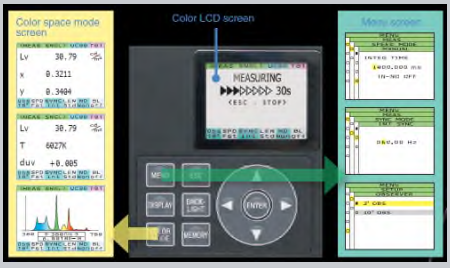


A diffraction grating is used direct light of varying wavelength on a linear CCD.

b) Color measurement devices: spectroradiometers

Device setup allows refined control of the measurement parameters that effect CIE color space coordinates.

- 2 vs 10 degree observers.
- u',v' vs x,y space
- Spectral shape



The devices are typically used with a computer USB interface to control acquisition synchronization with monitor display state and to analyze acquired data to produce defined reports.

b) Color measurement devices: colorimeters

Colorimeters:

- Colorimeters are devices that measure the light transmitted through a limited set of filters to estimate color coordinates.
- Popular colorimeters include:
  - X-Rite i1 Display Pro (4 filter/detector)
  - Data Color Spyder 5 (7 filter/detector)
- Good luminance accuracy with rapid measurement rate.
- Color coordinate accuracy is not as good at a spectroradiometer.
  - Errors due to the light spectral shape.
  - Filters can degrade with time (humidity)
  - Temperature dependence and drift.

However, colorimeters are low in cost (~ $250) and offer good performance for quality control applications.

b) Color measurement devices: i1 Display Pro

- The X-Rite i1 Display Pro measures luminance through a lens placed in contact on the surface of the display device.
- Ambient illuminance can be measured by rotating a diffuser to cover the lens.
- The device is also sold as:
  - OEM i1 Display Pro
  - NEC SpectraSensor Pro
  - Quato Silver Haze 3 OEM
  - HP DreamColor
  - Wacom i1d3
- Four filter/detector sensors record signals reflecting red, green, and blue response and a neutral (white) response. The sensors and filters are sealed with an o-ring to preserve the filter transmission characteristics.

https://displaycalibrations.com/x-rite_i1_measurement_solutions_info.html

b) Color measurement devices: i1 Basic Pro 2

I1 Basic Pro 2

- A field grade spectrophotometer with modest cost ($1.0K - $1.4K).
- Holographic diffraction grating with 128-pixel diode array with built-in wavelengths check.
- Standards based certificate of performance.

However:

- Uncertain temperature drift issues.
- Time consuming for many measures.

Potentially useful for monitor color QC when used in addition to a colorimeter for gray scale QC.

b) Color measurement devices: software, open source.

Argyll CMS

- Argyll CMS 2.0.1 (July 2018) is an open source, ICC compatible color management system. It was developed and it is being maintained and well supported by Graeme Gill (Melbourne, Australia).
- The software includes routines to interface with a large number of spectroradiometers an colorimeters.
- In addition to source code, executables are available for Windows, Apple OS, Linux, and an Android color meter application.
- https://argyllcms.com

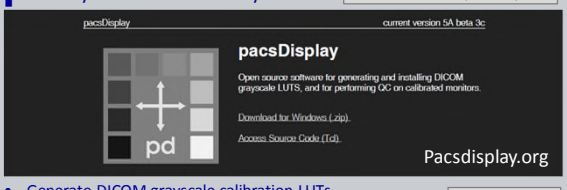
DisplayCal

- DisplayCal 3.6 (June 2018) is an open source display calibration and characterization software package powered by Argyll CMS. It is managed by Florian Hoch (Stuttgart, Germany).
- https://displaycal.net/

b) Color measurement devices: software, pd.

pd By and for Medical Physicists

Open Source
2003 - Development started.
2006 - GNU License release.
2013 - GitHub repository



- Generate DICOM grayscale calibration LUTs.
- Access EDID content & monitor models.
- Automatically load LUTs via graphics card.
- Display image quality test patterns.
- View real time colorimeter values.
- Perform QC on calibrated monitors.
- Supports numerous photometers (Argyll CMS)

i1Display Pro
(recommended)

b) Color measurement devices: software, pd.

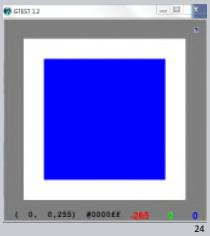
pd software package:

I1meter

Continuousy reads the i1 Display Pro meter to report luminance or illuminance. Values can be held and copied to a spreadsheet.

gtest

A utility application allowing color or gray test regions to be rapidly set with the digital drive values shown.



b) Color measurement devices: software, commercial.

Commercial software is widely available:

- Bundled with a colorimeter.
  - DataColor (Spyder 5)
  - X-Rite (i1 Display Pro, i1 Basic Pro 2)
- Software companies.
  - SpectraCal (CalMAN 2018)
  - ….
- Medical display company
  - Eizo (RadiCS software)
  - ….

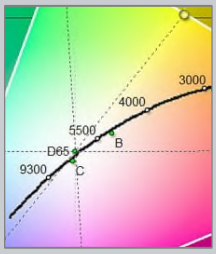
c) White point & gray tracking

c) White point and gray tracking(3 pgs.)

c) White point & gray tracking

- CIE defines the coordinates of a white light similar to daylight.
- D65, x=0.31271, y=0.32902 (2° observer)
- D65 is the defined white point for sRGB, aRGB and dRGB (draft).
- Recent professional guidelines have recommended this as the white point for medical monitors.
  - ACR-AAPM-SIIM electronic imaging guidelines.
  - AAPM TG270 draft report.

- Specifying white point as D65 is preferred as opposed to the color temperature which is commonly used in monitor specifications.
- D65 is similar to a color temperature of 6500°.



c) White point & gray tracking

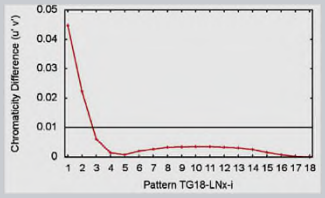
The white point of a monitor may vary with gray level, particularly for LCD devices.

- IEC 62563 ed 1, amendment 1 (2015) defines methods for grayscale chromaticity tracking using u',v' measures at 18 gray level.

$$\Delta u'_i v'_i = ((u_i'-u_{18}')^2 + (v_i'-v_{18}')^2)^{1/2}$$

- Badano et. al., Med. Phys., 43, 4023 (2016)

reports the results of AAPM TG196 evaluations of gray tracking using various colorimeters.

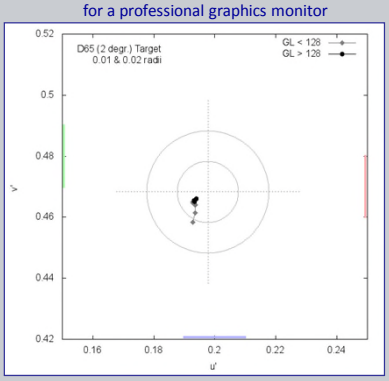


c) White point & gray tracking

- Maintaining monitor white point within 0.01 of D65 for all luminance values above 5 cd/m² is likely acceptable.
- Maintaining white point deviations within 0.005 would be desirable.
- Professional recommendations are made in AAPM TG270.

- pacsDisplay lumResponse QC (open source software)
- i1 Display Pro meter
- Argyll USB driver

Evaluation of chromaticity vs gray level for a professional graphics monitor



u',v' data acquired as a part of GSDF 18 level QC test

d) Defined color spaces

d) Defined color spaces (6 pgs.)

d) Defined color spaces

- sRGB is a standard RGB color space created cooperatively by HP and Microsoft in 1996 for use on monitors, printers and the Internet.
- the sRGB gamma cannot be expressed as a single numerical value. The overall gamma is approximately 2.2, consisting of a linear (gamma 1.0) section near black, and a non-linear section elsewhere
- IEC 61966-2-1:1999 is the official specification of sRGB. It provides viewing environment, encoding, and colorimetric details.

http://en.wikipedia.org/wiki/SRGB

sRGB Reference Document

IEC 61966-2-1
Colour Measurement and Management
in Multimedia Systems and Equipment
Part 2-1: Default RGB Colour Space – sRGB

1. GENERAL
   1. Introduction
   2. Scope
   3. Normative References
   4. Definitions
2. REFERENCE CONDITIONS
   1. Reference Display Conditions
   2. Reference Viewing Conditions
   3. Reference Observer Conditions
3. ENCODING CHARACTERISTICS
   1. Introduction
   2. Transformation from RGB values to 1931 CIE XYZ values
   3. Transformation from 1931 CIE XYZ values to RGB values

ANNEX A: Ambiguity in the Definition of the Term "Gamma"
ANNEX B: sRGB and ITU-R BT.709-2 Compatibility
ANNEX C: Usage Guidelines
ANNEX D: Typical Viewing Conditions
ANNEX E: Recommended Treatment for Viewing Conditions
ANNEX F: Bibliography

d) Defined color spaces

- The Adobe RGB color space is an RGB color space developed by Adobe Systems in 1998.
- It was designed to encompass most of the colors achievable on CMYK color printers, but by using RGB primary colors on a computer display.
- A gamma of 2.2 is assumed.
- The color space encompasses roughly 50% of the visible colors specified by the Lab color space, improving upon the gamut of the sRGB color space primarily in cyan-greens.

aRGB Reference Document

Adobe RGB (1998)
Color Image Encoding
Version 2005-05, May 2005

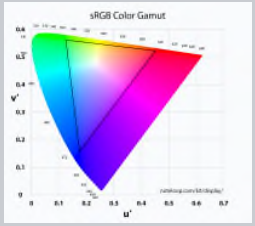
Introduction
1. Scope
2. References
3. Terms
4. Requirements
   1. General
   2. Reference Viewing Environment
   3. Adobe RGB (1998) Color Image Encoding
5. Indicating the use of Adobe RGB (1998) ..

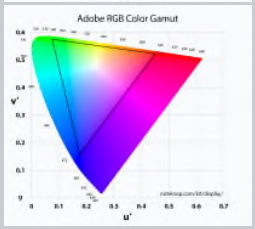
Annex A: The Adobe RGB (1998) ICC profile
Annex B: Practical tolerances for display devices
Annex C: Implementation notes

http://http://en.wikipedia.org/wiki/Adobe_RGB_color_space
http://www.adobe.com/digitalimag/pdfs/AdobeRGB1998.pdf

d) Defined color spaces

- sRGB is the nominal color space for the majority of consumer and business monitors in use today. However, the actual color space may differ from the sRGB definition.
- aRGB is a more saturated color space (i.e. extended gamut) found in professional graphics monitors. These are often capable of being calibrated to either the sRGB or aRGB standards.





d) Defined color spaces

(1) IEC 62563 terminology

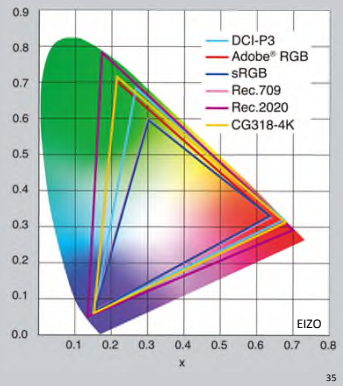
Specification (1)	sRGB	aRGB	ACR	dRGB
Luminance Response	~2.2 power function	2.199 power function	DICOM GSDF	DICOM GSDF
Color Gamut	HDTV based ITU-R BT.709-5	'Wide' (extended G)	-nd-	[*] (referenced)
L_{max} , cd/m²	80	160 (125-200)	350/420/250	350 (250-450)
L_{min} , cd/m²	-nd-	0.56	L_{max} / LR	L_{max} / LR
Luminance Ratio (LR)	-nd-	287.9 (230-400)	350 (> 250)	350 (300-400)
White Point	D65	D65	D65	D65
Gray tracking	-nd-	-nd-	-nd-	IEC MT51
Surround	20% refl. lx	Gray (D65, 2°) 20% L_{max}	-nd-	Gray (D65, >2°) 20% L_{max}
Ambient Illumination, lx	64 (D50)	32 (D65) (16-64)	20-40	-nd-
Veiling Glare	1.0%	accounted	-nd-	-nd-
L_{amb} , cd/m²	-nd-	-nd-	$L_{amb} < 1/4\ L_{min}$	$L_{amb} < [1/4, 2/3]\ L_{min}$

d) Defined color spaces

The color space of new display monitors is becoming much larger.

DCI-P3 was defined by the Digital Cinema Initiatives (DCI) and published by SMPTE in 2010 and 2011. Since 2015, Apple monitors supporting DCI-P3 have been available

UHDTV was officially approved in 2012 as a standard by the International Telecommunication Union (ITU), standardizing both 4K and 8K resolutions for the format in ITU-R Recommendation BT.2020



UHD Monitors

UHD Professional Class Monitors

Manf.	Model	GSDF	Size (in)	Pitch, mm	Lmax, cd/m²
• Eizo	FlexScan EV3237	√	31.5	.18	300
• NEC	PA322UHD	√	31.5	.18	350
• DELL	UP3214Q	√	31.5	.18	350

Current 4k UHD monitors use a Sharp IGZO IPS panel.

e) QC assessments: gray tracking & color space

e) QC assessments of gray tracking & color space(? pgs)

e) QC assessments: gray tracking & color space

TG 270 Recommendations:

- *For acceptance or annual testing, the white point of the display should be measured over the full luminance range in 8-bit gray level steps of 15.*
- *These steps correspond to the 18 point response steps, and the same patterns or automated routine described for luminance measurements may be used.*
- *The measurement should exclude gray levels with luminance less than 5 cd/m2, where the color receptors of the eye are less sensitive to color differences.*
- *The recorded chromaticity coordinates should be converted to the CIE 1976 UCS diagram coordinates (u', v'). Once converted, the color distance Δ to a target value, D65, should be calculated for each gray level measurement according to Equation 2.8:*

$$\Delta(u',v') = \sqrt{\left(u'_1 - u'_{\text{target}}\right)^2 + \left(v'_1 - v'_{\text{target}}\right)^2}. \quad (2.8)$$

Annual white point gray tracking measures for diagnostic and modality displays can be performed as a part of luminance response QC.

e) QC assessments: gray tracking & color space

TG 270 Acceptable limits

TABLE VIII. Recommended Color Distance from a Standard Illuminant (e.g., $\Delta_{D65}(u',v')$)

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

TABLE IX. Recommended Color Distance Limits between Displays

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

For diagnostic displays, the acceptable maximum deviation of the white point from the recommended D65 target is 0.01

e) QC assessments: gray tracking & color space

RGB Color Space QC

- There are currently no specific Medical Physics recommendation for the assessment of medical monitor color space.
- Color space conformance amongst monitors is significant for modalities such as Nuclear Medicine where color contributes to the interpretation.
- It is suggested that the u',v' color coordinates of the R, G, and B primary monitor colors be measured when the white point and gray tracking are assessed

Color space assessment can quickly done using a colorimeter and color test images.

Questions?

?