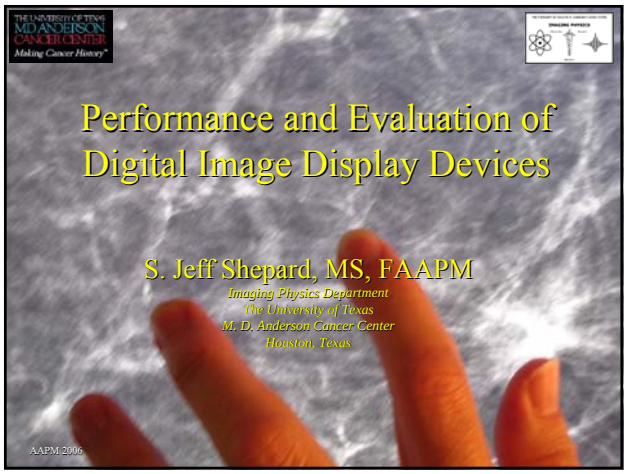


Performance and Evaluation of Digital Image Display Devices

- Standards
  - ACR, Teleradiology, Digital Image Data Management
  - AAPM OR-3 (TG-18)
- Display technology overview
  - CRT
  - AMLCD
- Performance characteristics
- Test methods (OR-3)
- QA program (OR-3)

Display Classes OR-3

- Class 1
  - Used for diagnostic interpretation
  - Most stringent performance and QA criteria
- Class 2
  - Non-diagnostic use
    - Fluoroscopy
    - Demographic display
  - Least stringent criteria
- QA console monitors should also adhere to Class 1 luminance calibration

Quality Assurance Standards (ACR)

CRT only

512, 1024, or 2048?

"As a test of the display, ***SMPTE pattern data files sized to occupy the full area used to display images*** on the monitor should be displayed. The overall SMPTE image appearance should be inspected to assure the absence of gross artifacts (e.g., blurring or ***bleeding*** of bright display areas into dark areas or ***aliasing of spatial resolution patterns***). Display monitors used for primary interpretation should be tested at least monthly. As a dynamic range test, ***both the 5% and the 95% areas should be seen*** as distinct from the respective adjacent 0% and 100% areas."

This is guaran-teed to cause this!

Contra-dicts DICOM PS3.14

AAPM OR-3 (TG-18)

Samei E, Badano A, Chakraborty D, Compton K, Cornelius C, Corrigan K, Flynn MJ, Hemminger B, Hangiandreou N, Johnson J, Moxley D, Pavlicek W, Roehrig H, Rutz L, Shepard SJ, Uzenoff R, Wang J, and Willis C, ***Assessment of Display Performance for Medical Imaging Systems***, American Association of Physicists in Medicine (AAPM) On-Line Report #3, AAPM, 2005.

http://www.aapm.org/pubs/reports/#OR

Performance Requirements Class 1

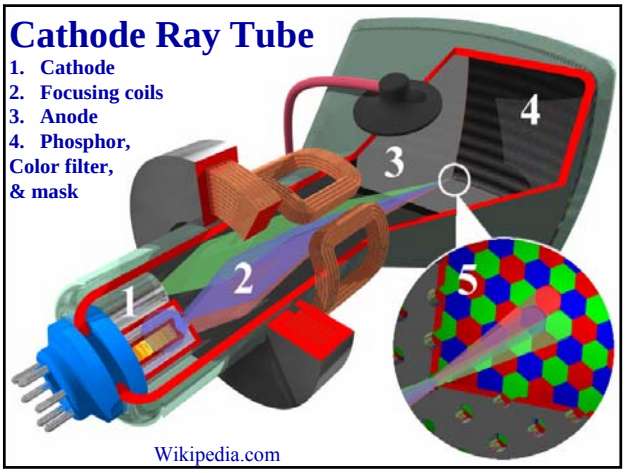
	ACR	AAPM OR-3
Geometric Distortion	No Gross Artifacts	< 2% variation
Reflection	Depends on L_{amb}	Depends on L_{amb}
Max. Luminance	$L_{max} \geq$ 50 ft-L (171 Cd/m^2)	$L_{max} \geq$ 170 Cd/m^2
Contrast	5% and 95% SMPTE visible	LR $\geq$ 250
Luminance Response	Not Specified	w/i 10% of GSDF
Luminance Uniformity	No Gross Artifacts	$\Delta L/L_{avg} \leq$ 30% 4 corners and center
Resolution	$\geq$ 2.5 lp/mm	$\geq$ 2.5 lp/mm
Noise	Not Specified	< Displayed radiographic image noise
Veiling Glare	Not Specified	Glare Ratio > 400

Display Technology Overview

- Cathode Ray Tube (CRT)
- Active-Matrix Liquid Crystal Diode (AMLCD or "LCD")
- Plasma Screen
  - Short life expectancy (luminance fade)
  - Static image burn-in,
  - Fragile
- DLP
- Color only

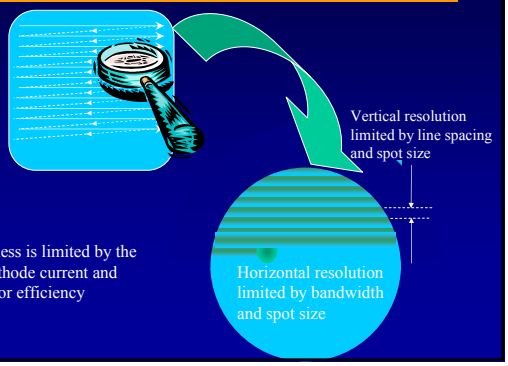
Cathode Ray Tube

1. **Cathode**
2. **Focusing coils**
3. **Anode**
4. **Phosphor, Color filter, & mask**



Wikipedia.com

Display Technology CRT



CRT Performance

- Luminance Ratio (LR) = L_{max} / L_{min}
  - Typical max phosphor luminance ~ 450 Cd/m^2
  - Typical black level ~0.5 Cd/m^2
  - Typical LR ~ 900:1
    - Human visual response limited to ~250:1
  - Veiling glare reduces LR
    - Scattered light in face plate
    - Stray electrons in tube
- Typically 256 discrete driving levels (up to 1024)

CRT Performance

- Uniformity
  - Decreased brightness and sharpness at edges due to more acute "landing angle" of e-beam
    - Dim edges
    - Fuzzy edges
  - Subject to stray magnetic field interference
    - Affects geometric uniformity (wavy lines)

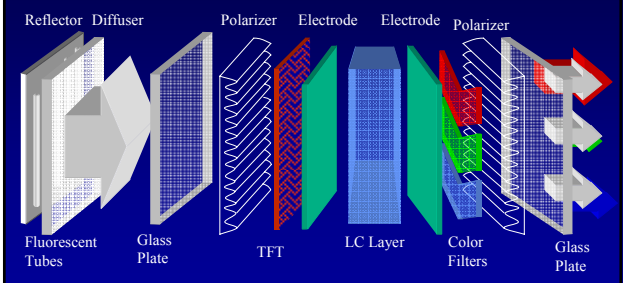
CRT Performance

- Phosphor efficiency fades with time
  - Compensate by increasing driving level as phosphor ages
  - Requires constant monitoring
  - ~2 year life expectancy

CRT Performance

- Artifacts
  - Phosphor burns
    - Ghost negative images burned in
    - Point defects (spots)
  - Impedance mismatch
    - "Bleeding" of white into black and vice-versa at B/W interfaces

Display Technology
LCD



LCD Performance

- **Resolution**
  - **Determined by Pixel Pitch (vertical and horizontal)**
    - **Up to 9 MP**
  - **Uniform across the entire surface**
  - **Never changes (always perfect)**

Vertical Resolution

Horizontal Resolution

LCD Performance

- Luminance Ratio = L_{max} / L_{min}
  - Typical max luminance > 600 Cd/m^2
  - Typical black level <1 Cd/m^2
  - LR > 1200:1 is possible (beyond human perception)
  - Typically 256 - 1024 discrete driving levels
    - Each "element" is modulated at 8 bits
    - Additional spatial and temporal modulation increases performance up to 11.5 bits. (Blume, et al)

LCD Performance

- Luminance Ratio changes with viewing angle
  - Minimized by adding birefringent layers, angling sub-pixel elements and changing molecular orientation of crystals in the LC layer.
  - Increases production costs

LCD Performance

- Backlights fade with time but very slowly
  - Increase driving level as tubes age
  - Requires occasional monitoring (slow process)
    - MDACC LCD's driving at 70% after 5 years (500 Cd/m^2)
  - Self-calibration, automatic adjustment
  - No veiling glare

LCD Performance

- Uniformity
  - Brightness and sharpness at edges identical to center (perfect everywhere)
  - Not affected by stray magnetic fields
  - Perfect image geometry (set by pixel matrix)
- Artifacts
  - Point defects (defective sub-pixels)

LCD Performance

- Future improvements
  - LED backlight arrays
    - Improved color
    - Wider viewing angle
    - Longer life expectancy
    - Lower power consumption
    - Max luminance may suffer
    - No grayscale in development

Display Performance

PARAMETER	LCD	CRT
MATRIX SIZE	UP TO 9 MP	5 MP MAX
RESOLUTION UNIFORMITY	EXCELLENT, CONSTANT	GOOD BUT UNSTABLE
MAXIMUM LUMINANCE	UP TO 600 CD/M^2	200 CD/M^2 MAX
MINIMUM LUMINANCE	DOWN TO 0.6 CD/M^2	DOWN TO 0.6 CD/M^2
LUMINANCE RATIO	UP TO 1200:1	UP TO 900:1, VARIES WITH AGE
OFF-AXIS LR	POOR	EXCELLENT
LUMINANCE STABILITY	UNKNOWN (> 3 YEARS)	1.7 YR MEAN TIME TO FAILURE
LUMINANCE UNIFORMITY	EXCELLENT	GOOD
VEILING GLARE	NO	YES
PHOSPHOR BURN/DEAD PIXELS	YES	YES
GEOMETRIC UNIFORMITY	EXCELLENT	GOOD
FOOTPRINT	SMALL	LARGE
HEAT PRODUCTION	LOW	HIGH

Display QC Tests

- OR-3 Tests (All Class 1 devices)
  - Diffuse and Specular Reflection
  - Luminance Uniformity (TG18-UNL10/80)
  - Chromaticity (TG18-UNL80)
  - Luminance Response (TG18-LN)
    - Angular dependence of LR
  - Noise (TG18-AFC)
  - Pixel Defects (TG18-UNL10/80, -LPH/LPV)
  - Resolution (TG18-CX, TG18-QC)
  - Veiling Glare (TG18-GX)
  - Geometric Uniformity (TG18-QC)

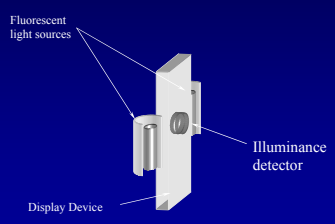
} CRT Only

Diffuse Reflectance

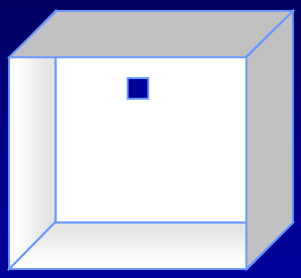
- Illuminance and
- Luminance of the Reflected Illuminance

$$R_D = \frac{\text{Luminance of reflected illuminance}}{\text{Illuminance of the display surface}}$$

Diffuse Reflectance

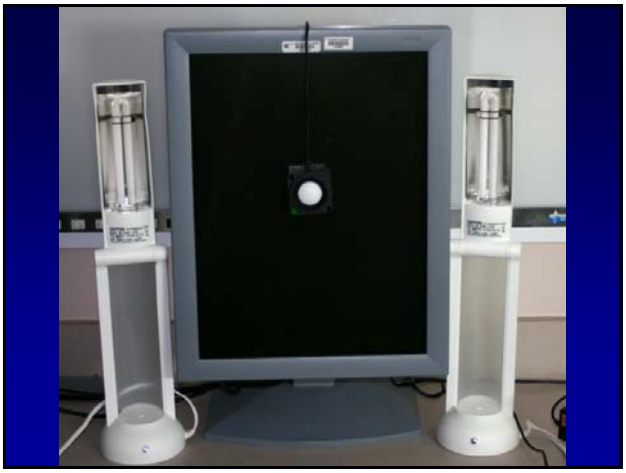


Diffuse Reflectance

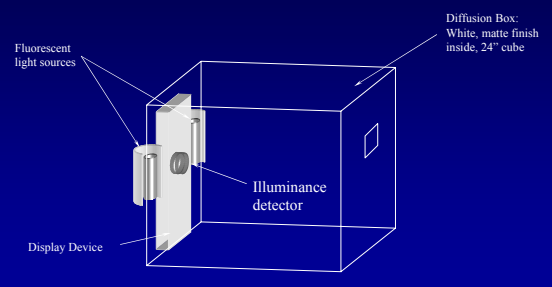


Diffusion Box:

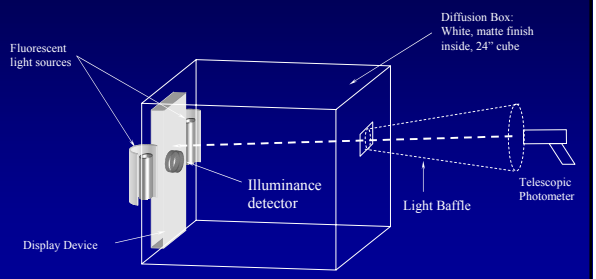
- White
- Matte finish inside
- 24” cube
- Sight hole in back

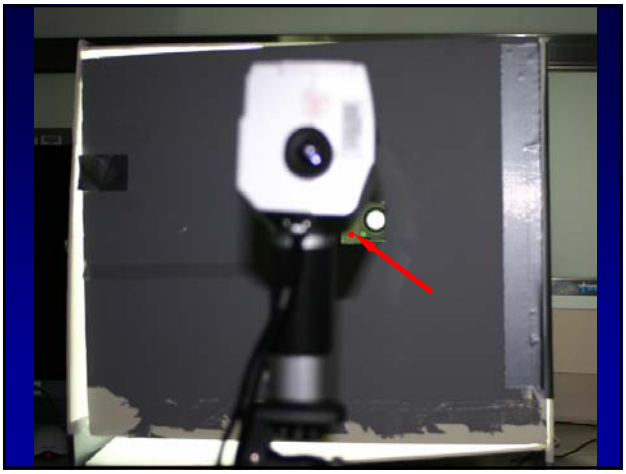


Diffuse Reflectance



Diffuse Reflectance





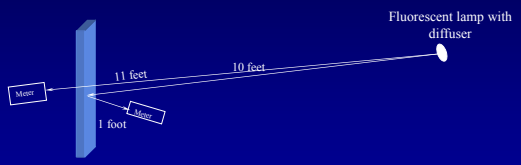
Reflection

- Diffuse Reflectance:

$$R_D = \frac{\text{Luminance of reflected illuminance}}{\text{Illuminance on the display surface}}$$

Used to set maximum reading room illumination

Specular Reflectance



Reflection

- Specular Reflectance:

$$R_S = \frac{\text{Luminance of reflected image}}{\text{Luminance of the light source}}$$

Reflection

- Ambient lightning
  - Set to maintain low-contrast sensitivity in darkest regions of an image
  - Depends on L_{min}, Diffuse reflection coefficient, and specular reflectance (measured at acceptance)

Initial Setup

Room Lighting Example:

- L_{max} = 400 cd/m^2

Source: OR-3, Table 5

L_{min} (cd/m^2)	Maximum Room Illuminance (lux)				
	R_d = 0.005	R_d = 0.010	R_d = 0.020	R_d = 0.040	R_d = 0.060
20	1000	500	250	125	83
10	500	250	125	62	42
4	200	100	50	25	17
2 (1.6)	100	50	25 (18)	12	8
1	50	25	12	6	4

L_{min} (cd/m^2)	Maximum Room Illuminance (lux)				
	R_d = 0.002	R_d = 0.004	R_d = 0.006	R_d = 0.008	R_d = 0.020	R_d = 0.040
20	349	175	87	35	17
10	192	96	48	19	10
4	105	52	26	10	5
2 (1.6)	63	31	20	6	3
1	42	21	10	4	2

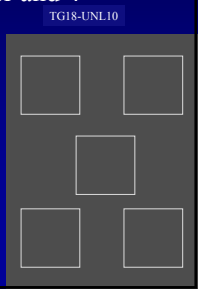
Source: OR-3, Table 4

Initial Setup

- Initial Set-Up
  - $L_{max} \geq 170$ Cd/m^2 (CRT)
  - $L_{max} \geq 400$ Cd/m^2 (LCD)
    - Affects life expectancy
  - L_{min} ($LR=L_{max}/L_{min} \sim 300$)
    - $L_{min} > 0.5$
  - Room Lighting

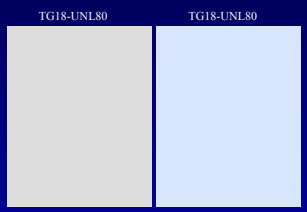
Luminance Uniformity

- AAPM TG18-UNL80
- Measure luminance in the center and 4 quadrants.
- Compare each reading to the average of all 5:
- $|L_i/L_{avg} - 1| \leq 0.3$
- Repeat using TG18–UNL10



Chromaticity

- Color Matching (Visual, TG18-UNL80) …



… or measure with a chromaticity meter.
Both u' and v' should match to within 0.01

Luminance Response

- AAPM OR-3-LN
  - 17 patterns, uniform 50% background with central 10% incrementally brighter from L_{min} to L_{max} in even steps.

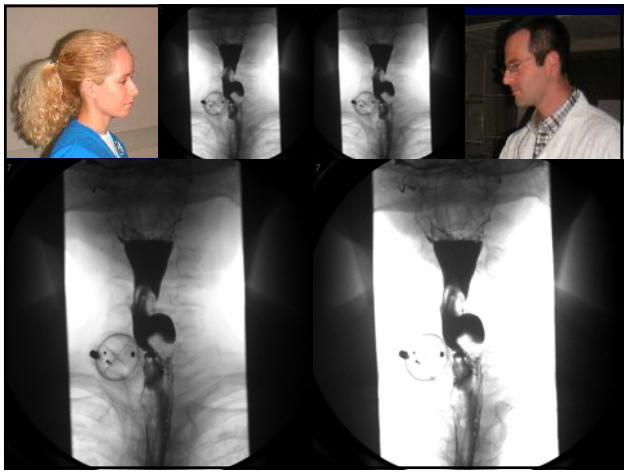
  - Room lights off (total darkness)
  - Default DICOM W/L settings
  - Measure each step and compare to GSDF

Luminance Response

- $L_{max} > 170$ Cd/m^2 (50 ft-L, CRT)
- $L_{max} > 400$ Cd/m^2 (117 ft-L, LCD)
- Response error $\leq$ 10% of GSDF
- Luminance Ratio = $L_{max}/L_{min} \geq 250$

Display Classes
OR-3

- Class 1
  - Used for diagnostic interpretation
  - Most stringent performance and QA criteria
- Class 2
  - Non-diagnostic use
    - Fluoroscopy
    - Demographic display
  - Least stringent criteria
- QA console monitors should also adhere to Class 1 luminance calibration



What DICOM do I need for a modality?

- Grayscale Standard Display Function

  Monitors must be capable of calibration to GSDF

  Warning! This is often an overlooked piece!

  Monitors are present in most modalities aka control workstation or QC workstation

- Kevin Junck, PhD
DICOM: What the Physicist Needs to Know

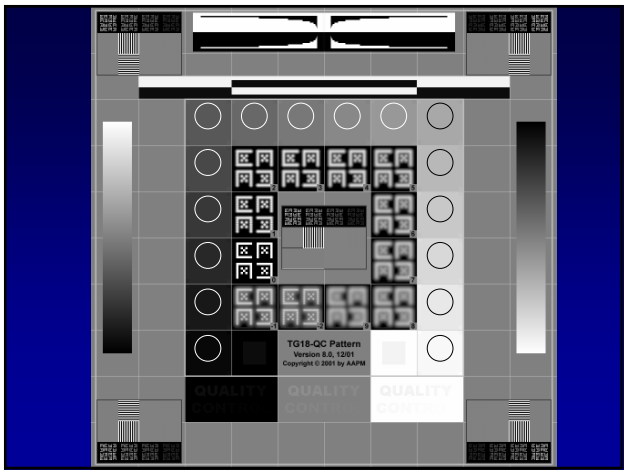
DICOM Image Quality

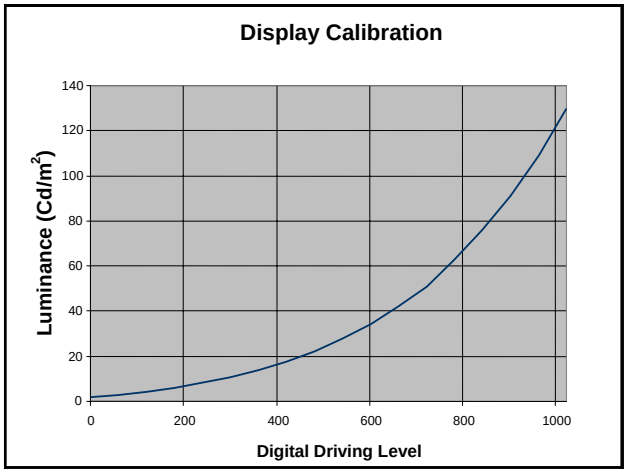
- Grayscale Standard Display Function (DICOM Part 14)

  Identifies a standard method to calibrate the luminance response of emissive (monitors), transmissive (film) and reflective (paper) media

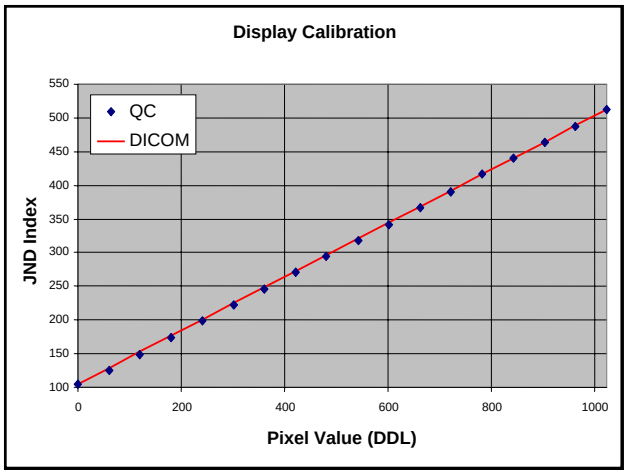
Image Quality (PACS)

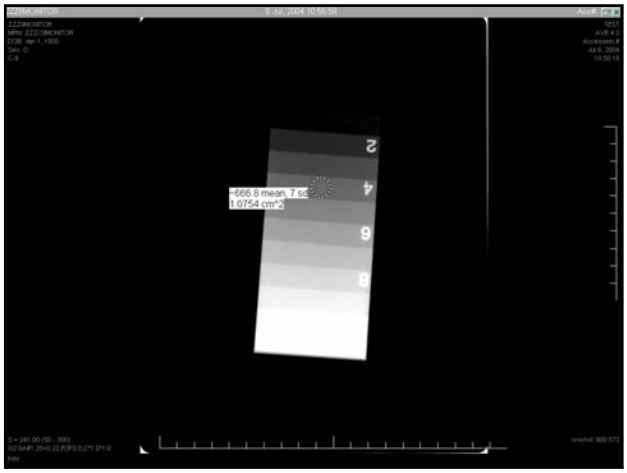
- Compare LUT on QC monitor to PS 3.14
  - Measure steps on the QC monitor with a photometer (See TG18)
  - Calculate JND's at min and max L for the monitor (PS 3.14, Table B1)
  - Calculate target JND's at each step assuming a linear increase with pixel value
  - Calculate JND's at each step from measured values
  - Calculate % of total JND range at each step
  - Compare to DICOM at each step

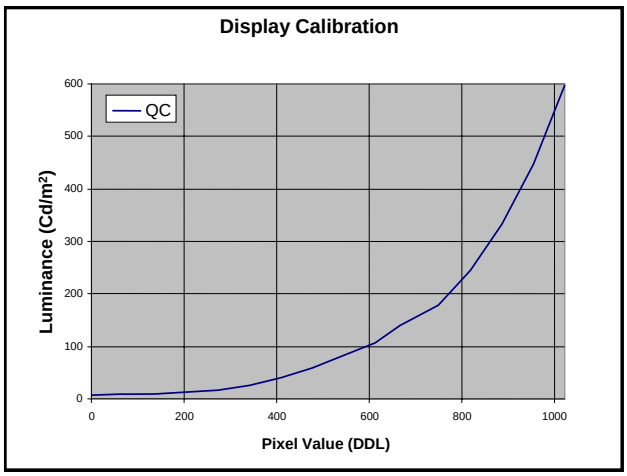


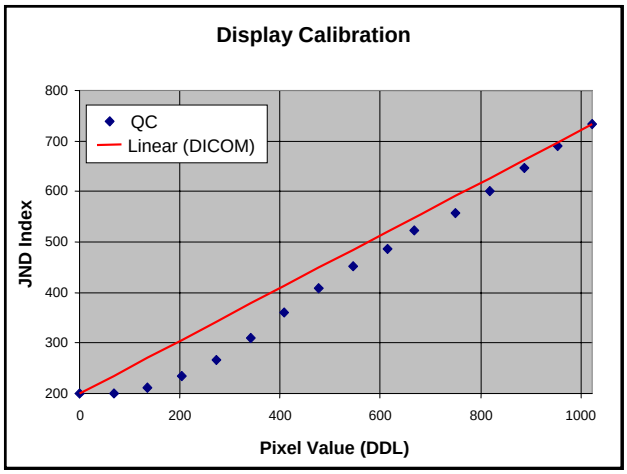


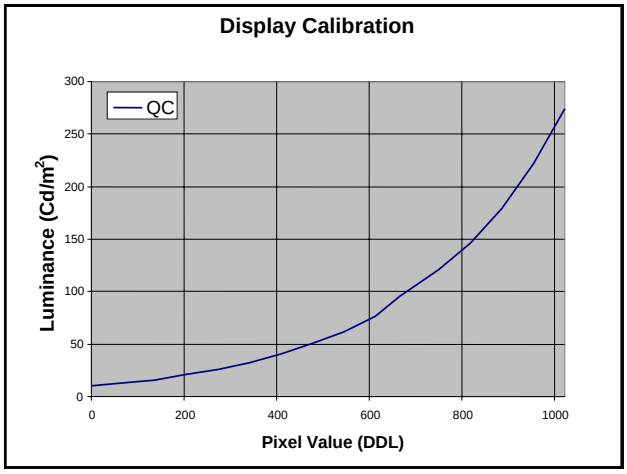
	Luminance	JND Index		% JND		
ddl	QC	QC	DICOM	QC	DICOM	Error
1023	130	512	512	100%	100%	
963.0	109.0	488	488	94%	94%	0%
903.0	91.2	464	464	88%	88%	0%
842.0	75.9	440	440	82%	82%	0%
782.0	63.0	416	416	76%	76%	0%
722.0	51.0	390	392	70%	71%	-1%
662.0	41.9	366	368	64%	65%	-1%
602.0	34.2	342	345	58%	59%	-1%
542.0	27.6	318	321	52%	53%	-1%
481.0	22.2	294	296	47%	47%	0%
421.0	17.7	271	273	41%	41%	0%
361.0	13.7	246	249	35%	35%	-1%
301.0	10.7	223	225	29%	29%	0%
241.0	8.1	199	201	23%	24%	-1%
181.0	5.9	174	177	17%	18%	-1%
120.0	4.2	149	153	11%	12%	-1%
60.0	2.9	125	129	5%	6%	-1%
0.0	2.04	105	105	0%	0%	

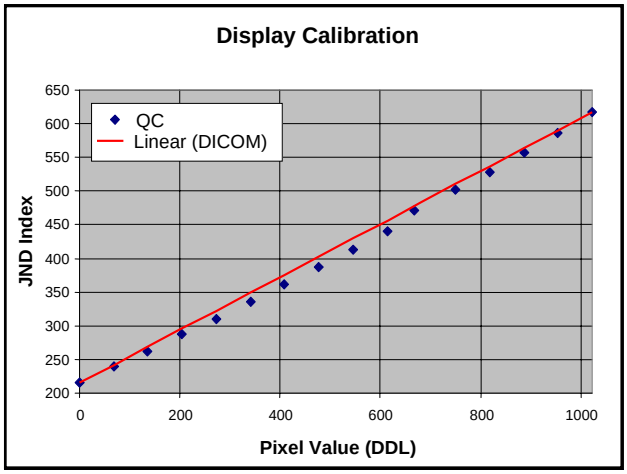

Display Calibration
QC
DICOM
JND Index
Pixel Value (DDL)
550
500
450
400
350
300
250
200
150
100
0
200
400
600
800
1000




Display Calibration
QC
Luminance (Cd/m²)
Pixel Value (DDL)
600
500
400
300
200
100
0
0
200
400
600
800
1000

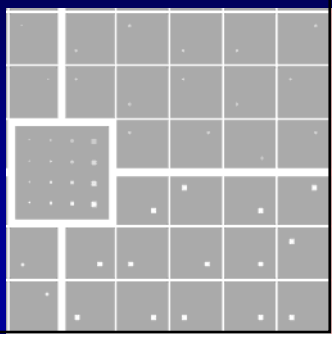

Display Calibration
QC
Linear (DICOM)
JND Index
Pixel Value (DDL)
800
700
600
500
400
300
200
0
200
400
600
800
1000


Display Calibration
QC
Luminance (Cd/m2)
Pixel Value (DDL)
300
250
200
150
100
50
0
0
200
400
600
800
1000


Display Calibration
QC
Linear (DICOM)
JND Index
Pixel Value (DDL)
650
600
550
500
450
400
350
300
250
200
0
200
400
600
800
1000

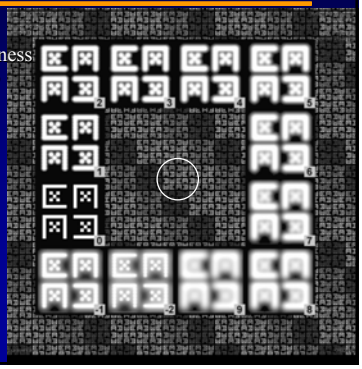
Noise

- TG18-AFC
- Count # quadrants in which most squares show a corner object.
- Don't count squares with more than one object!
- Passing score is ≥3

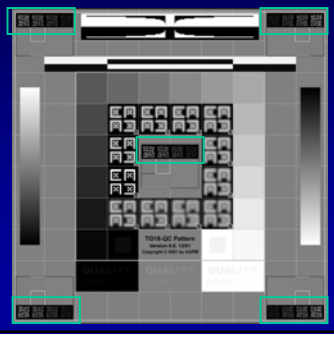


Resolution

- AAPM OR-3-CX
- Match observed sharpness of small Cx patterns to simulated blur of large Cx patterns
- Repeat in four corners
- Passing score is ≤4



Resolution (OR-3-QC)



Veiling Glare

- White regions contaminate nearby black ones
  - Stray electrons
  - Light scattering in glass/mask

Veiling Glare

- Measure black level in center of all-black field (L_N)
- Measure white level in center of all-white field (L_B)
- Measure black level in center with surrounding at peak white (L)

Glare Ratio (R_G) = $(L_B - L_N)/(L - L_N)$

Should exceed 400

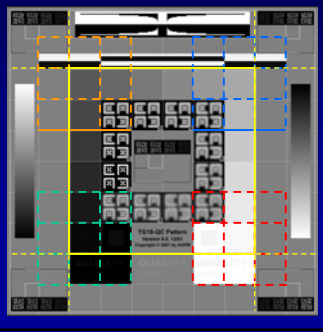
L_N: TG18-GQN

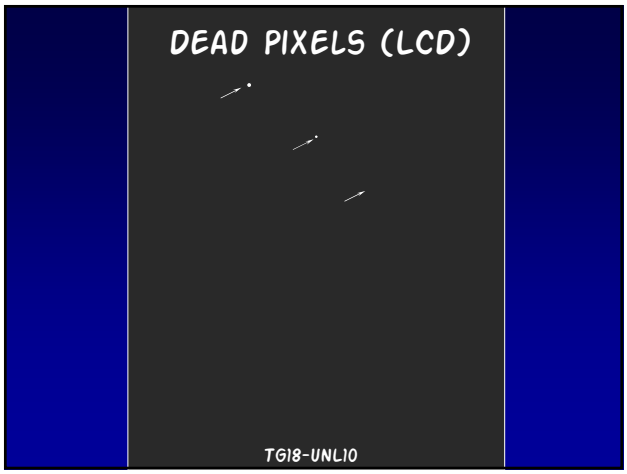
L_B: TG18-GQB

L:TG18-GQ

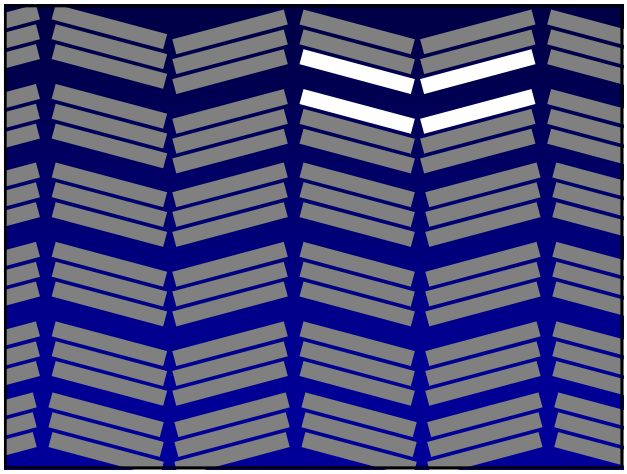
Geometric Distortion

$\leq 2\%$

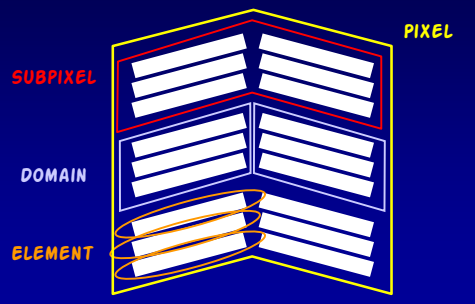



DEAD PIXELS (LCD)
TG18-UNL10


February



Pixel Definition



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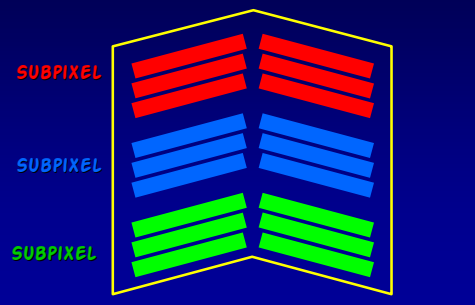
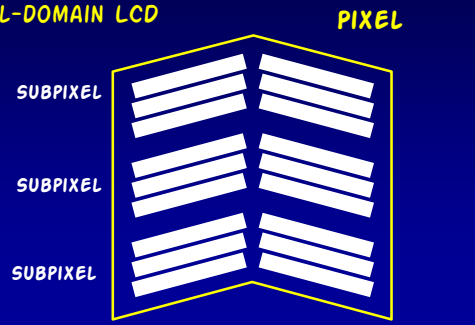
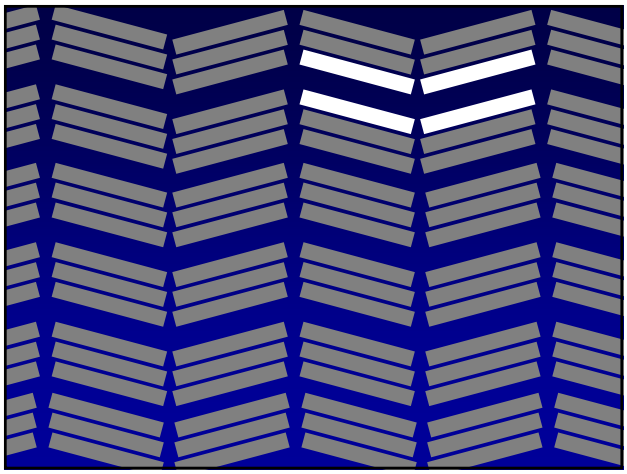
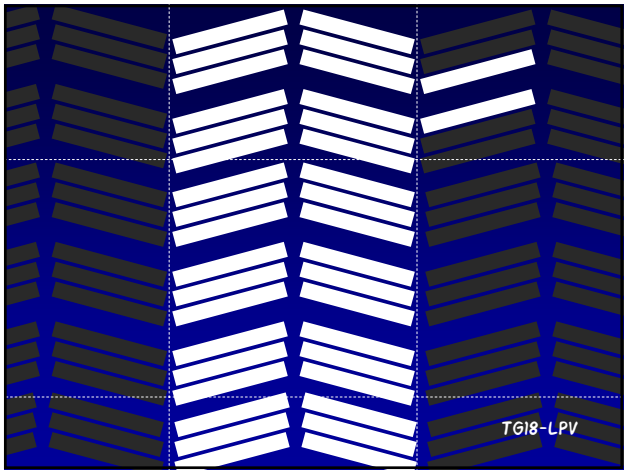


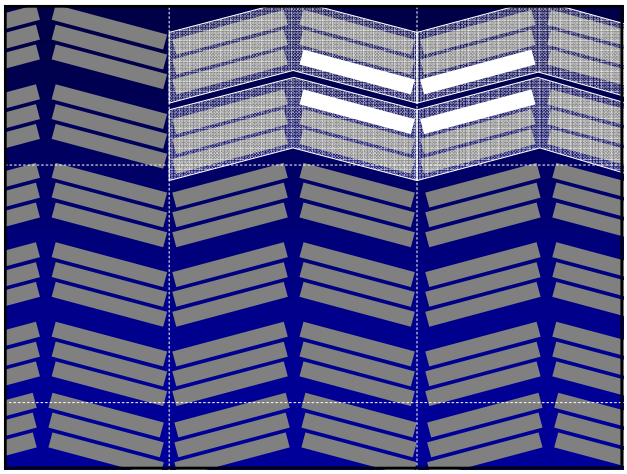
Pixel Definition

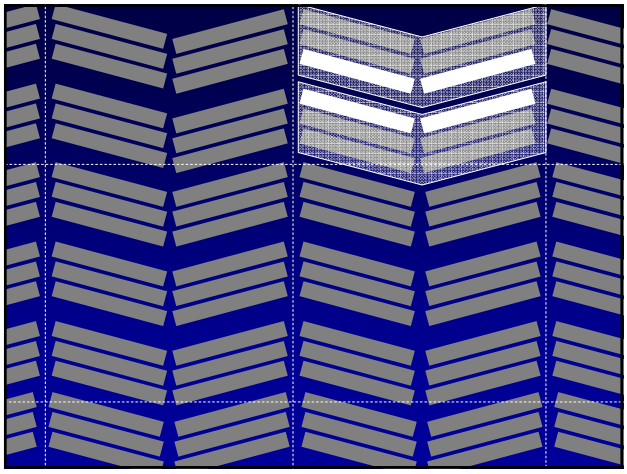


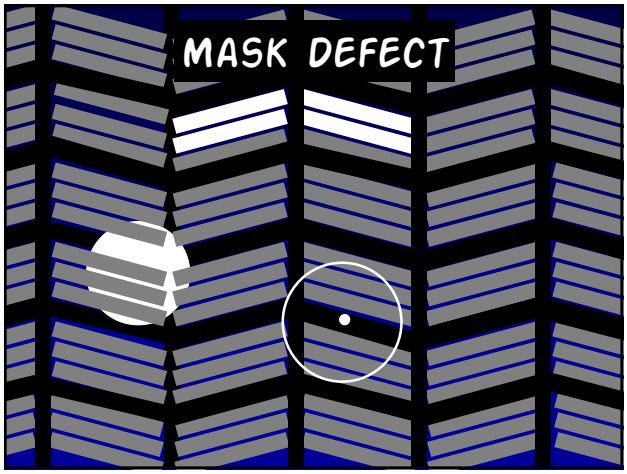


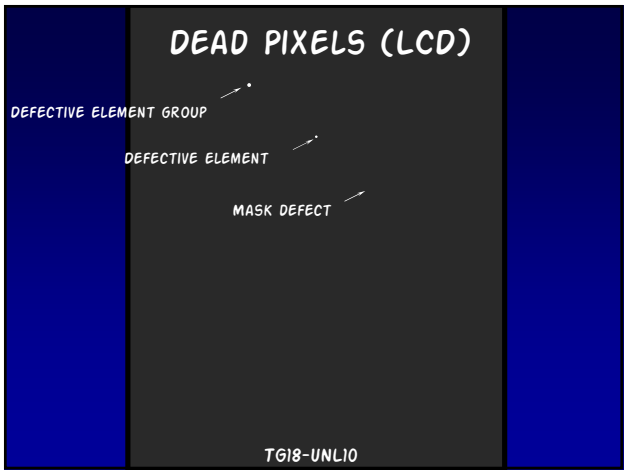

TG18-LPH


TG18-LPV






MASK DEFECT



Dead Pixels

- Defective Pixels
  - 3,000,000 pixels in a 3MP display
    - 9,000,000 sub-pixels
    - 54,000,000 individual elements!!!
  - 15 defective elements
    - One in 4,500,000
    - 0.00002%
- Is this good or bad?

Dead Pixels

- Performance specifications vary by manufacturer
  - Total number of "bad" subpixels (≤ 15)
  - # "Bad" subpixels per 1-cm circle (≤ 3)
  - Maximum # adjacent "bad" subpixels (≤ 3)
- Incorporate desired specifications into the RFP

Display QC

- QC Program
  - Acceptance
  - Initial Set-up
  - Annual QC
  - Monthly/Quarterly QC
  - Daily QC

AAPM OR-3

Assessment of Display Performance for Medical Imaging Systems

Display QC

OR-3 Quality control Tests

- Performed by individuals who "develop and maintain familiarity with the tests" and are under the supervision of a Medical Physicist.
  - ➢Understands Technology
  - ➢Limitations of Test instrumentation
  - ➢Test procedures
  - ➢Image quality requirements
  - ➢Consequences of negative results

Display QC

- OR-3 is based on CRT performance
- Modify the OR-3 list of CRT tests by eliminating:
  - Resolution (fixed by pixel pitch)
  - Geometric distortion (fixed by pixel pitch)
  - Veiling glare (non-existent in LCD)

Display QC

- Self-calibrating displays
  - Emerged during development of OR-3
  - Verify stability during test drive (Thompson, SK, et al, JDI 2003)
    - During warm-up,
    - Repeatedly over the course of several days,
    - Day-to-day for a week,
    - Week-to-week for a month,
    - Month-to-month for a quarter.

Display QC

- Self-calibrating displays
  - Eliminates need for luminance response measurement except at annual test.
  - Use monthly subjective tests to identify graphics card failures.

Display QC

- OR-3 Acceptance Tests
  - Diffuse and Specular Reflection
  - Luminance Uniformity (TG18-UNL10/80)
  - Chromaticity (TG18-UNL80)
  - Noise (TG18-AFC)
  - Pixel Defects (TG18-UNL10/80, -LPH/LPV)
  - Luminance Response (TG18-LN) and Luminance Ratio
    - Angular dependence of LR (@ ±45 degrees from normal)
  - Resolution (TG18-CX of TG18-QC)
  - Veiling Glare (TG18-GQX)
  - Geometric Uniformity (TG18-QC)

CRT Only

Display QC

- Annual (OR-3 Table 8c)
  - Same as acceptance, w/o Reflection and Luminance Ratio tests
  - Luminance Response (Objective)
  - Noise
  - Chromaticity
  - Pixel defects and phosphor burns
  - Resolution
  - Veiling Glare
  - Geometric Uniformity

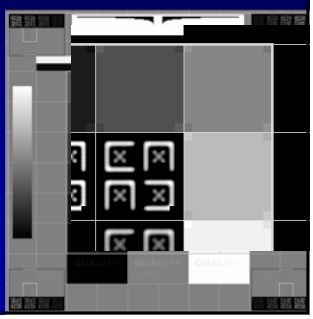
CRT Only

Display QC

- Monthly/Quarterly Tests (OR-3 Table 8b)
  - Cleanliness (glass cleaner and soft cloth)
  - Ambient lighting (reset to acceptance)
  - Subjective luminance uniformity & chromaticity (matching monitors)
  - Pixel defects
  - Luminance response (TG18-QC)
    - Non-Self-Calibrating: Objective
    - Self-calibrating: Subjective

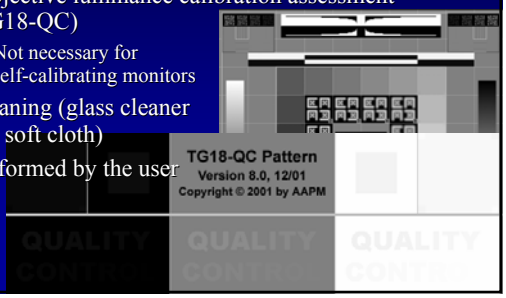
Display QC

- Monthly subjective luminance response assessment (TG-18 QC)
  - Default W/L
  - All 4 objects should be visible in every step.
  - Self-calibrating only
- Luminance Response measurements
  - Non-self-calibrating
  - Same as acceptance

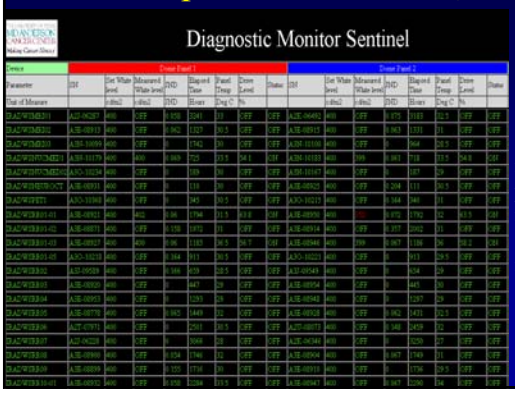


Display QC

- Daily
  - Subjective luminance calibration assessment (TG18-QC)
    - Not necessary for self-calibrating monitors
  - Cleaning (glass cleaner and soft cloth)
  - Performed by the user



Experience – LCD QC



Remote Status Monitoring can facilitate rapid problem recognition and resolution.

Created by Raimund Polman

Performance and Evaluation of Digital Image Display Devices

- Standards
  - ~~ACR~~
  - AAPM OR-3 (TG-18, OR-3)
    - Test methods
    - QA program
- Display technologies
  - CRT
  - AMLCD
  - Plasma, DLP not appropriate for Dx
  - Future: OLED, PLED, SCED, NED
    - Grayscale?

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