Image Quality for the Radiation Oncology Physicist: Review of the Fundamentals and Implementation

Image Quality Review I: Basics and Image Quality
TH-A-16A-1 Thursday 7:30AM - 9:30AM Room: 16A

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Disclosures

• Trustee, American Board of Radiology
• Author, Essential Physics of Medical Imaging

Outline

• Image quality and ROC analysis
• Image quality fundamentals
  – Contrast resolution, noise, NPS
  – Spatial resolution, detail, MTF
  – Digital sampling and aliasing
  – Contrast – detail analysis
• Detector uniformity and flat-fielding
• Cone Beam CT issues
• QA – QC resources
Image Quality

**Technologist-Therapist:**
Work with the patient and the instruments to produce the best possible images.

**Medical Physicist:**
Optimize image quality of each medical imaging procedure to maximize diagnostic performance

**Radiologist/Radiation Oncologist:**
Optimize image interpretation skills for the most accurate diagnosis/evaluation possible

- maximize diagnostic performance
  - sensitivity
  - specificity

Receiver-Operator Characteristic (ROC) distribution relationship to Image Quality and information

decision threshold
false negatives
false positives
normal
decision parameter
abnormal

The ability to detect abnormality (disease) when it is present

sensitivity = \( \frac{TP}{TP + FN} \)
specificity = \frac{TN}{TN + FP}

The ability to exclude abnormality (disease) when it is not present.

Normal decision parameter

Overlapping distributions -- real world

Ideal performance
In ROC analysis, which of the following is a measure of sensitivity?

1. TP/(TP+FP)  
2. TP/(TP+FN)  
3. FP/(FP+TN)  
4. TN/(TN+FP)  
5. TP/(TP+FP+TN+FN)

Reference: Essential Physics of Medical Imaging, Bushberg, Seibert, Leidholdt, Boone, 3rd Ed. Lippincott Williams & Wilkens, 2012. Chapter 4, Image Quality
Image Quality

Contrast Resolution
- contrast
- noise

Spatial Resolution
- input functions
- digital sampling

Contrast / Detail

Contrast
- subject contrast
- detector contrast
- digital contrast
Subject Contrast

\[ C = \frac{A - B}{A} \]

Subject Contrast

- X-ray spectrum
- Low kVp
- Med kVp
- High kVp

Bone contrast example

- Good bone contrast
- Good lung contrast
**Subject Contrast**

scattered radiation reduces subject contrast

\[ C = \frac{A - B}{A + S} \]

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**Subject Contrast**

contrast agents (obviously) affect contrast

digital subtraction angiography with iodine contrast agent in vessel
double contrast GI study

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**Contrast**

subject contrast
- detector contrast
- digital contrast
Detector contrast (screen film)

detector contrast is the derivative of the characteristic curve

latitude

acceptable
Detector contrast (screen film)

\[ \text{OD}_1 - \text{OD}_2 = \text{radiographic contrast} \]

Radiographic contrast (screen film)

\[ \text{OD}_1 - \text{OD}_2 = \text{radiographic contrast} \]

Contrast

subject contrast
detector contrast
digital contrast
Detector contrast (digital)

Characteristic Curve:
Exposure in, GS out
multiple exposures
test object step wedge

Detector contrast (digital)

digital radiography

GS − GS
GS
= contrast

digital manipulation of contrast
contrast enhancement (post-acquisition)
"window and leveling"
The subject contrast generated in a patient is most dependent on which acquisition parameter?

13% 1. Generator waveform
13% 2. kV
37% 3. mAs
20% 4. Focal spot
17% 5. Collimation

The subject contrast generated in a patient is most dependent on which acquisition parameter?

1. Generator waveform
2. kV
3. mAs
4. Focal spot
5. Collimation

**Image Quality**

Contrast Resolution
- contrast
- noise

Spatial Resolution
- input functions
- digital sampling

Contrast / Detail

**Noise**

Low Noise  |  Medium Noise  |  High Noise

\[
\text{SNR} = \frac{\mu}{\sigma} \propto \frac{N}{\sqrt{N}} = \sqrt{N} \quad \text{Fractional noise} = \frac{1}{\sqrt{N}}
\]

![Graph showing SNR vs. Signal (photons/mm²)]
Manipulation of digital detector contrast

Characterizing image noise

RMS noise (\(\sigma\))

\[
\sigma^2 = \frac{\sum_{i=0}^{N} (x_i - \bar{x})^2}{N-1}
\]

Noise sources:
- Quantum \(n_q\)
- Electronic \(n_e\)
- Pattern \(n_p\)
- Anatomic \(n_a\)

Ideally, noise should always be quantum limited; the RMS noise also does not indicate noise correlation.

\[
\sigma = \sqrt{n_q + n_e + n_p + n_a}
\]

Overall noise dominated by quantum fluctuations over a defined range.
What level of noise?
...depends on incident number of photons efficiency of detection, signal conversion, and #photons detected / unit volume

Example: variance for CT image reconstruction

\[
\sigma^2 \propto \frac{1}{w^2 h Q}
\]

\( w \) pixel dimension
\( h \) slice thickness
\( Q \) # photons

Contrast resolution is determined by contrast and noise

Contrast to Noise Ratio (CNR)

\[
SNR = \frac{\bar{X}_{S} - \bar{X}_{bg}}{\sigma_{bg}} \quad \text{CNR} = \frac{(\bar{X}_{S} - \bar{X}_{bg})}{\sigma_{bg}}
\]

Characterizing image noise

Noise Power Spectrum: NPS(f)

\[
NPS(u,v) = \left( \Delta x \Delta y \right) \left| \int \int \int \left[ \phi \left( x, y \right) - 1 \right] e^{-j2\pi(u x + v y)} \, dx \, dy \right|^2
\]

Fourier Transform
Characterizing image noise – noise texture

Noise Power Spectrum: $NPS(f)$

$$NPS(u,v) = \left(\frac{\Delta x \Delta y}{XY}\right) \left[ \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} [I(x,y) - \bar{I}] e^{-j2\pi(ux+vy)} dx dy \right]^2$$

Noise Power Spectrum: $NPS(f)$

A total of 1,000,000 photons/mm² are incident on a 100% efficient digital detector with pixels of 0.1 mm x 0.1 mm. What is the estimated SNR?

<table>
<thead>
<tr>
<th>Option</th>
<th>SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td>1.10</td>
</tr>
<tr>
<td>10%</td>
<td>2.32</td>
</tr>
<tr>
<td>30%</td>
<td>3.100</td>
</tr>
<tr>
<td>23%</td>
<td>4.320</td>
</tr>
<tr>
<td>27%</td>
<td>5.1000</td>
</tr>
</tbody>
</table>

Hint: 0.1 mm x 0.1 mm = 0.01 mm²
A total of 1,000,000 photons/mm$^2$ are incident on a 100% efficient digital detector with pixels of 0.1 mm x 0.1 mm. What is the estimated SNR?

1. 10
2. 32
3. **100**
4. 320
5. 1000

$10^6 / \text{mm}^2 \times 10^{-2} \text{ mm}^2 = 10^4; \sqrt{10^4} = 100$

Chapter 4, Image Quality

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*Image Quality*

- **Contrast Resolution**: contrast, noise
- **Spatial Resolution**: input functions, digital sampling
- **Contrast / Detail**

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![Diagram showing object in an imaging system with an image output]
Point Spread Function (PSF)

Line Spread Function (LSF)

Edge Spread Function (ESF)
The convolution integral

\[ I(x, y) = \int_{x'} \int_{y'} I(x', y') h(x-x', y-y') \, dx' \, dy' \]
Input signal amplitude

Output signal amplitude

\[ f = 0.5 \text{ cycles/mm} \]

\[ f = 1.0 \text{ cycles/mm} \]
input signal amplitude

output signal amplitude

f = 1.5 cycles / mm

$\Delta$

Spatial Frequency (cycles/mm)

MTF(f)

MTF(f)

Spatial Frequency (cycles/mm)
\[ f = 2.0 \text{ cycles/mm} \]
Practical way for measuring the MTF of an imaging system

\[
MTF(f) = \left| \frac{\int_{-\infty}^{\infty} LSF(x) e^{j2\pi fx} dx}{\int_{-\infty}^{\infty} LSF(x) dx} \right|
\]
**Geometry Issues**

- Magnification
  \[ M = \frac{a + b}{a} \]
  for a point source

**Focal spot and geometric magnification**

- Amount of blur is dependent on magnification

\[ f_{blur} = \frac{1}{(M - 1)FS} \] mm

**Image Quality**

- Contrast Resolution
  - contrast
  - noise

- Spatial Resolution
  - input functions
  - digital sampling

- Contrast / Detail
Detector element affects aliasing.

Detector elements affect resolution.

Detector aperture width affects aliasing.

Sampling pitch affects aliasing.

Nyquist Criterion: \[ F = \frac{1}{2\Delta} \]

Have to sample at least twice per period.
Nyquist Criterion

aliasing

frequency f

OK to over-sample

Nyquist Criterion

not OK to under-sample

Nyquist Criterion

not OK to under-sample
With $F_w = 5$ cycles/mm ($\Delta = 0.100$ mm)

**aperture blurring**

**Rect Function**
Typical measurement of resolution

Bar phantom analysis and determination of lp/mm

Typical measurement of resolution

Where \( d \) is the del dimension …
**Image Quality**

Contrast Resolution
- contrast
- noise

Spatial Resolution
- input functions
- digital sampling

Contrast / Detail

---

**the contrast detail curve**

combines the effects of spatial resolution and contrast resolution

Looking for the “just visible” disks
the contrast detail curve

Rose criterion: \[ \text{SNR} = \frac{\sqrt{a} \cdot A}{\sigma} \]

- \( a = \) contrast
- \( A = \) area of object
- \( \sigma = \) StdDev noise

“Visibility” requires SNR of at least 3.

mathematical approach to combining contrast & spatial resolution?
A contrast-detail image is acquired and processed (A). A second image is acquired (B) with different acquisition or processing parameters. What is the likely cause for the change in the C-D curves?

17% 1. Image B is processed with a spatial blurring filter

23% 2. Image B is processed with a spatial sharpening filter

23% 3. Image B is acquired with more mAs

13% 4. Image B is acquired with more filtration

23% 5. Image B is unchanged.

contrast resolution – Noise Power Spectrum (NPS)

\[ NPS(u, v) = \frac{\Delta x \Delta y}{\int \int \left[ 1 - e^{-2\pi i u x} - 1 - e^{-2\pi i v y} \right]^2 dx dy} \]

how an imaging system “passes” noise

spatial resolution – Modulation Transfer Function (MTF)

\[ MTF(f) = \frac{\int LSF(x) e^{-2\pi f x} dx}{\int LSF(x) dx} \]

how an imaging system “passes” signal

**DQE: Information recording & retrieval efficiency**

\[ DQE(f) = \frac{SNR^4(f)_{\text{det}}}{SNR^4(f)_{\text{m}}} = \frac{MTF^4(f)}{\phi NPS(f)} \]

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A contrast-detail image is acquired and processed (A). A second image is acquired (B) with different acquisition or processing parameters. What is the likely cause for the change in the C-D curves?


1. Image B is processed with a spatial blurring filter
2. Image B is processed with a spatial sharpening filter
3. Image B is acquired with more mAs
4. Image B is acquired with more tube filtration
5. Image B is unchanged.

Detector Uniformity Issues

2-D flat-field correction

- Non-functioning components:
  - Dead pixels in columns and/or rows
- Intensity variations:
  - Uneven phosphor coating
  - Optical coupling (vignetting, barrel distortion)
  - Converter sensitivity
- Variation in offset and gain of sub-panels
- Variation in black-level correction

Uncorrected flat-panel image
**Uncorrected flat-panel image**

- Identify location of pixel defects: 
  - Interpolate bi-linearly (4 nearest neighbors)
- Column, row defects:
  - Interpolate linearly (2 surrounding neighbors)

**Example “raw” image & flat-field**

- Background variations
- Column, line defects: “Del” dropouts
- Avg. Inverted background: Column, line repair
- Nonnormalized values
- Processed image: Image pixel value to exposure relationship
- Contrast resolution enhancement: proprietary processing

**Flat-field pre-processing**

- Screen-Film
- aSi/CsI Flat-Panel
- CR

MDACC: Chris Shaw, et al
MITA Industry Definitions for Image Data States

RAW DATA

Detector Data

Detector Corrected Data

PRESENTATION DATA (aka "For Presentation")

Image for Viewing on a Display

ORIGINAL DATA (aka "For Processing")

Nonlinear processing

LINEARIZED DATA

Inverse CONVERSION FUNCTION

CBCT issues

- Large area detector
- Geometric rotation accuracy
- Diverging radiation beam along z-axis
- X-ray scatter and beam uniformity
- HU accuracy and percent noise
- Cone beam reconstruction artifacts
- Radiation dose measurements
An Integrated CT Image Quality / Dosimetry Phantom

- noise power spectrum (NPS)
- modulation transfer function (MTF)
- dosimetry

2D NPS  3D NPS

Noise Power Spectra Assessment

MTF Assessment

Cone Beam CT artifacts

Defriese phantom

fairly aggressive cone beam acquisition

more conventional helical acquisition

circular geometry

helical geometry
CT image quality evaluation

<table>
<thead>
<tr>
<th></th>
<th>Old Era</th>
<th>New Era</th>
</tr>
</thead>
<tbody>
<tr>
<td>phantom</td>
<td>complicated</td>
<td>basic</td>
</tr>
<tr>
<td>analysis</td>
<td>simple</td>
<td>more sophisticated</td>
</tr>
<tr>
<td>results</td>
<td>clinically useful</td>
<td>useful &amp; quantitative</td>
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</tbody>
</table>

QA and QC

- Quality assurance (QA)*: “The planned and systematic activities implemented in a quality system so that quality requirements for a product or service will be fulfilled.”

- Quality control (QC)*: “The observation techniques and activities used to fulfill requirements for quality.”

*The American Society for Quality
# QC resources

- AAPM Task Group Reports
- ACR / AAPM / SIIM technical standards
- NCRP / ICRU Reports
- Accreditation program guidelines
- Manufacturer’s guidelines
- Automated software evaluation with specifically-designed phantoms and/or software …

## AAPM reports

**Applications for Diagnostic**

<table>
<thead>
<tr>
<th>#</th>
<th>Description</th>
<th>Year</th>
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<tbody>
<tr>
<td>14</td>
<td>X-ray generators</td>
<td>1985</td>
</tr>
<tr>
<td>25</td>
<td>X-ray survey</td>
<td>1988</td>
</tr>
<tr>
<td>74</td>
<td>General x-ray QC</td>
<td>2002</td>
</tr>
<tr>
<td>93</td>
<td>CR testing &amp; QC</td>
<td>2006</td>
</tr>
<tr>
<td>116</td>
<td>DR Exposure</td>
<td>2009</td>
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<tr>
<td>150</td>
<td>DR detector</td>
<td>IP</td>
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<tr>
<td>151</td>
<td>DR clinical QC</td>
<td>IP</td>
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</table>

**Applications for CT**

<table>
<thead>
<tr>
<th>#</th>
<th>Description</th>
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<tbody>
<tr>
<td>39</td>
<td>CT testing QC</td>
<td>1993</td>
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<tr>
<td>96</td>
<td>CT dosimetry</td>
<td>2008</td>
</tr>
<tr>
<td>111</td>
<td>Future of CT dose</td>
<td>2010</td>
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<tr>
<td>204</td>
<td>SSDIE</td>
<td>2011</td>
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<tr>
<td>220</td>
<td>CT Patient size</td>
<td>IP</td>
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<tr>
<td>233</td>
<td>CT Perf Evaluation</td>
<td>IP</td>
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<tr>
<td>246</td>
<td>CT Patient Dose</td>
<td>IP</td>
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</tbody>
</table>

**Applications for therapy IGRT**

<table>
<thead>
<tr>
<th>#</th>
<th>Description</th>
<th>Year</th>
</tr>
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<tbody>
<tr>
<td>104</td>
<td>kV imaging</td>
<td>2009</td>
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<td>142</td>
<td>Med Accel QC</td>
<td>2009</td>
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<tr>
<td>179</td>
<td>IGRT systems</td>
<td>2012</td>
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<tr>
<td></td>
<td>ACR–AAPM Technical Std for Perf Monitoring of IGRT</td>
<td>2014</td>
</tr>
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## AAPM Report 179

<table>
<thead>
<tr>
<th>Modes of acquisition</th>
<th>Flat panel detector</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

** Modes of acquisition**

- Projection Imaging
- Cone beam CT

**IQ Test**

<table>
<thead>
<tr>
<th>Safety system</th>
<th>Daily</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniformity</td>
<td>Monthly / Semi-annual</td>
</tr>
<tr>
<td>Image density</td>
<td>Optional monthly</td>
</tr>
<tr>
<td>Noise</td>
<td>Monthly / Semi-annual</td>
</tr>
<tr>
<td>Contrast detail</td>
<td>Monthly / Semi-annual</td>
</tr>
<tr>
<td>Resolution</td>
<td>Monthly / Semi-annual</td>
</tr>
</tbody>
</table>

**Geometry:**

- Isocenter: Daily
- Scaling: Monthly / Annually

**X-ray generator:**

- Annual

**Dosimetry:**

- Annual
Which of the following QC tests is performed on a daily basis for a cone-beam CT scanner used for IGRT?

- **1. Image Uniformity**
- **2. Spatial Resolution**
- **3. Noise Distribution**
- **4. Contrast Detail**
- **5. Isocenter Verification**


**Summary**

- An understanding of basic image quality fundamentals is essential to performing QA and QC in a knowledgeable manner.

- Increased use of imaging in radiation therapy requires medical physicists to engage in converting QA/QC “information” into knowledge through experiential efforts.

- Both qualitative and quantitative QC tools are important in verifying system performance.