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:

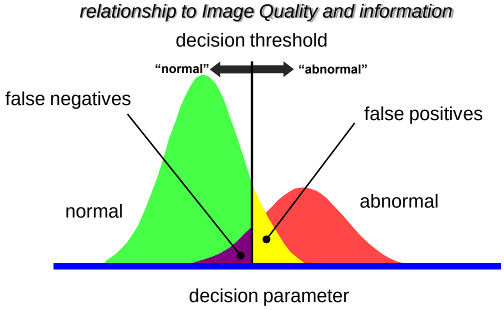
Optimize image interpretation skills for the most accurate diagnosis/evaluation possible

→ **maximize diagnostic performance**

- **sensitivity**
- **specificity**

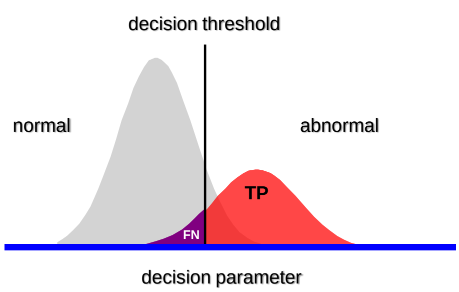
Receiver-Operator Characteristic (ROC) distribution

relationship to Image Quality and information



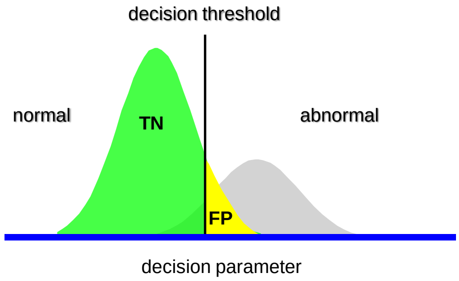
The ability to detect abnormality (disease) when it is present

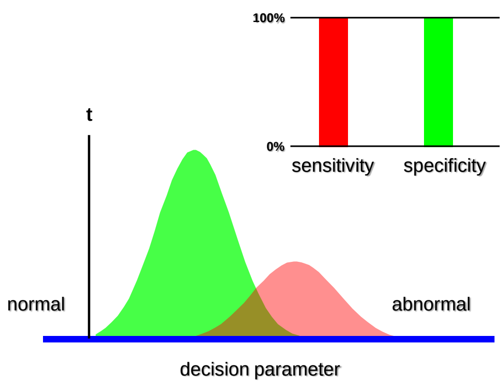
$$\text{sensitivity} = \frac{TP}{TP + FN}$$

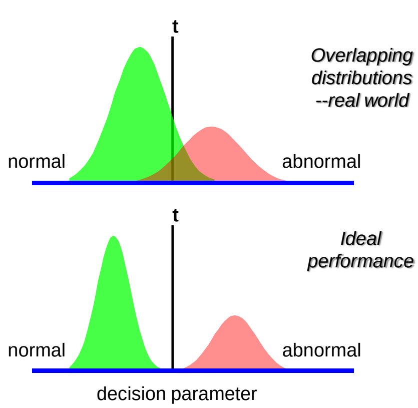


$$\text{specificity} = \frac{TN}{TN + FP}$$

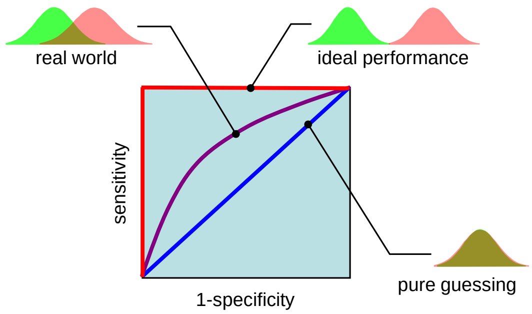
The ability to exclude abnormality (disease) when it is not present







receiver operating characteristic (ROC) curve



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

28%	1. TP/(TP+FP)
21%	2. TP/(TP+FN)
17%	3. FP/(FP+TN)
10%	4. TN/(TN+FP)
24%	5. TP/(TP+FP+TN+FN)

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

1. TP/(TP+FP) ..Positive Predictive Value
2. ✓ TP/(TP+FN)…. Sensitivity
3. FP/(FP+TN) … False Positive Fraction
4. TN/(TN+FP)…. Specificity
5. TP+TN/(TP+FP+TN+FN) ... Accuracy

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**

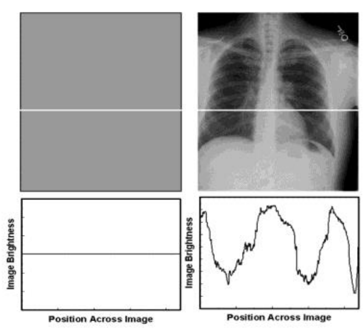


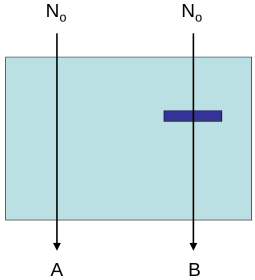
Image with no contrast   Image with contrast

Contrast

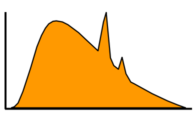
- subject contrast
- detector contrast
- digital contrast

Subject Contrast

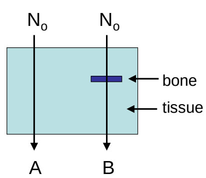
$$C = \frac{A - B}{A}$$

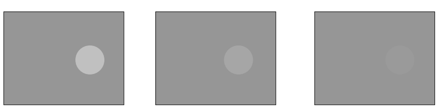


Subject Contrast



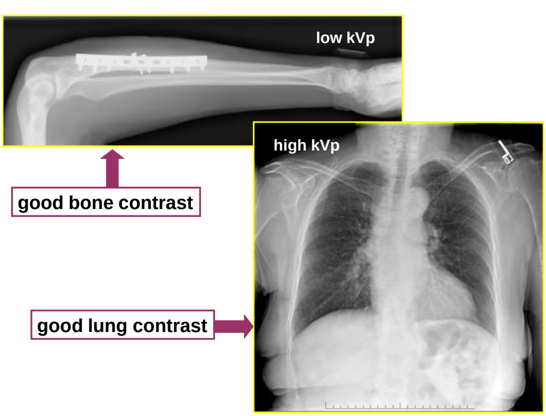
x-ray spectrum





low kVp   med kVp   high kVp

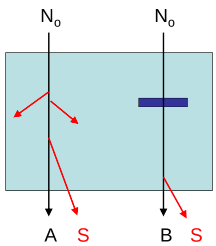
bone contrast example



Subject Contrast

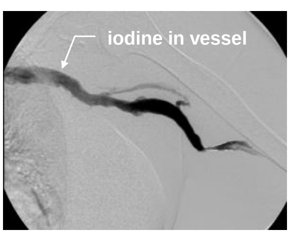
scattered radiation reduces subject contrast

$$C = \frac{A - B}{A + S}$$

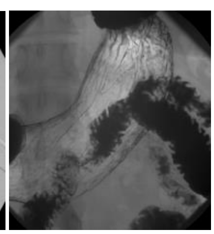


Subject Contrast

contrast agents (obviously) affect contrast



digital subtraction angiography with iodine contrast agent in vessel

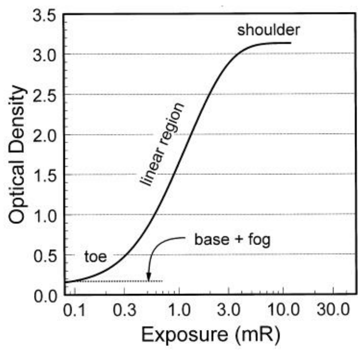


double contrast GI study

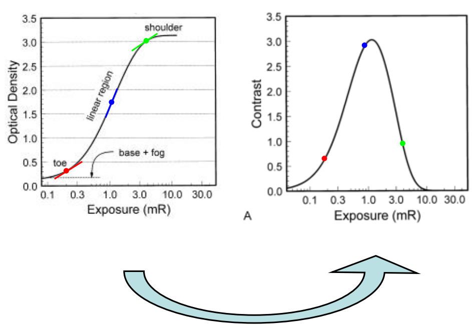
Contrast

- subject contrast
- detector contrast
- digital contrast

Detector contrast (screen film)

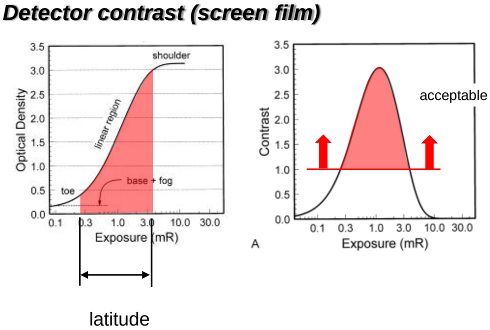


Detector contrast (screen film)

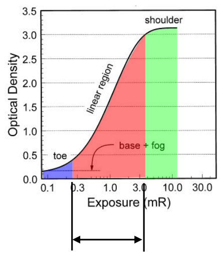


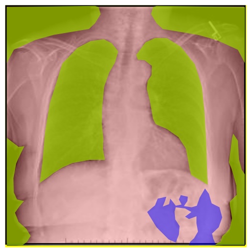
detector contrast is the derivative of the characteristic curve

Detector contrast (screen film)



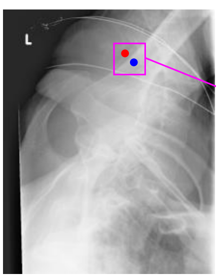
Detector contrast (screen film)

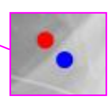




latitude

Radiographic contrast (screen film)





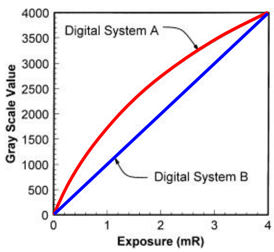
$OD_1 - OD_2$ = radiographic contrast

screen film radiography

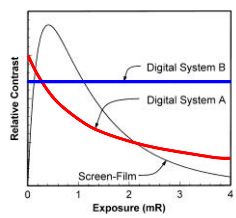
Contrast

- subject contrast
- detector contrast
- digital contrast

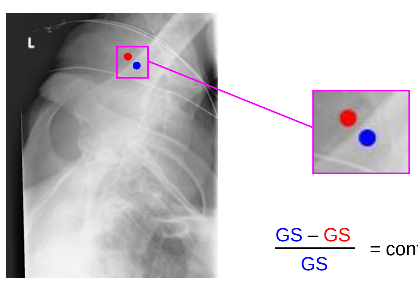
Detector contrast (digital)



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

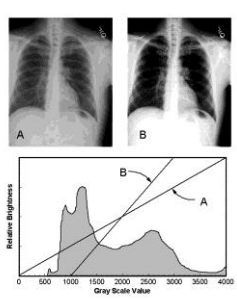


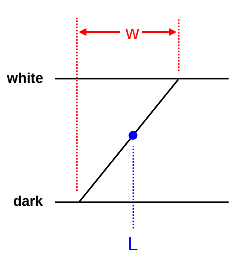
Detector contrast (digital)



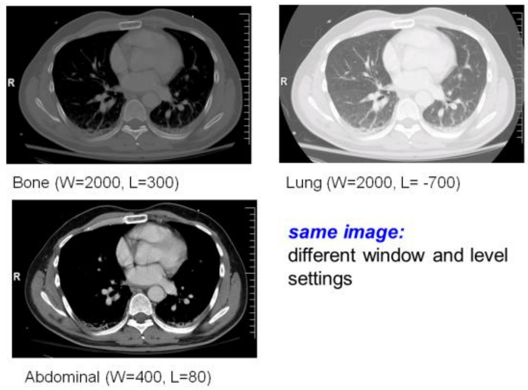
digital radiography

$$\frac{GS - GS}{GS} = \text{contrast}$$





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

Reference: Essential Physics of Medical Imaging, Bushberg, Seibert, Leidholdt, Boone, 3rd Ed. Lippincott Williams & Wilkens, 2012. Chapter 7, Radiography.

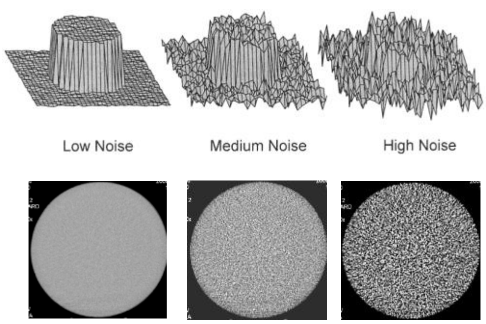
Image Quality

Contrast Resolution — **contrast**, **noise**

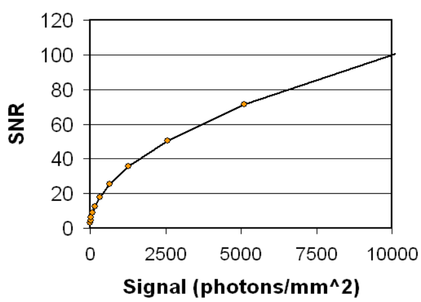
Spatial Resolution — **input functions**, **digital sampling**

Contrast / Detail

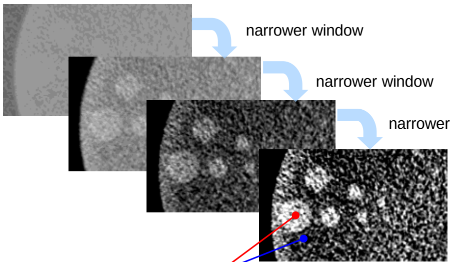
Noise



$$SNR = \frac{\mu}{\sigma} \propto \frac{N}{\sqrt{N}} = \sqrt{N} \qquad \text{Fractional noise} = \frac{1}{\sqrt{N}}$$



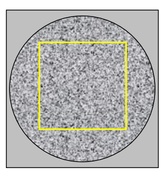
Manipulation of digital detector contrast



screen film ↔ contrast limited

digital images ↔ noise limited

Characterizing image noise



RMS noise (σ)

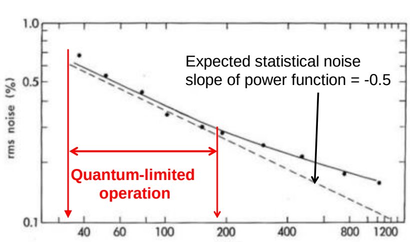
$$\sigma^2 = \frac{\sum_{i=0}^{N}\left(x_i - \bar{x}\right)^2}{N-1}$$

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

$$\sigma = \sqrt{n_q + n_e + n_p + n_a}$$



$$\sigma = \sqrt{n_q + n_e + n_p + n_a}$$

Overall noise dominated by quantum fluctuations over a defined range

<u>What level of noise?</u>
…depends on incident number of photons
efficiency of detection, signal conversion,
and #photons detected / unit volume

Example: variance for
CT image reconstruction

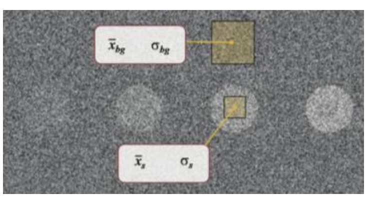
$$\boldsymbol{\sigma^2 \propto \frac{1}{w^2 h\, Q}}$$

w pixel dimension
h slice thickness
Q # photons

Contrast resolution is determined by contrast and noise

Contrast to Noise Ratio (CNR)

$$SNR = \frac{\bar{X}_{bg}}{\sigma_{bg}} \qquad CNR = \frac{(\bar{X}_S - \bar{X}_{bg})}{\sigma_{bg}}$$



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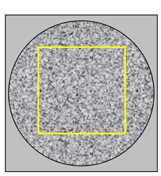
Characterizing image noise

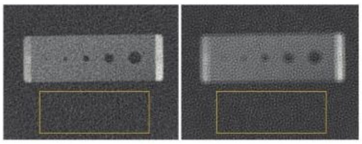
Noise Power Spectrum: NPS(f)



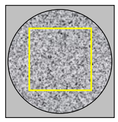
$$NPS(u,v) = \left(\frac{\Delta x\ \Delta y}{XY}\right)\left| \frac{1}{\hat{I}} \int_{-X/2}^{X/2}\int_{-Y/2}^{Y/2} [I(x,y) - \hat{I}]\ e^{-j2\pi(ux+vy)} dx\ dy \right|^2$$

Fourier Transform

Characterizing image noise – noise texture

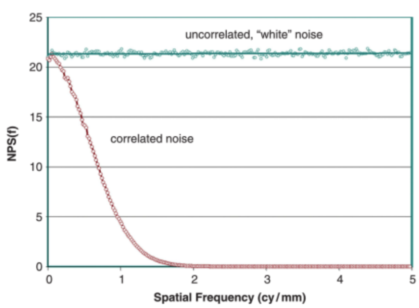


Noise Power Spectrum: NPS(f)



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

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?

10%	1. 10
10%	2. 32
30%	3. 100
23%	4. 320
27%	5. 1000

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 / mm^2 x 10^{-2} mm^2 = 10^4 ; $\sqrt{10^4}$ = 100

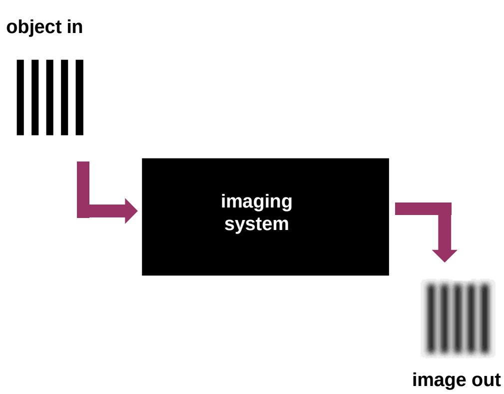
Reference: Essential Physics of Medical Imaging, Bushberg, Seibert, Leidholdt, Boone, 3rd Ed. Lippincott Williams & Wilkens, 2012. Chapter 4, Image Quality

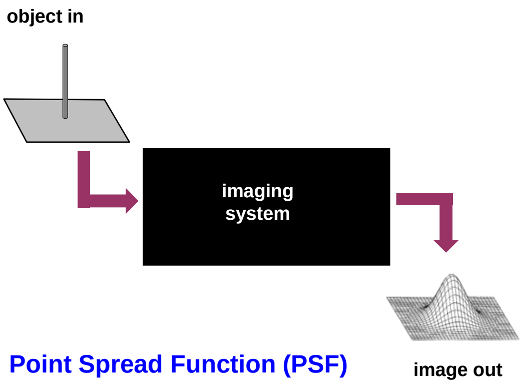
Image Quality

Contrast Resolution — **contrast**, **noise**

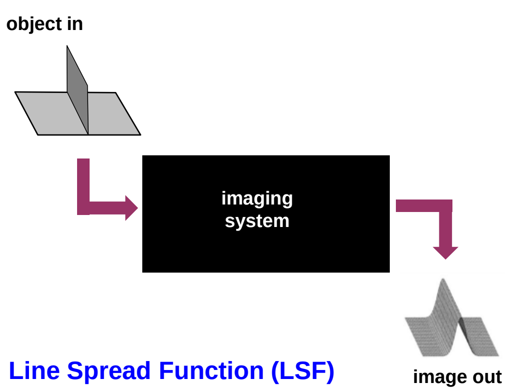
Spatial Resolution — **input functions**, **digital sampling**

Contrast / Detail

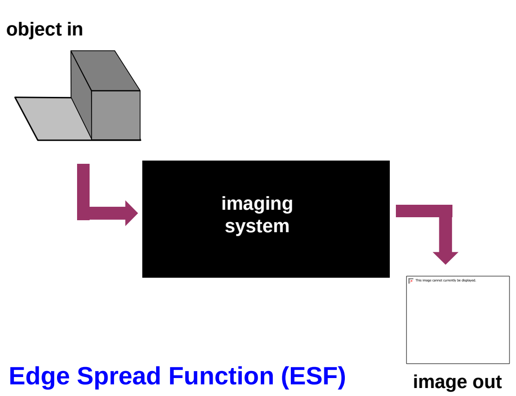




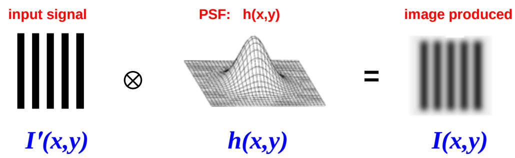
Point Spread Function (PSF)



Line Spread Function (LSF)

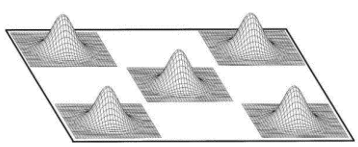


Edge Spread Function (ESF)

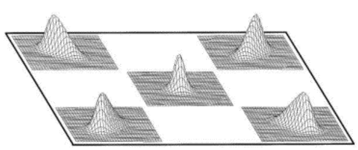


$$I(x,y) = \int_{x'}\int_{y'} I'(x',y') \quad h(x-x', y-y') \quad dx' \quad dy'$$

The convolution integral



stationary



non-stationary

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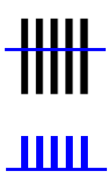
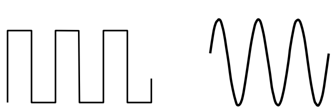


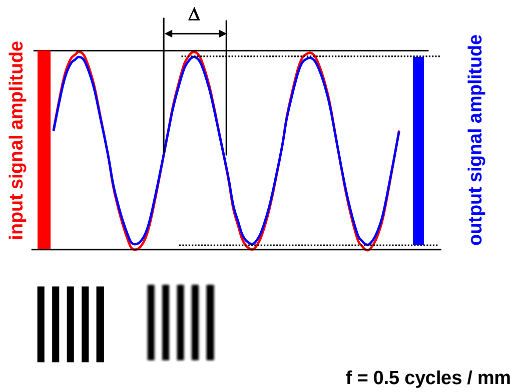
Spatial Frequency

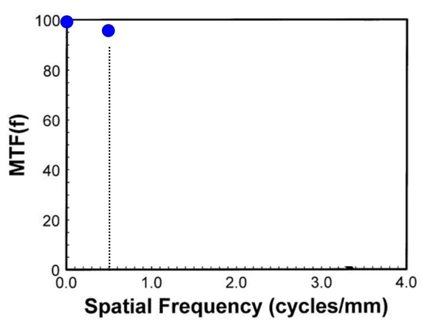
cycle/mm, mm^{-1}

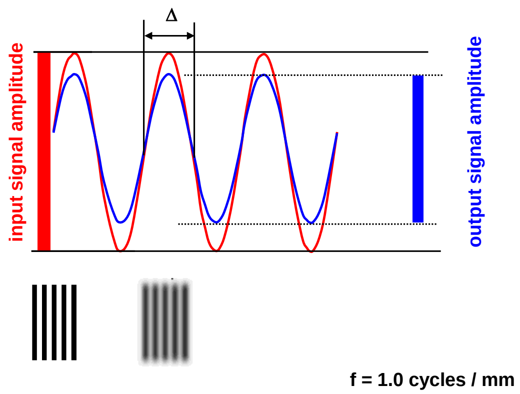
line pair / mm (lp/mm)

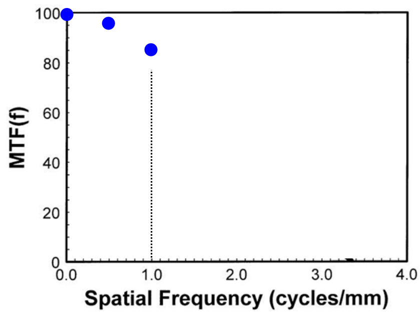


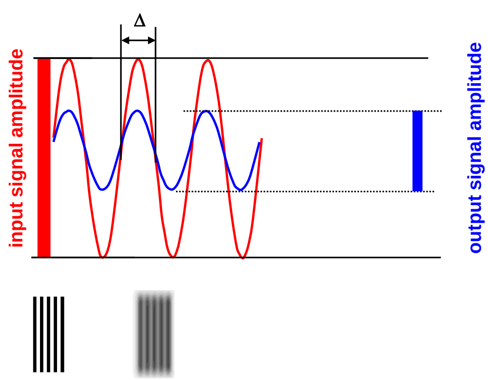
square wave **sine wave**

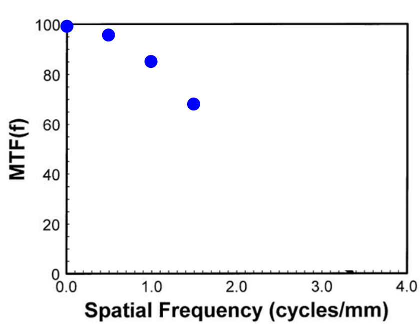

Δ
input signal amplitude
output signal amplitude
f = 0.5 cycles / mm

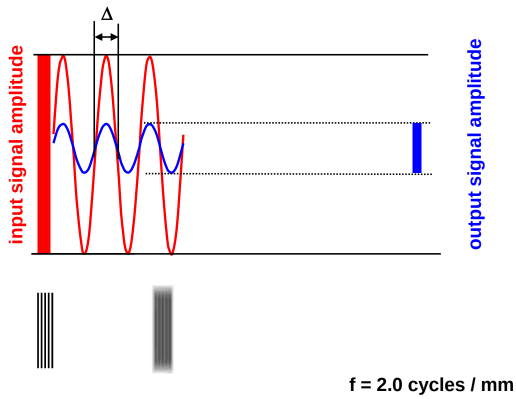

100
80
60
40
20
0
MTF(f)
0.0
1.0
2.0
3.0
4.0
Spatial Frequency (cycles/mm)

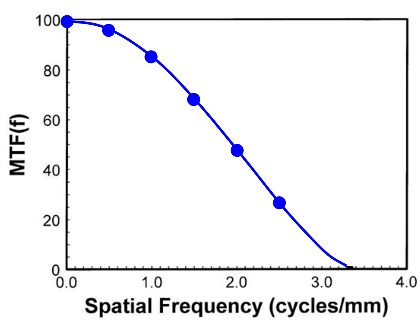

Δ
input signal amplitude
output signal amplitude
f = 1.0 cycles / mm

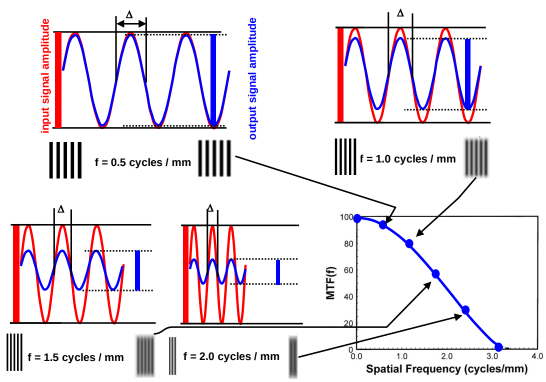

100
80
60
40
20
0
MTF(f)
0.0
1.0
2.0
3.0
4.0
Spatial Frequency (cycles/mm)

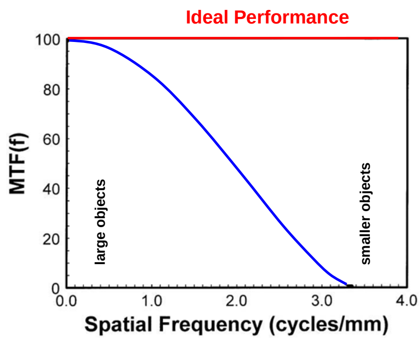

Δ
input signal amplitude
output signal amplitude
f = 1.5 cycles / mm


100
80
60
40
20
0
MTF(f)
0.0
1.0
2.0
3.0
4.0
Spatial Frequency (cycles/mm)

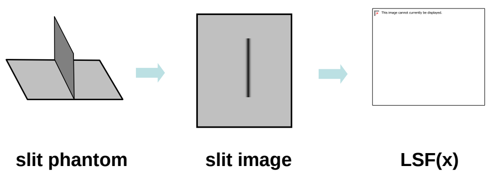

Δ
input signal amplitude
output signal amplitude
f = 2.0 cycles / mm

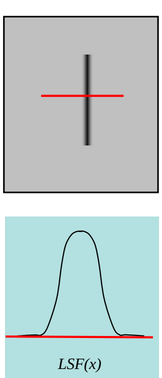

100
80
60
40
20
0
MTF(f)
0.0
1.0
2.0
3.0
4.0
Spatial Frequency (cycles/mm)


input signal amplitude
output signal amplitude
f = 0.5 cycles / mm
f = 1.0 cycles / mm
f = 1.5 cycles / mm
f = 2.0 cycles / mm
MTF(f)
Spatial Frequency (cycles/mm)

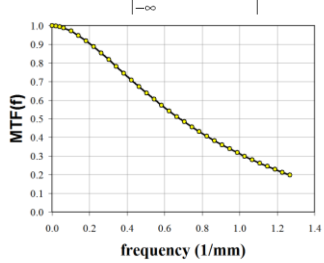


Practical way for measuring the MTF of an imaging system

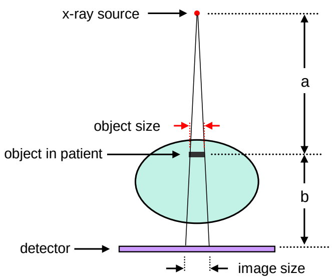




$$MTF(f) = \frac{\left| \int_{-\infty}^{\infty} LSF(x)\, e^{-j2\pi fx}\, dx \right|}{\left| \int_{-\infty}^{\infty} LSF(x)\, dx \right|}$$



Geometry Issues

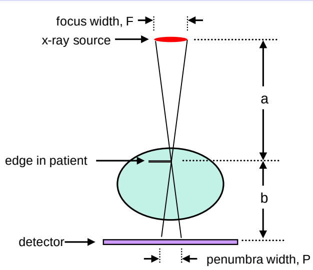


Magnification

M = (a + b)/a

for a point source

Focal spot and geometric magnification



Amount of blur is dependent on magnification

Large focus (1.2 mm)

Small focus (0.6 mm)

$$f_{blur} = \frac{1}{(M-1)FS}$$

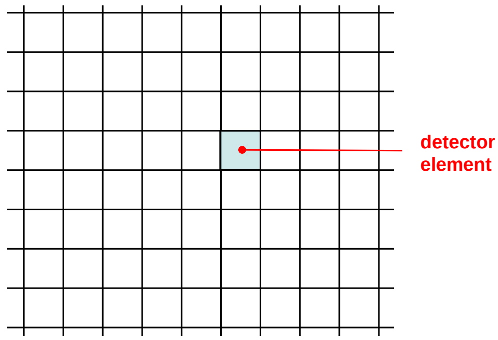
mm⁻¹ … mm

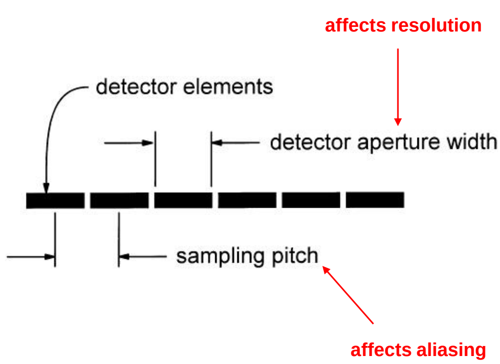
Image Quality

Contrast Resolution — **contrast**, **noise**

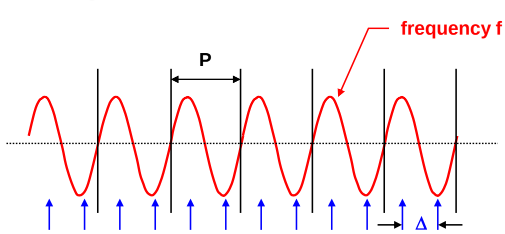
Spatial Resolution — **input functions**, **digital sampling**

Contrast / Detail



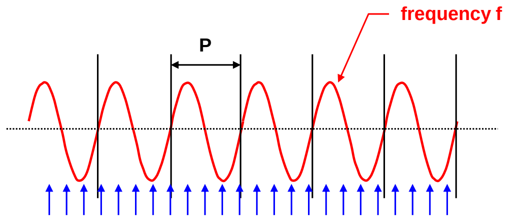


aliasing



Nyquist Criterion: $F = 1 / 2\Delta$

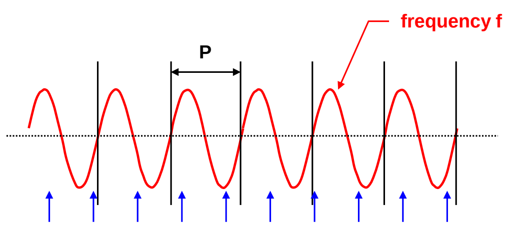
have to sample at least twice per period *aliasing*



Nyquist Criterion

OK to over-sample

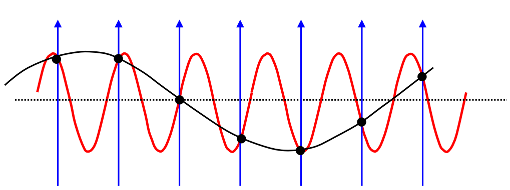
aliasing



Nyquist Criterion

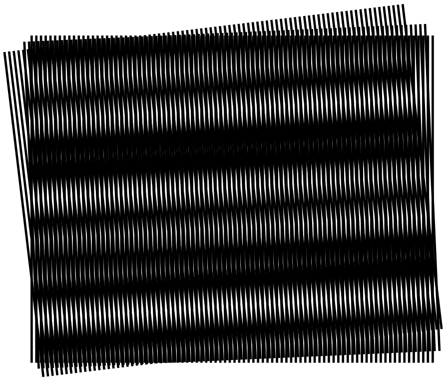
not OK to under-sample

aliasing

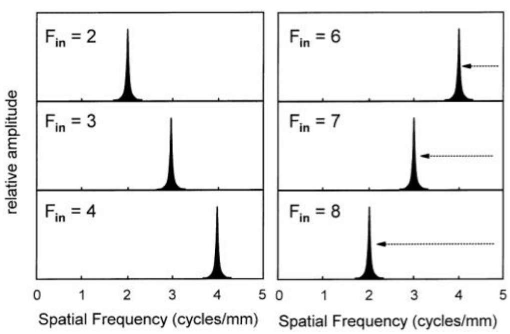


Nyquist Criterion

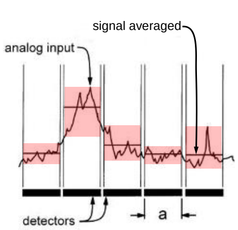
not OK to under-sample

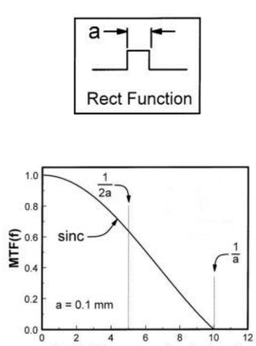


With F_n = 5 cycles / mm (Δ = 0.100 mm)



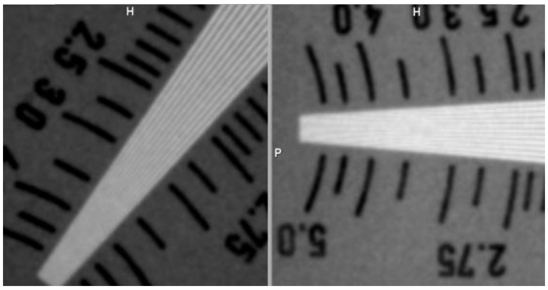
aperture blurring



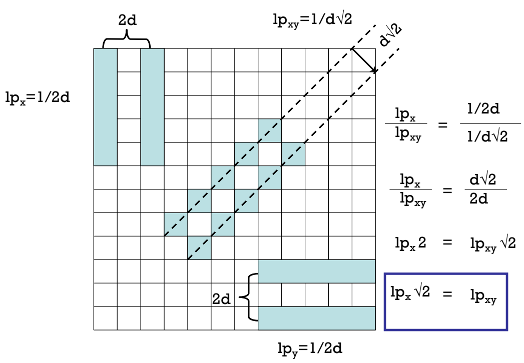


Typical measurement of resolution

Bar phantom analysis and determination of lp/mm



Where d is the del dimension …



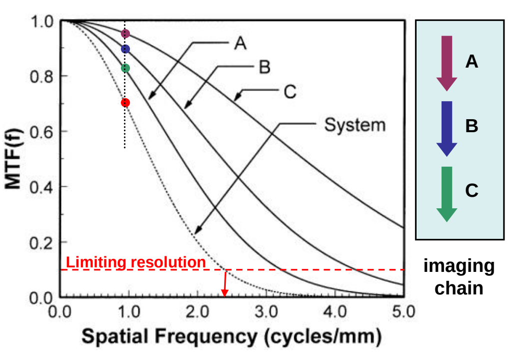
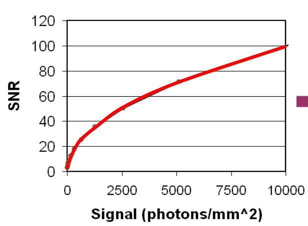


Image Quality

Contrast Resolution
- contrast
- noise

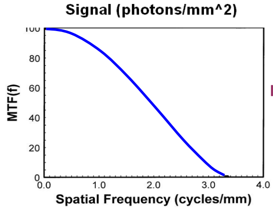
Spatial Resolution
- input functions
- digital sampling

Contrast / Detail



SNR $\propto \sqrt{N}$

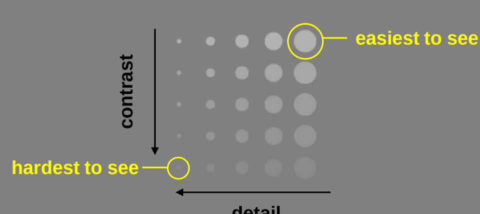
→ contrast resolution



→ spatial resolution

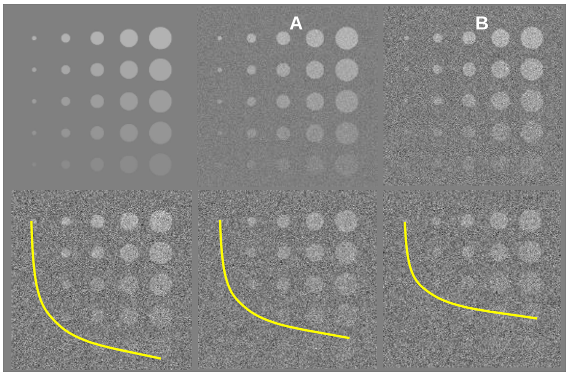
the contrast detail curve

combines the effects of spatial resolution and contrast resolution

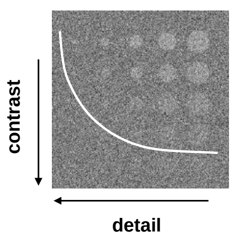


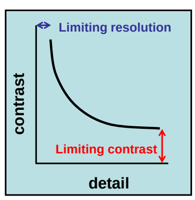
Looking for the "just visible" disks

the contrast detail curve



the contrast detail curve

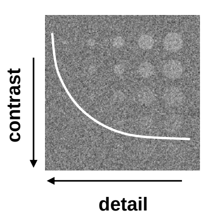




Rose criterion: $\mathrm{SNR} = \dfrac{a\sqrt{A}}{\sigma}$

a = contrast
A = area of object
σ = StdDev noise

"Visibility" requires SNR of at least 3….



mathematical approach to combining contrast & spatial resolution ?

contrast resolution – Noise Power Spectrum (NPS)

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

how an imaging system "passes" noise

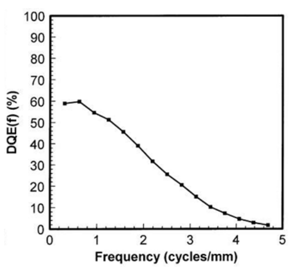
spatial resolution – Modulation Transfer Function (MTF)

$$MTF(f) = \frac{\int_{-\infty}^{\infty} LSF(x)\ e^{-2\pi i f x}\ dx}{\int_{-\infty}^{\infty} LSF(x)\ dx}$$

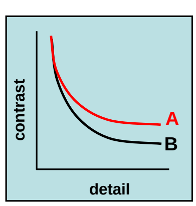
how an imaging system "passes" signal

DQE: Information recording & retrieval efficiency

$$DQE(f) = \frac{SNR^2(f)_{out}}{SNR^2(f)_{in}} = \frac{MTF^2(f)}{\phi\ \ NPS(f)}$$



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

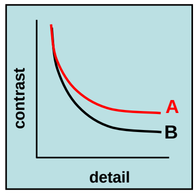
23% 3. Image B is acquired with more mAs

13% 4. Image B is acquired with more filtration

23% 5. Image B is unchanged.

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?

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



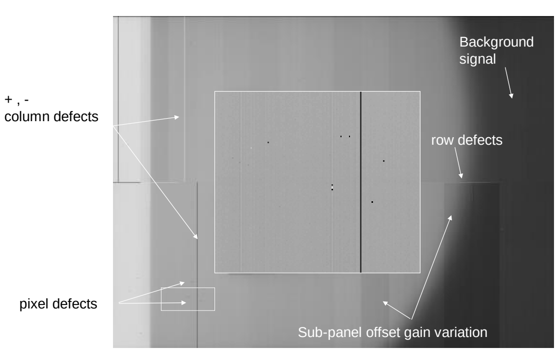
1. Image B is processed with a spatial blurring filter
2. Image B is processed with a spatial sharpening filter
3. Image B is acquired with more mAs ✓
4. Image B is acquired with more tube filtration
5. Image B is unchanged.

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

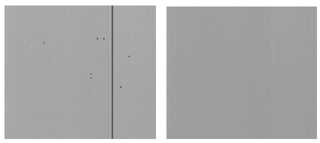
Pixel and column defects

Identify location of pixel defects:

Interpolate bi-linearly
(4 nearest neighbors)

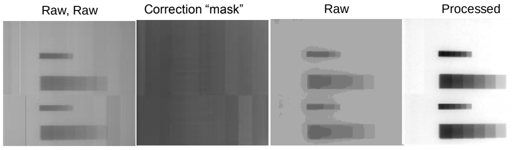
Column, row defects:

Interpolate linearly
(2 surrounding neighbors)



Example "raw" image & flat-field

Raw, Raw	Correction "mask"	"For Processing" (original) Raw	"For Presentation" (presentation) Processed

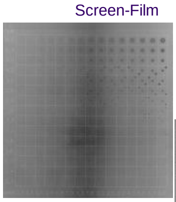


Background variations Column, line defects "Del" dropouts	Avg, inverted background Column, line, pixel repair Normalized values	Pre-processed image Image pixel value to exposure relationship?	Contrast, resolution enhancement; proprietary processing

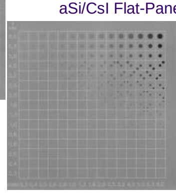
Flat-field pre-processing

125 kVp
2 mAs

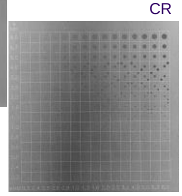
Screen-Film



aSi/CsI Flat-Panel



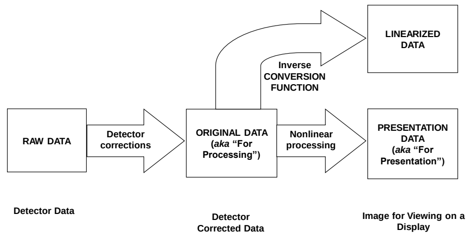
CR



Low contrast resolution ↑

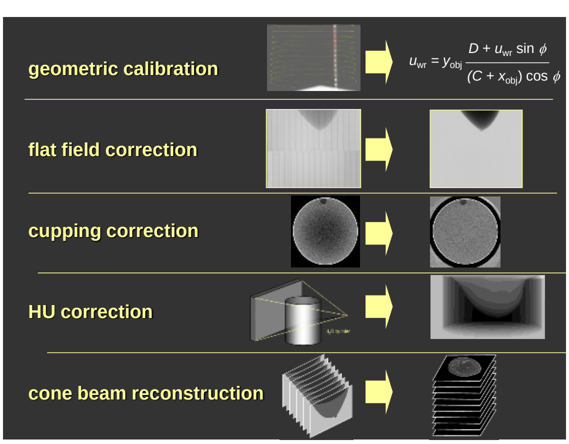
MDACC: Chris Shaw, et al

MITA Industry Definitions for Image Data States

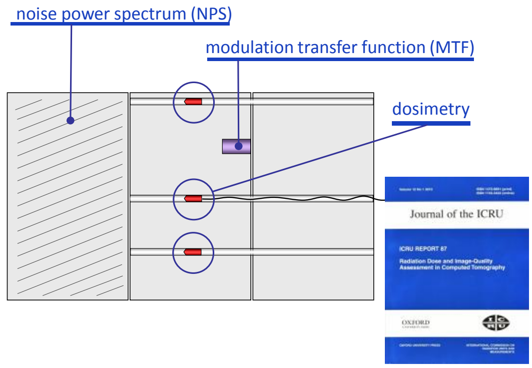


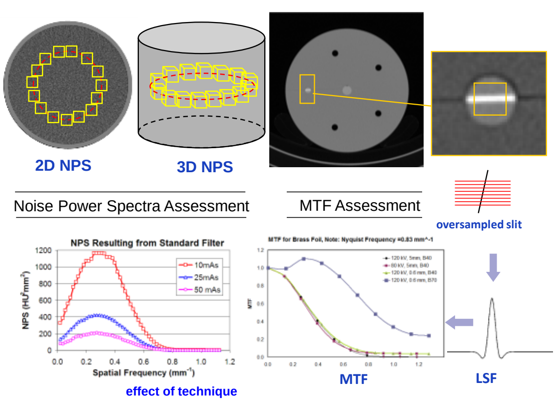
CBCT issues

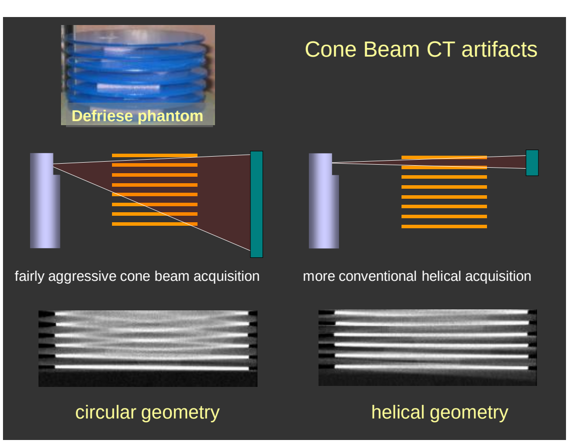
- Large area detector
- Geometric rotation accuracy
- Diverging radiation beam along z-axis
- X-ray scatter and beam uniformity
- HU accuracy and percent noise
- Cone beam reconstruction artifacts
- Radiation dose measurements

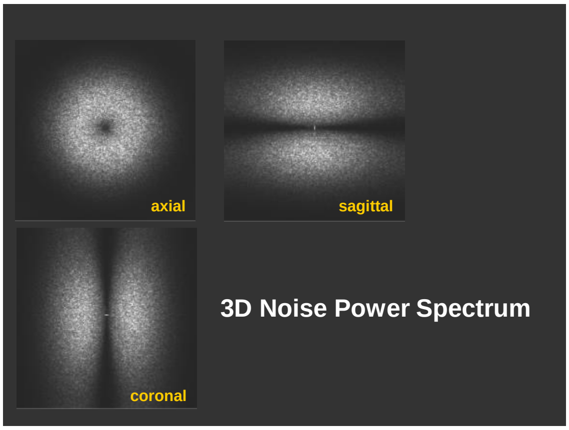


An Integrated CT Image Quality / Dosimetry Phantom

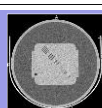
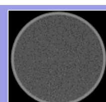
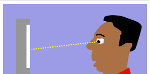








CT image quality evaluation

	Old Era	New Era
phantom	 complicated	 basic
analysis	 simple	$MTF(f) = \frac{\int_{-\infty}^{\infty} LSF(x)\, e^{-2\pi i f x}\, dx}{\int_{-\infty}^{\infty} LSF(x)\, dx}$ more sophisticated
results	clinically useful	useful & quantitative

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

- #14: X-ray generators (1985)
- #25: X-ray survey (1988)
- #74: General x-ray QC (2002)
- #93: CR testing & QC (2006)
- #116: DR Exposure (2009)
- #150: DR detector (IP)
- #151: DR clinical QC (IP)

Applications for CT

- #39: CT testing QC (1993)
- #96: CT dosimetry (2008)
- #111: Future of CT dose (2010)
- #204: SSDE (2011)
- #200: CT Phantoms (IP)
- #220: CT Patient size (IP)
- #233: CT Perf Evaluation (IP)
- #246: CT Patient Dose (IP)

Applications for therapy IGRT

- #104: kV imaging (2009)
- #142: Med Accel QC (2009)
- #179: IGRT systems (2012)
- ACR–AAPM Technical Std for Perf Monitoring of IGRT (2014)

AAPM Report 179

Modes of acquisition
Flat panel detector

- **Projection Imaging**
- **Cone beam CT**

QC Test	AAPM 179
Safety system	Daily
IQ: Uniformity	Monthly / Semi-annual
IQ: Image density	Optional monthly
IQ: Noise	Monthly / Semi-annual
IQ: Contrast detail	Monthly / Semi-annual
IQ: Resolution	Monthly / Semi-annual
Geometry: isocenter	Daily
Geometry: 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?

20%	1. Image Uniformity
13%	2. Spatial Resolution
27%	3. Noise Distribution
27%	4. Contrast Detail
13%	5. Isocenter Verification

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. Signal/Noise Ratio
4. Contrast Detail
5. ✓ Isocenter Accuracy

Reference: Quality assurance for image-guided radiation therapy utilizing CT-based technologies: A report of the AAPM TG-179. Med. Phys. 39 (4), April 2012. Available at aapm.org/pubs/reports/RPT_179

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