Tradeoffs in Image Quality and Radiation Dose for CT

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Image Quality

- Image quality has many components and is influenced by many technical parameters.
- While image quality has always been a concern for the physics community, *clinically acceptable* image quality has become even more of an issue as strategies to reduce radiation dose – especially to pediatric patients– become a larger focus.

Purpose of This Presentation

- Describe several (not all) of the components of CT image quality:
  - noise
  - slice thickness (Z-axis resolution)
  - low contrast resolution
  - high contrast resolution
- Then describe how each of these may be affected by technical parameter selection.
- Paying particular attention to the *tradeoffs* that exist between different aspects of image quality
- Especially when the reduction of radiation dose is one of the objectives.

Components of CT image quality

- Noise
- Slice thickness (Z-axis resolution)
- Low contrast resolution
- High contrast resolution

Noise – Part 1

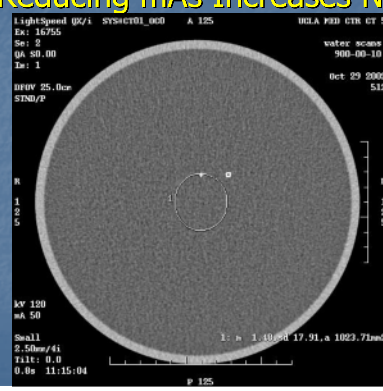
- In its *simplest* definition
  - is the measured standard deviation of voxel values in a homogenous (typically water) phantom
- Influenced by many parameters:
  - kVp
  - mA
  - Exposure time
  - Collimation/Reconstructed Slice Thickness
  - Reconstruction algorithm
  - Helical Pitch/Table speed
  - Helical Interpolation Algorithm
  - Others (Focal spot to isocenter distance, detector efficiency, etc.)

Reducing mAs Increases Noise

- Noise $\propto \dfrac{1}{\sqrt{mAs}}$
- If mAs is reduced by ½,
  - noise increases by √2 =1.414 →(40% increase)

Reducing mAs Increases Noise

Reducing mAs Increases Noise



Slice Thickness (Z-axis Resolution)

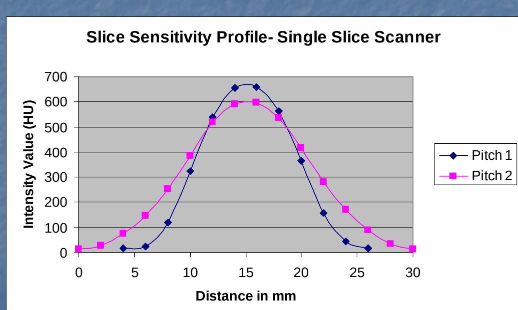
- Reconstructed slice thickness has become more complex when going from axial to helical to multidetector helical scanning.
- This discussion focuses only on the reconstructed slice width in helical scanning and the factors that *may* influence it, which include:
  - X-ray Beam Collimation (single slice scanners)
  - Detector Width (multidetector scanners)
  - Pitch/Table speed*
  - Interpolation Algorithm*

*Note: For some manufacturers' multidetector scanners, the reconstructed slice thickness is *independent* of table speed because of the interpolation algorithm used. Hence, these last two items are tightly linked.

Slice Thickness – Single Detector

- For single detector helical scanners using either the 180 LI or 360 LI interpolation algorithm, higher pitch scans produced larger effective slice thicknesses.
  - 180 LI
    - Pitch 1.5, FWHM increased 10-15% over FWHM at pitch=1.0
    - Pitch 2.0, FWHM increased 30% over FWHM at pitch 1.0

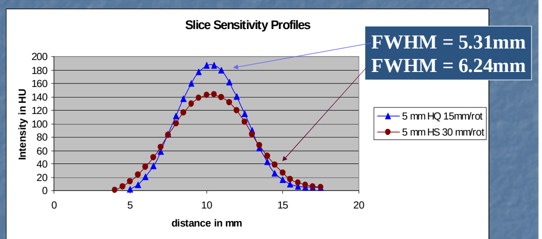
Slice Thickness – Single Detector



Slice Thickness (Z-axis Resolution)

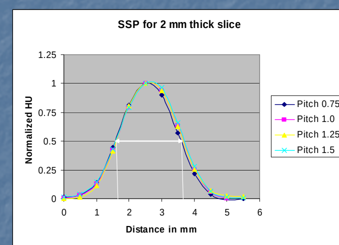
- Multidetector helical scanners, these trends are not quite so clear
  - Ability to interpolate data collected from multiple detectors
  - Different interpolation algorithms available

Slice Thickness (Z-axis Resolution)



Differences in Slice Sensitivity Profile due to differences in table speed in a Multidetector CT scanner (GE LightSpeed Qx/I)

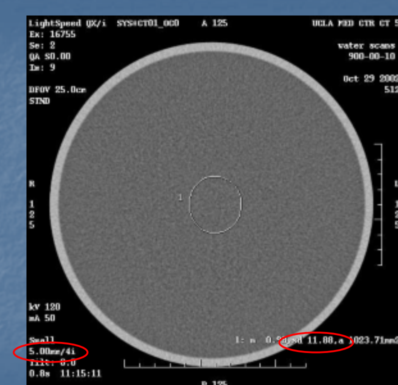
Slice Thickness (Z-axis Resolution)

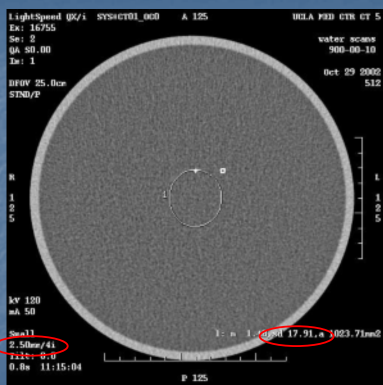


No Differences in Slice Sensitivity Profile due to different table speed in a Multidetector CT scanner (Siemens Sensation 16)

Slice Thickness (Z-axis Resolution)

- However, increasing z-axis resolution by reducing slice thickness results in a TRADEOFF with increased noise and possibly dose
  - Increase in z-axis resolution vs. Increase in Noise
- Implication for dose- 1
  - Going to thinner slices increases noise
  - This may tempt user to increasing mAs,
  - Which would increase dose
- Implication for dose- 2
  - Thinner beam collimations *may* have higher dose (shown later)





Indirect effects on dose

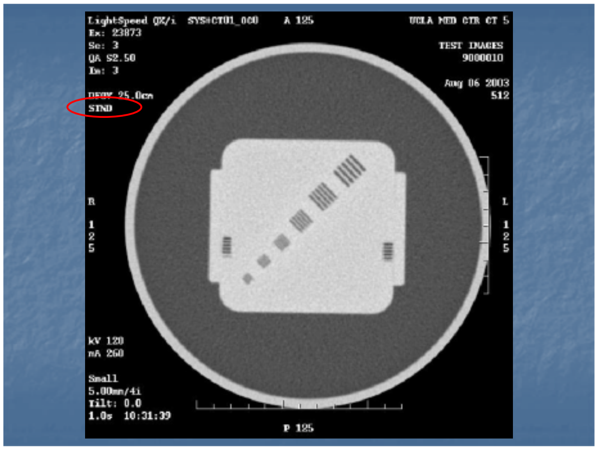
- To compensate for increased noise, we may increase mAs to get back to **noise levels equivalent to original**

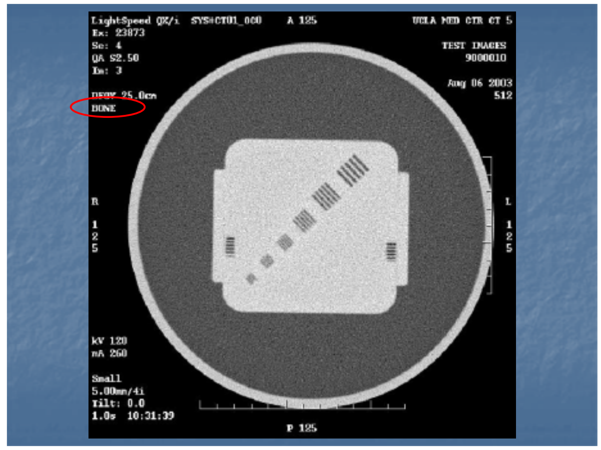
High Contrast (Spatial) Resolution

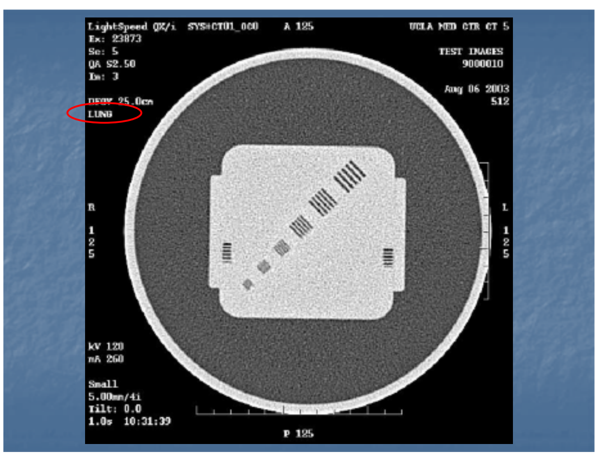
- High contrast or spatial resolution within the scan plan - determined using objects having a large signal to noise ratio.
- This test measures the system's ability to resolve high contrast objects of increasingly smaller sizes (increasing spatial frequencies).
- Several quantitative methods have been described
  - E.g. MTF using a thin wire

High Contrast (Spatial) Resolution

- High contrast spatial resolution is influenced by factors including:
  - System geometric resolution limits
    - focal spot size
    - detector width
    - ray sampling,
  - Pixel size
  - Properties of the convolution kernel /mathematical reconstruction filter







High Contrast (Spatial) Resolution

- However, increasing x-y plane resolution by via reconstruction algorithm can result in a TRADEOFF with a nominal increase (certainly a change) in noise
  - Increase in x-y plane resolution vs. Change in Noise

Low Contrast Resolution

- Low contrast resolution is often determined using objects having a very small difference from background (typically from 4-10 HU difference).
-
- Because the signal (the difference between object and background) is so small, noise is a significant factor in this test.

Low Contrast Resolution

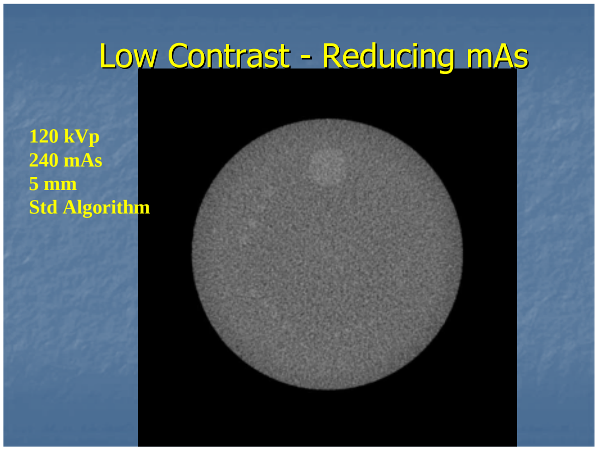
- This test measures the system's ability to resolve low contrast objects of increasingly smaller sizes (increasing spatial frequencies).
- Influenced by many of the same parameters as noise

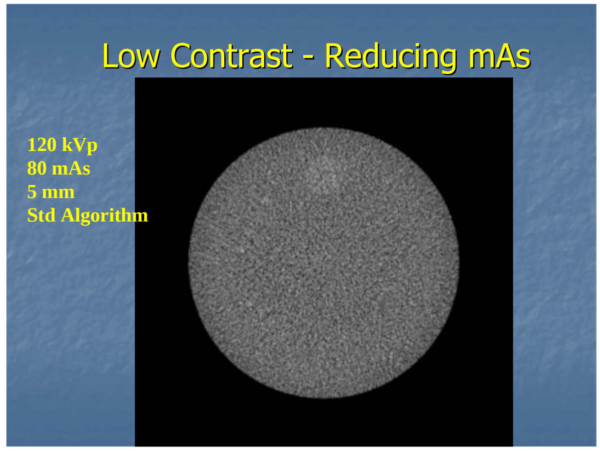
Low Contrast Resolution

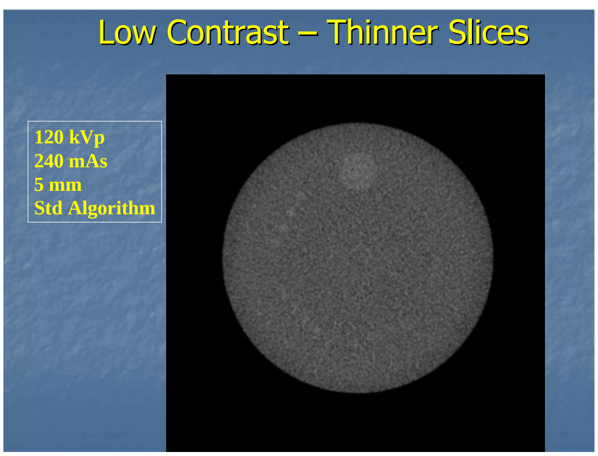
- An example of a low contrast resolution phantom is that in used by the ACR CT Accreditation program.
- This phantom consists of:
  - A single 25mm rod for reference and measurements,
  - Sets of 4 rods, each is decreasing in diameter from:
    - 6mm,
    - 5mm,
    - 4mm
    - 3mm
    - 2mm (typically not visible unless a very, very high technique is used).
  - All approximately 6 HU from background

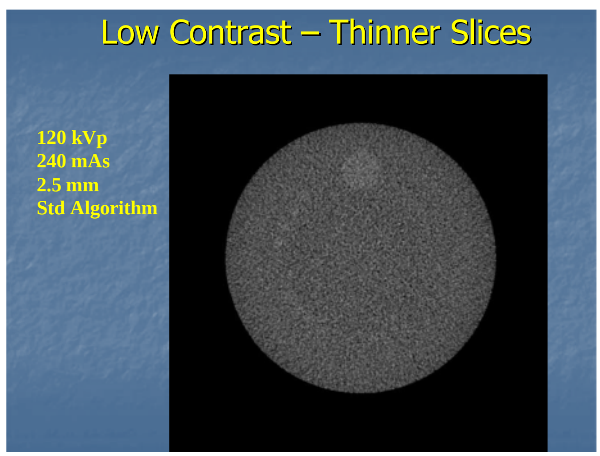
Low Contrast Resolution

Noise can influence low contrast resolution


Low Contrast - Reducing mAs
120 kVp
240 mAs
5 mm
Std Algorithm


Low Contrast - Reducing mAs
120 kVp
80 mAs
5 mm
Std Algorithm


Low Contrast – Thinner Slices
120 kVp
240 mAs
5 mm
Std Algorithm


Low Contrast – Thinner Slices
120 kVp
240 mAs
2.5 mm
Std Algorithm

Reducing Radiation Dose in CT: Implications for Image Quality

- Several mechanisms to reduce dose in CT exams.
- Each has implications for diagnostic image quality
- Examine phantoms and clinical images

Reducing Radiation Dose

- From FDA Notice dated 11-2-01
  - http://www.fda.gov/cdrh/safety.html
- For Pediatric and Small Adult Patients
  - Reduce tube current (mA)
  - Increase table increment (axial) or pitch
  - Develop mA settings based on patient weight (or diameter) and body region
  - Reduce number of multiple scans w/contrast
  - Eliminate inappropriate referrals for CT

What Parameters Influence Dose?

- kVp
- mA and scan time (mAs)
- Pitch (Table Speed)
- Collimation (?)
- Dose Reduction Options
- Scanner make, model
- Indirect Effects of Algorithm and Collimation

Beam Energy - kVp

kVp	$CTDI_w$-Head	$CTDI_w$- Body
80	14 mGy	5.8 mGy
100	26 mGy	11 mGy
120	**40 mGy**	**18 mGy**
140	55 mGy	25 mGy

(Other factors constant at 300 mA, 1 s, 10 mm)

- **Dose DECREASES w/ decreased kVp**
- **Nearly 40% going from 140 to 120 kVp**

Beam Energy – kVp Implication for Image Quality

- However, reducing beam energy ALONE:
  - Will increase noise
    - May have to increase mAs to get acceptable noise, which offsets some of dose savings
  - May increase signal contrast for some tissues and iodine (High Z) due to increased photoelectric
  - May significantly increase beam hardening artifact if beam energy gets too low (e.g. 80 kVp)

mA* time (mAs)

mAs	$CTDI_w$-Head	$CTDI_w$- Body
100	13 mGy	5.7 mGy
200	26 mGy	12 mGy
300	**40 mGy**	**18 mGy**
400	53 mGy	23 mGy

(All other factors constant at 120 kVp, 10 mm)

- **Dose DECREASES Linearly with mAs**

mA* time (mAs) Implication for Image Quality

Increased Noise

Pitch, Table Speed (Helical Scans)

- $CTDI_{vol} \propto 1/P$
  - P =2 50% of dose at P=1
  - P =1.5 67% of dose at P=1
  - P =0.75 133% of dose at P=1
  - (When all other factors are held constant)

Pitch, Table Speed (Helical Scans) Implication for Image Quality

- Increasing Pitch:
  - Increases Effective Slice thickness
    - In ALL Single Detector CT
    - In some MultiDetector CT
    - Increased Volume Averaging
  - Increased Helical Artifact

NOTE:

- Some manufacturers (e.g. Siemens and Philips) use
  - "effective mAs" or "mAs/slice", which is = $\frac{mA*time}{pitch}$
  - AND when pitch is increased,
  - **mA*time is increased proportionately**
  - **To keep "effective mAs" constant**
- Any dose savings anticipated from increasing pitch are not realized because mA*time is increased.

Collimation- Single Detector

mm	$CTDI_w$-Head	$CTDI_w$- Body
1	45 mGy	19 mGy
3	41 mGy	18 mGy
5	40 mGy	18 mGy
7	40 mGy	18 mGy
10	40 mGy	18 mGy

(Other factors constant at 120 kVp, 300 mA, 1 s)

- **$CTDI_w$ approx. independent of collimation**
  - **except very thin slices**

Collimation - MultiDetector

Beam Collimation	$CTDI_w$-Head	$CTDI_w$- Body
1x5	60 mGy	26 mGy
2x5	46 mGy	20 mGy
4x5	40 mGy	18 mGy

(Other factors constant at 120 kVp, 300 mA, 0.8 s)

- **$CTDI_w$ MAY CHANGE w/ beam collimation**
  - **again, higher at narrower beam collimation**

Collimation - Implications for Image Quality

- Reducing Collimation :
  - Increases Z-axis Resolution
  - Increases Noise
  - May increase Dose for some scanners

Applications to Imaging Tasks

- High Noise Task (Can Tolerate Noise)
  - Lung Nodule Detection
  - Coronary Calcium Detection
- Low Noise Task (Cannot Tolerate Noise)
  - Abdominal Scans
  - Diffuse Lung Dz
- Medium Noise Task
  - Brain
  - Peds Abdomen, Chest

We can always lower Radiation dose…. Can Radiation Dose be too low?

- If we lower the radiation dose so low that the Dx task cannot be accomplished
- But we would like to lower it JUST to the level where it can be accomplished
- How to know where that threshold is?

Summary

- Many methods to reduce radiation dose
- Each has Image Quality implications
  - Increased noise
  - Slice broadening
  - Increased artifacts, etc.
- Appropriate tradeoffs MAY be Diagnostic Exam/Task Dependent
  - What are requirements of imaging exam?
  - How to establish those requirements?

Current/Future Questions

- Dose Reduction Technologies
- Impacts of tube current modulation on noise
  - Should reduce dose but maintain noise
  - How to assess in the field? How to assess the dose reduction? How to ensure the noise is maintained?