Tradeoffs in CT Image Quality and Radiation Dose

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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

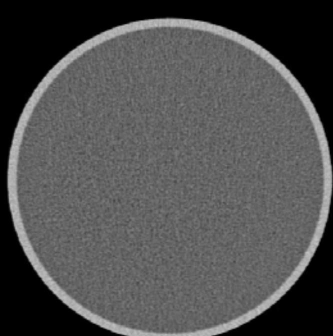
- In its *simplest* definition
  - is the measured standard deviation of voxel values in a homogenous (typically water) phantom
- Influenced by many parameters:
  - kVp
  - mA
  - Exposure time
  - Collimation/Reconstructed Slice Thickness
  - Reconstruction algorithm
  - Helical Pitch/Table speed
 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

Reducing mAs Increases Noise

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

Reducing mAs Increases Noise

120 kVp
40 mAs
2.5 mm
Std Alg



Reducing mAs Increases Noise

Slice Thickness (Z-axis Resolution)

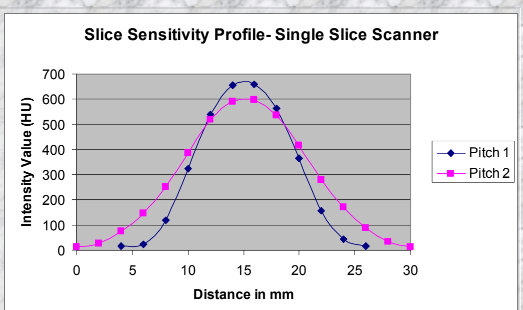
- Reconstructed slice thickness has become more complex when going from axial to helical to multidetector helical scanning.
- This discussion focuses only on the reconstructed slice width in helical scanning and the factors that *may* influence it, which include:
  - X-ray Beam Collimation (single slice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

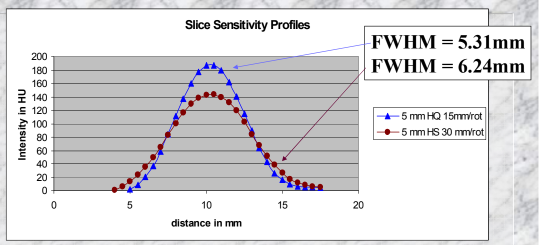
Slice Thickness – Single Detector



Slice Thickness (Z-axis Resolution)

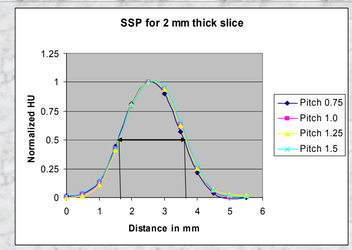
- Multidetector helical scanners, these trends are not quite so clear
  - Ability to interpolate data collected from multiple detectors
  - Different interpolation algorithms available

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)

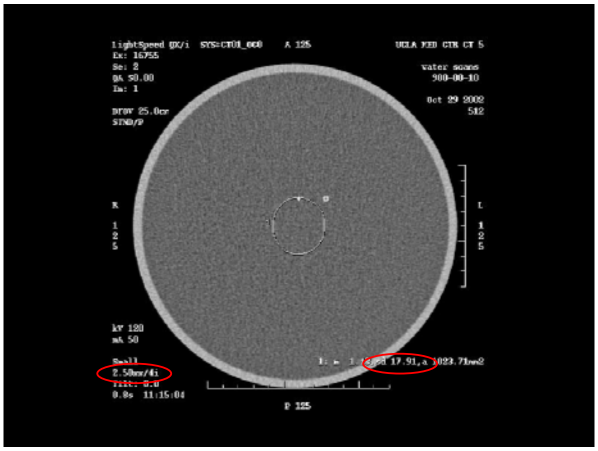
Slice Thickness (Z-axis Resolution)



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

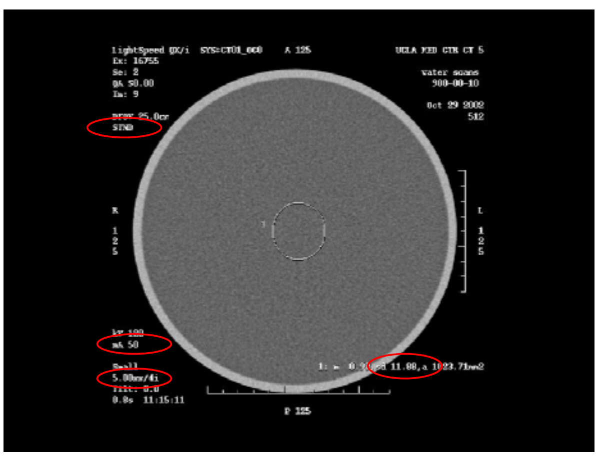
Slice Thickness (Z-axis Resolution)

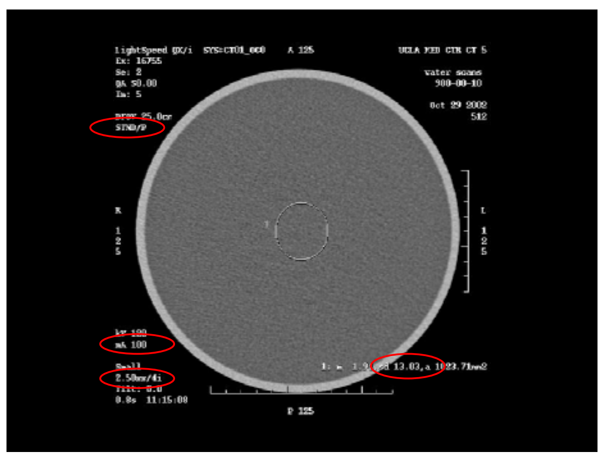
- However, increasing z-axis resolution by reducing slice thickness results in a TRADEOFF with increased noise and possibly dose
  - Increase in z-axis resolution vs. Increase in Noise
- Implication for dose- 1
  - Going to thinner slices increases noise
  - This may tempt user to increasing mAs,
  - 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**





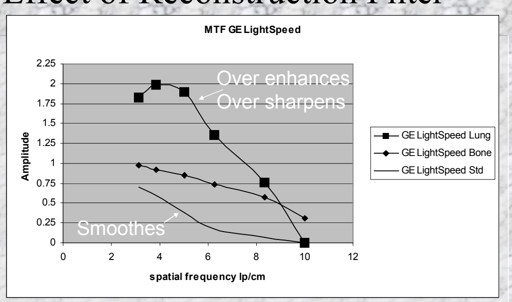
High Contrast (Spatial) Resolution

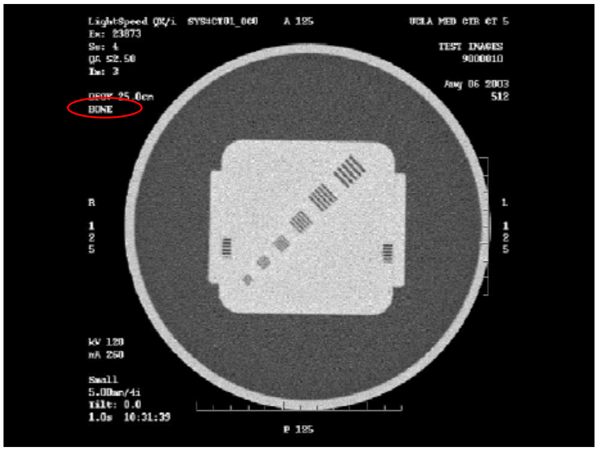
- High contrast or spatial resolution within the scan plan - determined using objects having a large signal to noise ratio.
- This test measures the system's ability to resolve high contrast objects of increasingly smaller sizes (increasing spatial frequencies).
- Several quantitative methods have been described
  - Scanning a wire to calculate the modulation transfer function – MTF
  - Scanning a bar pattern phantom to calculate MTF using the Droege-Morin approach)

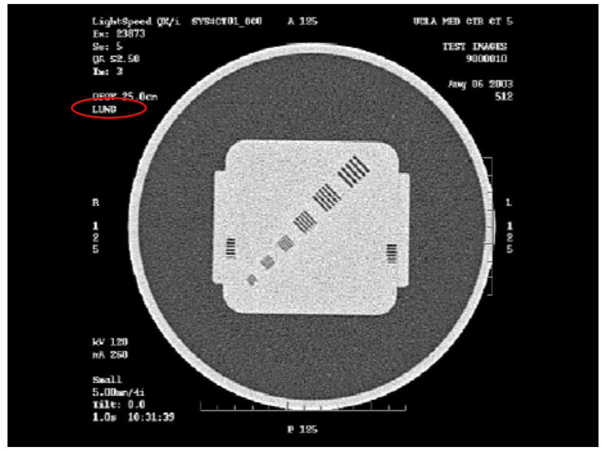
High Contrast (Spatial) Resolution

- 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

Effect of Reconstruction Filter




LightSpeed QX/i SYS#CT01_060 A 125
UCLA MED CTR CT 5
Ex: 23873
Se: 4
QA 52.50
Im: 3
TEST IMAGES
9000010
Aug 06 2003
512
DFOV 25.0cm
BONE
R
L
kV 120
mA 260
Small
5.00mm/4i
Tilt: 0.0
1.0s 10:31:39
P 125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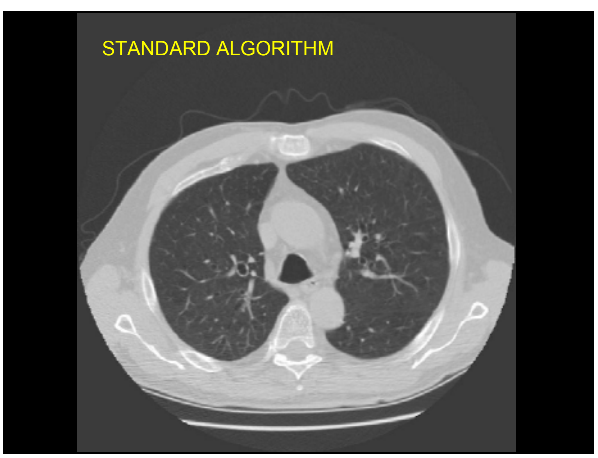
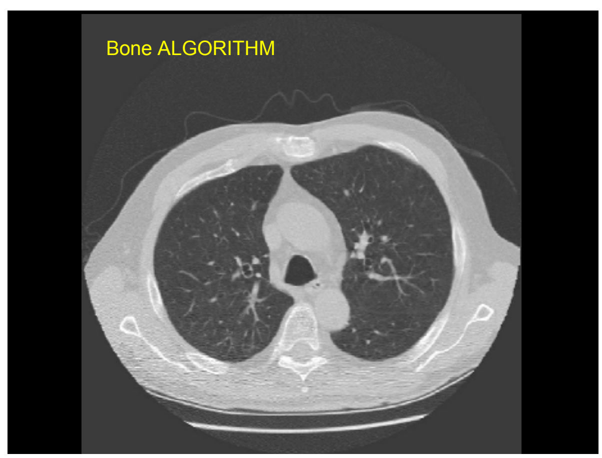
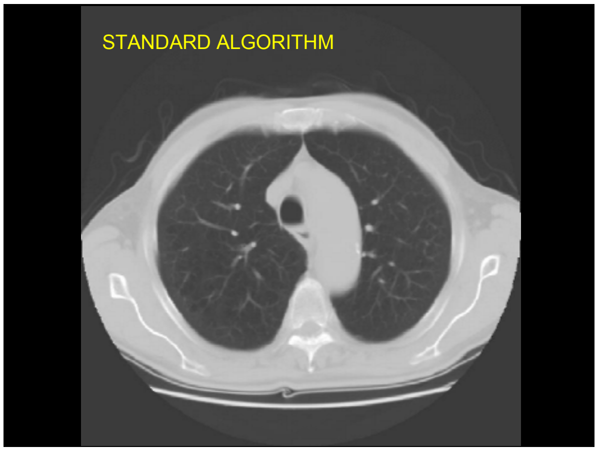
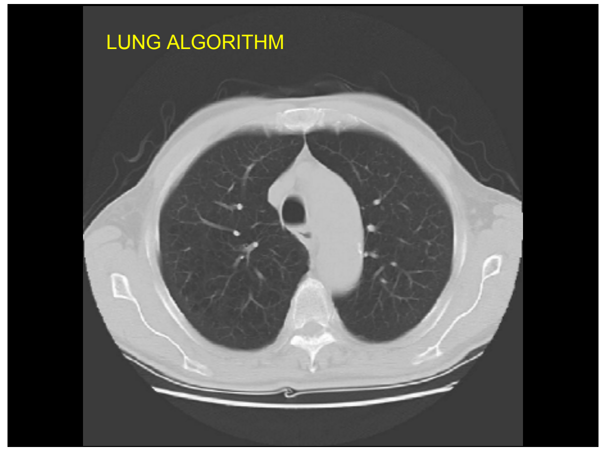

STANDARD ALGORITHM


Bone ALGORITHM



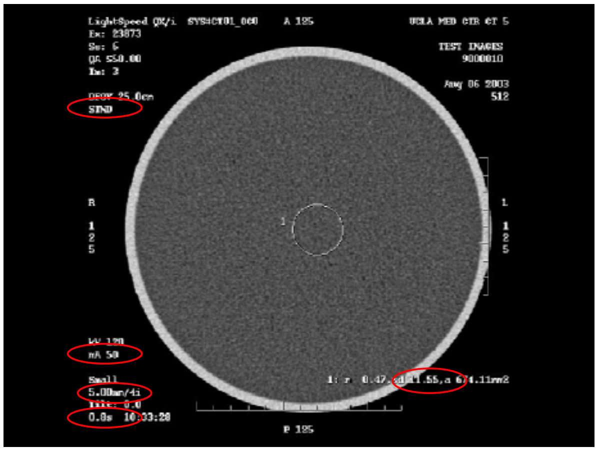


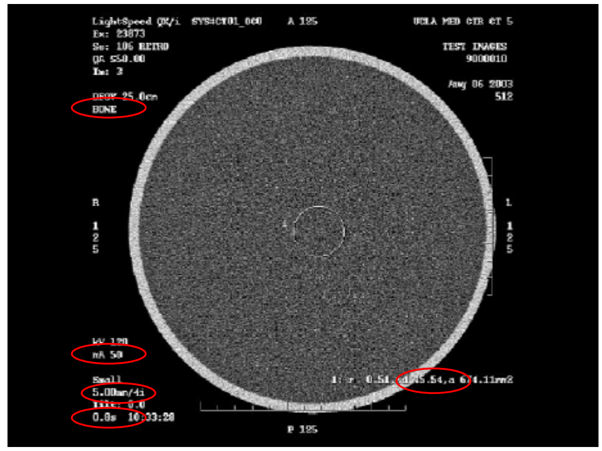
High Contrast (Spatial) Resolution

- 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

Noise – Part 2

- Standard deviation does not tell the whole story


LightSpeed QX/i
UCLA MED CTR CT 5
TEST IMAGES
Aug 06 2003
DFOV 25.0cm
STND
kV 120
mA 50
5.00mm/4i
0.8s 10:33:28
P 125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TEST IMAGES
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DFOV 25.0cm
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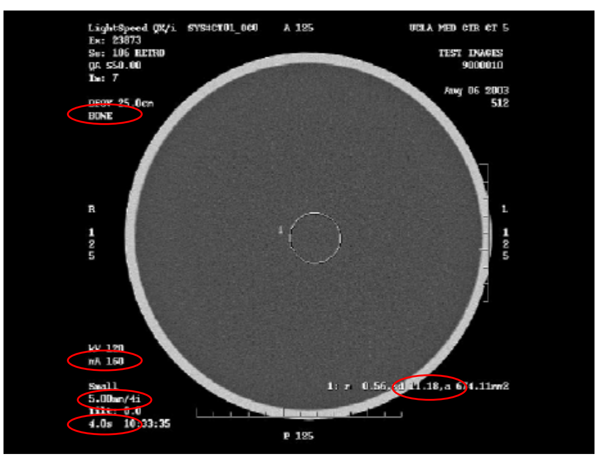
kV 120
mA 50
5.00mm/4i
0.8s 10:33:28
P 125


LightSpeed QX/i
UCLA MED CTR CT 5
TEST IMAGES
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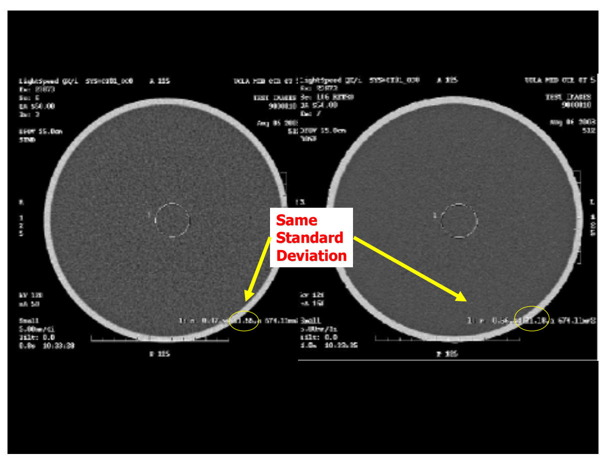
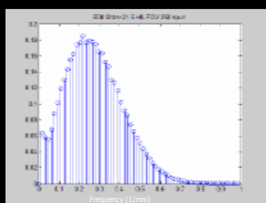
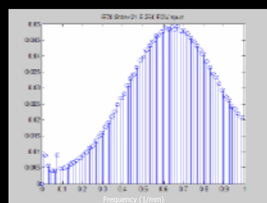
DFOV 25.0cm
BONE
kV 120
mA 160
5.00mm/4i
4.0s 10:33:35
P 125


Same
Standard
Deviation

Noise Power Spectrum

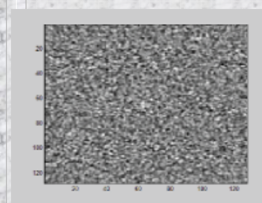


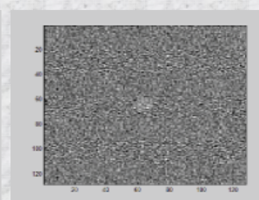
B30 convolution kernel 21.5 HU



B70 convolution kernel 21.5 HU

Noise Power Spectrum





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.
- 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

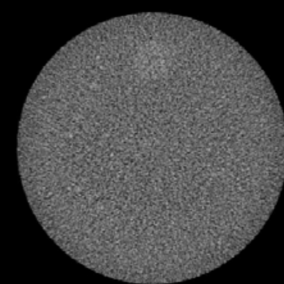
- An example of a low contrast resolution phantom is that in use by the ACR CT Accreditation program.
- This phantom consists of:
  - A single 25mm rod for reference and measurements,
  - Sets of 4 rods, each is decreasing in diameter from:
    - 6mm,
    - 5mm,
    - 4mm
    - 3mm
    - 2mm (typically 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

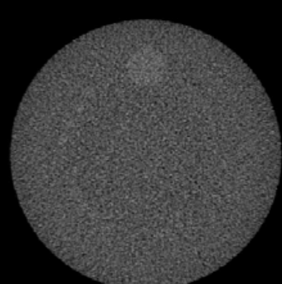
Low Contrast - Reducing mAs

120 kVp
80 mAs
5 mm
Std Algorithm



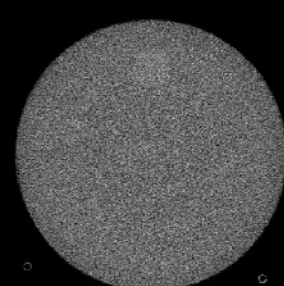
Low Contrast – Thinner Slices

120 kVp
240 mAs
2.5 mm
Std Algorithm



Low Contrast - Recon Algorithm

120 kVp
240 mAs
5 mm
Bone 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

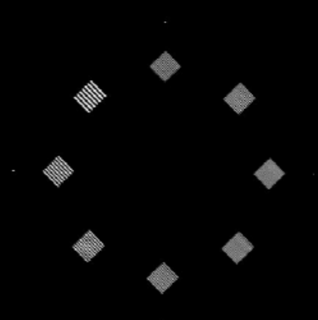
- Reducing Collimation :
  - Increases Z-axis Resolution
  - Increases Noise
  - May increase Dose for some scanners

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

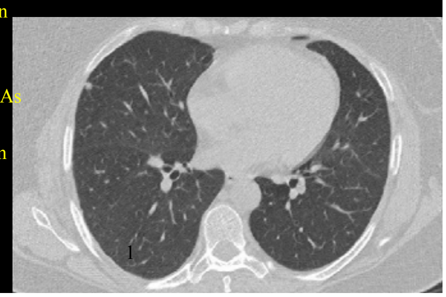
High Contrast - Reducing mAs

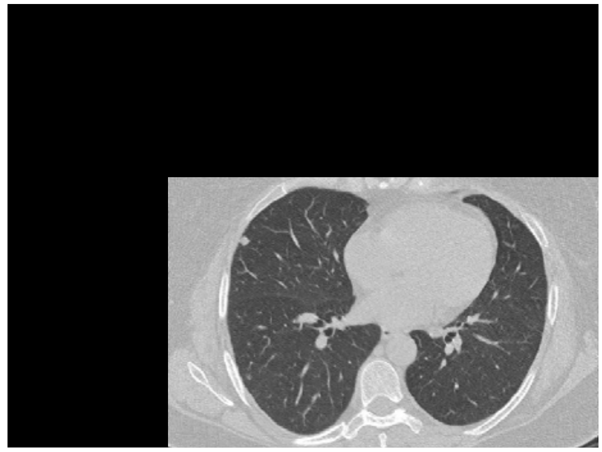
120 kVp
80 mAs
5 mm
Bone Algorithm

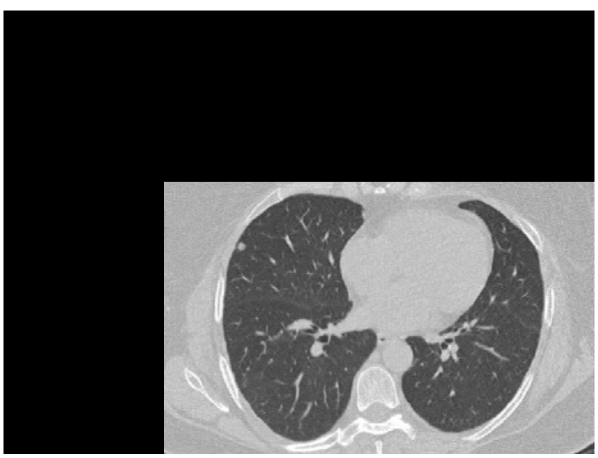


Lung Cancer Screen

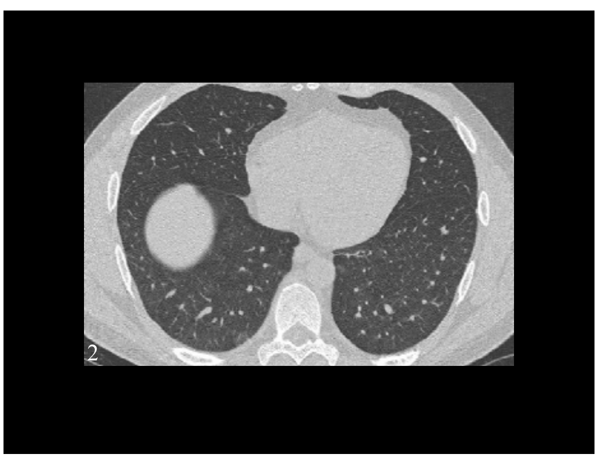
- Task: Detect Nodule(s) in Aerated Lung
- Siemens Volume Zoom
- 0.5 sec/rotation
- 140 kV
- 140 mA
- 40 effective mAs
- 1.25 mm
- B50f algorithm








11 Image Series
1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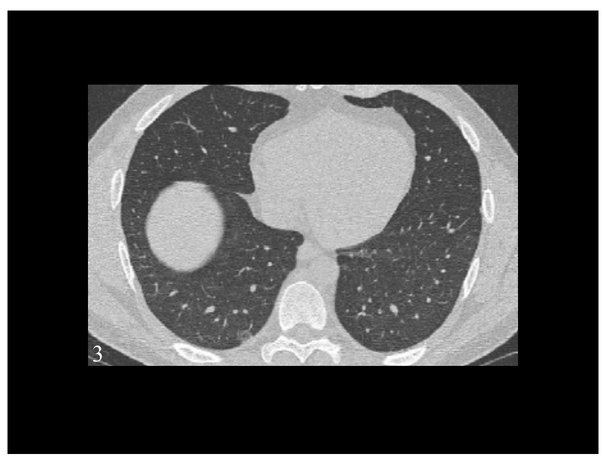
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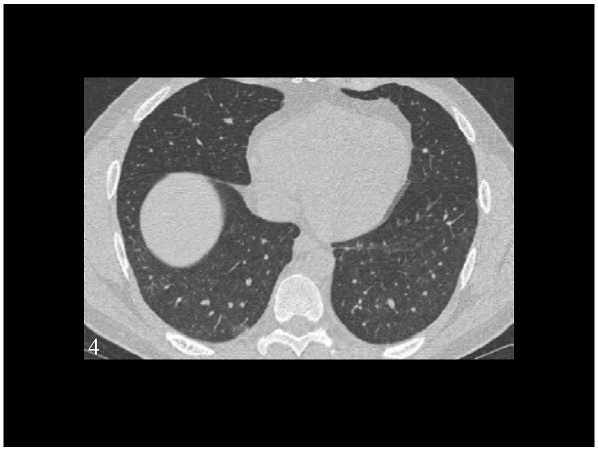
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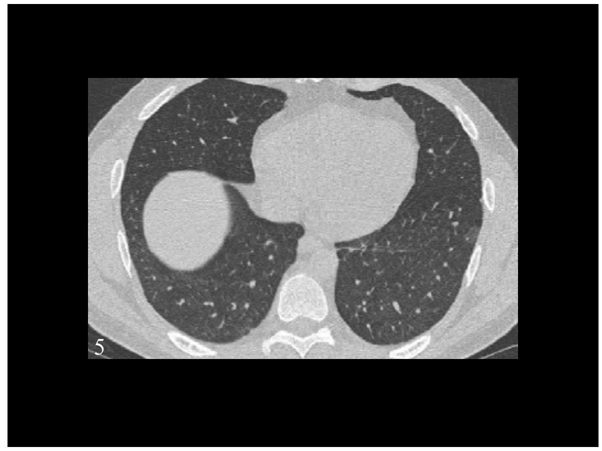
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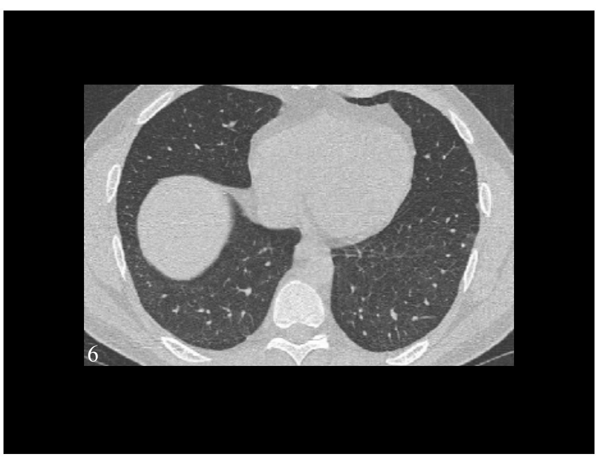
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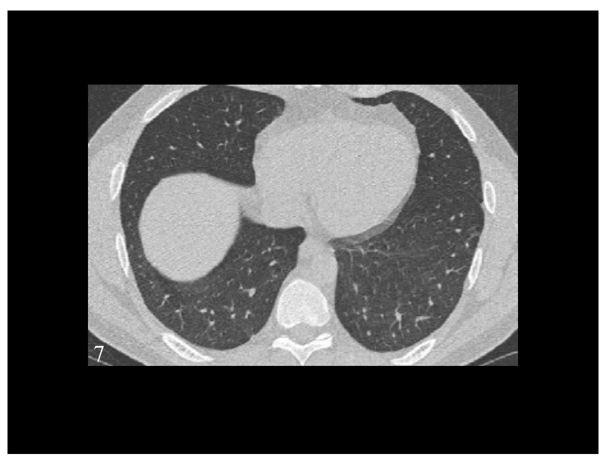
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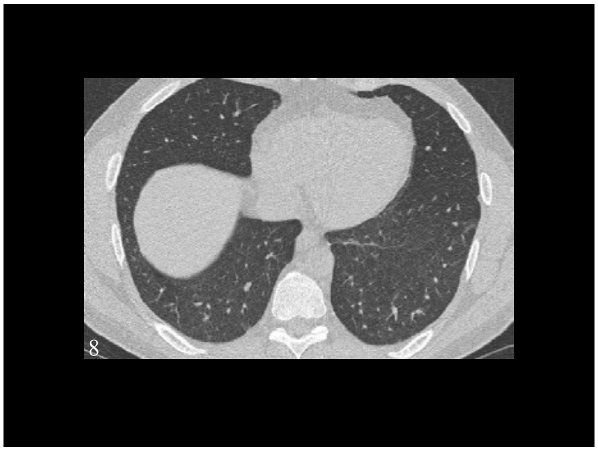
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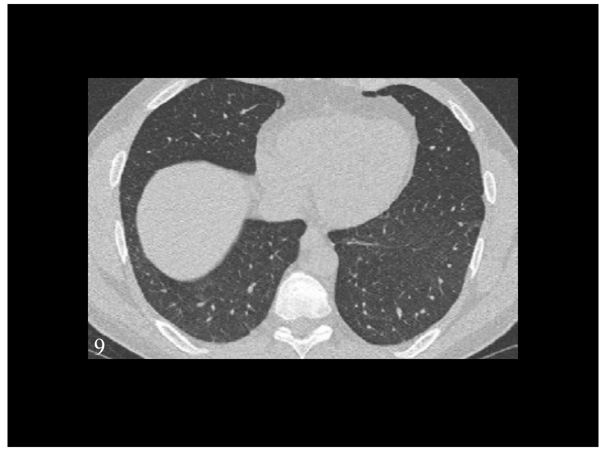
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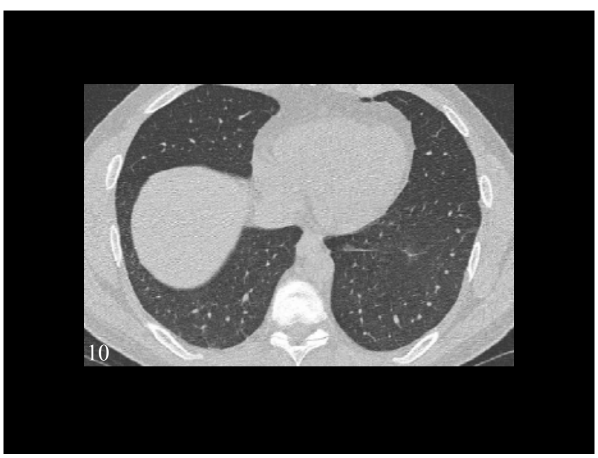
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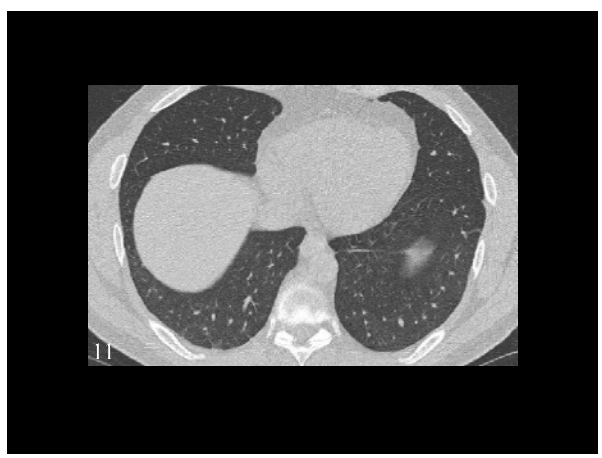
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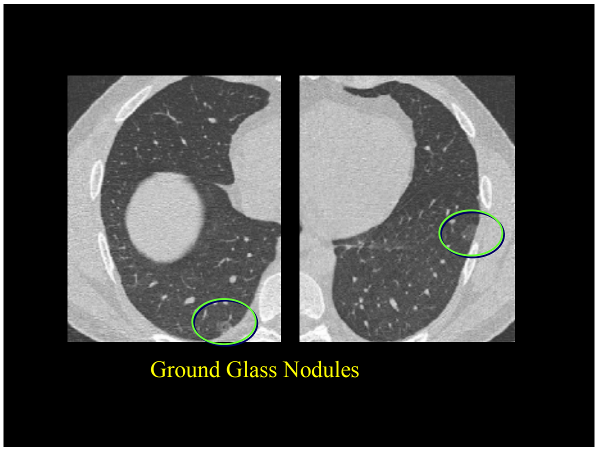
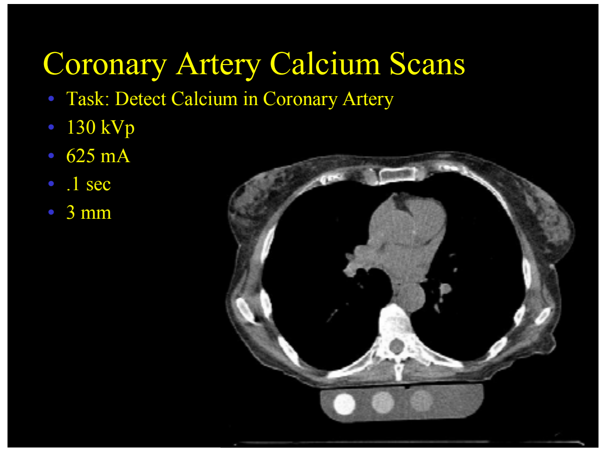
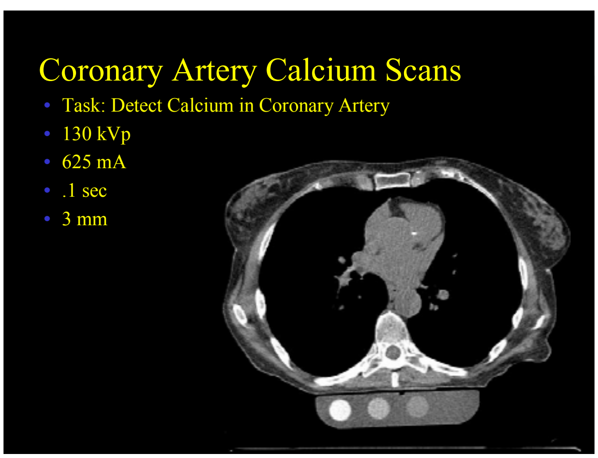

Ground Glass Nodules


Coronary Artery Calcium Scans
• Task: Detect Calcium in Coronary Artery
• 130 kVp
• 625 mA
• .1 sec
• 3 mm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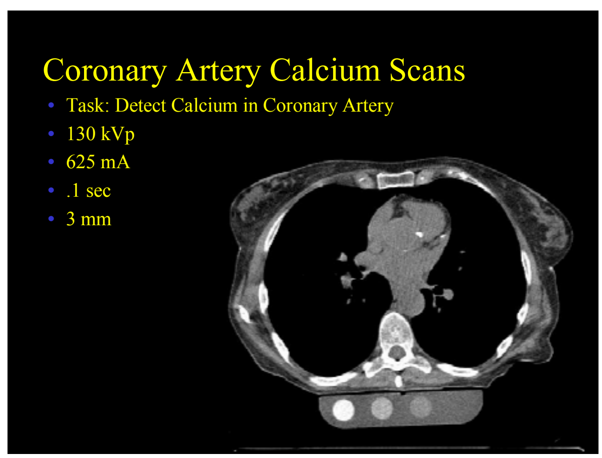
• 3 mm


Coronary Artery Calcium Scans
• Task: Detect Calcium in Coronary Artery
• 130 kVp
• 625 mA
• .1 sec
• 3 mm

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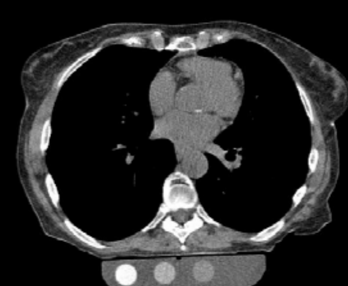

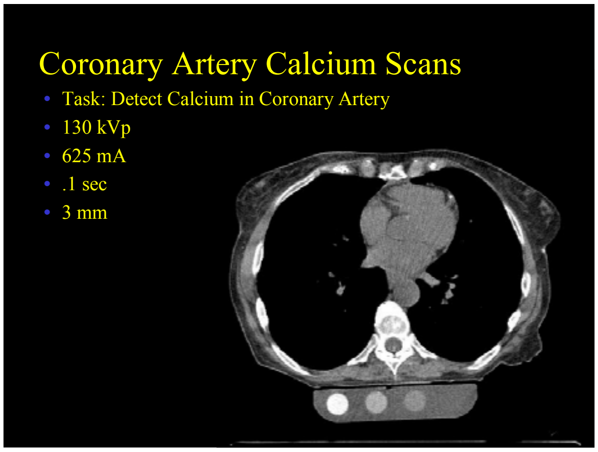
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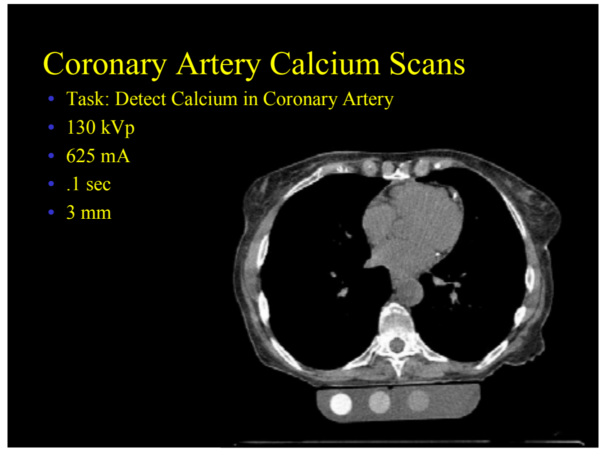
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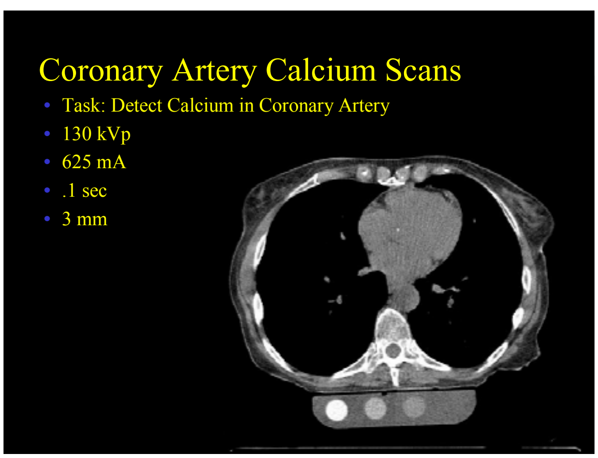
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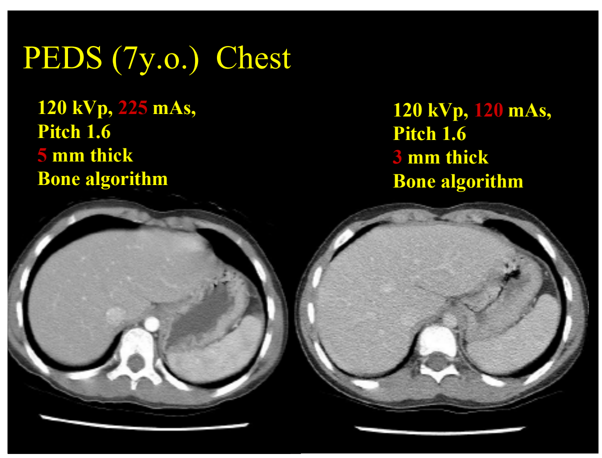
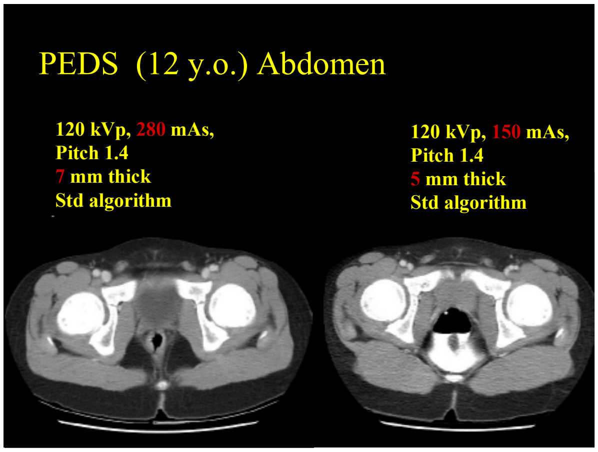
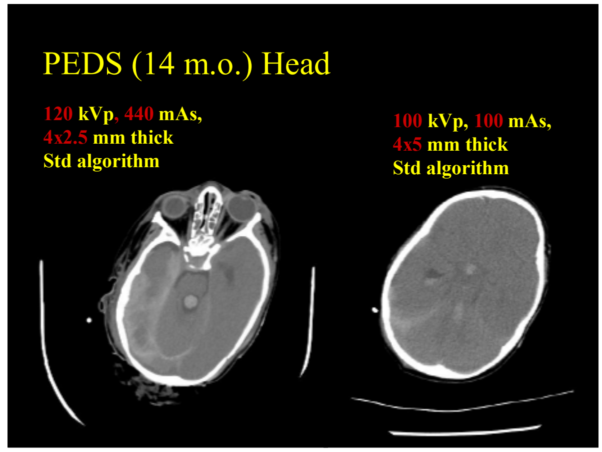
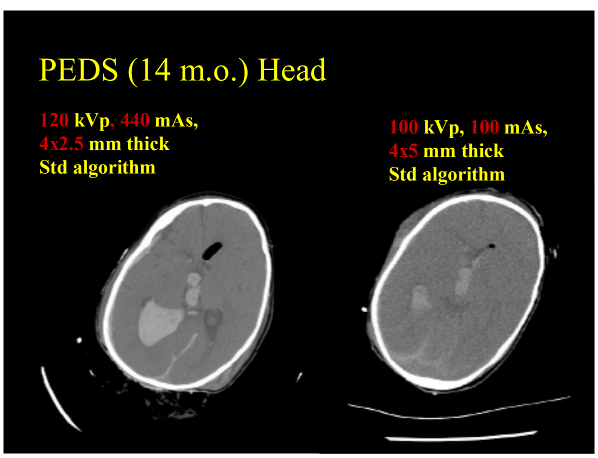
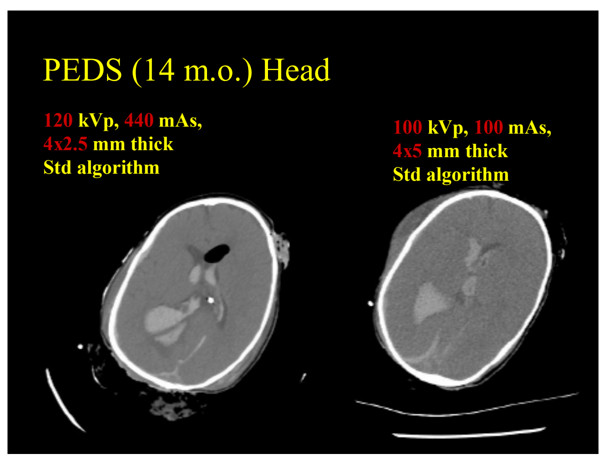

PEDS (7y.o.) Chest
120 kVp, 225 mAs,
Pitch 1.6
5 mm thick
Bone algorithm
120 kVp, 120 mAs,
Pitch 1.6
3 mm thick
Bone algorithm


PEDS (12 y.o.) Abdomen
120 kVp, 280 mAs,
Pitch 1.4
7 mm thick
Std algorithm
120 kVp, 150 mAs,
Pitch 1.4
5 mm thick
Std algorithm


PEDS (14 m.o.) Head
120 kVp, 440 mAs,
4x2.5 mm thick
Std algorithm
100 kVp, 100 mAs,
4x5 mm thick
Std algorithm


PEDS (14 m.o.) Head
120 kVp, 440 mAs,
4x2.5 mm thick
Std algorithm
100 kVp, 100 mAs,
4x5 mm thick
Std algorithm


PEDS (14 m.o.) Head
120 kVp, 440 mAs,
4x2.5 mm thick
Std algorithm
100 kVp, 100 mAs,
4x5 mm thick
Std algorithm

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?