A Systematic Review of CT Imaging Chain and Dose Implications

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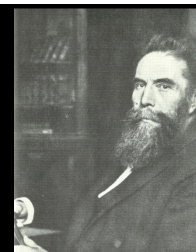
"A new kind of Ray"

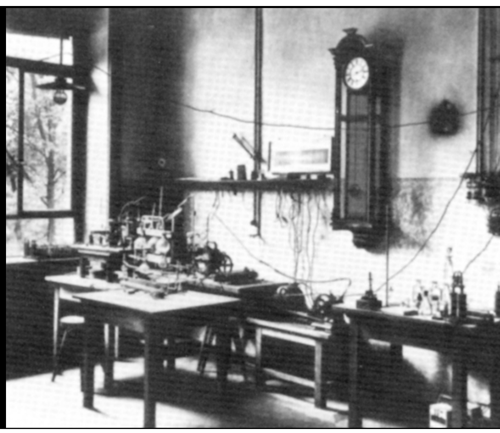

EINE NEUE ART
VON
STRAHLEN.
Dr. W. RÖNTGEN,
WÜRZBURG.

W. Rontgen

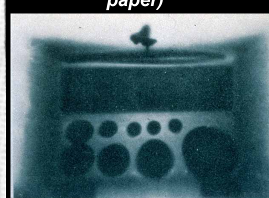
Dec 28, 1895

On a New Kind of Rays, cover of first edition reprint.

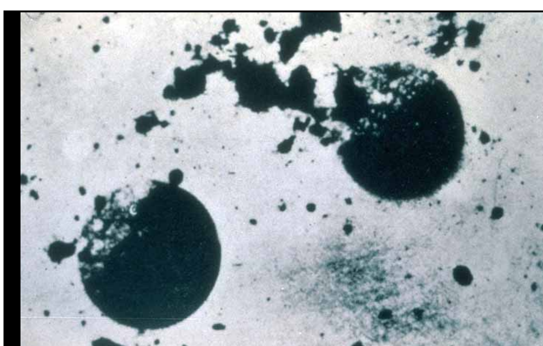




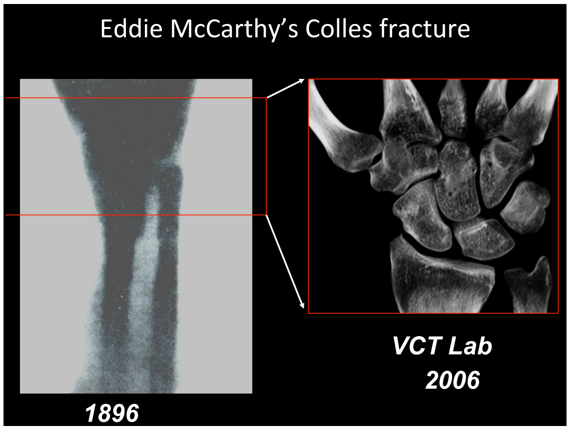
Roentgen's Wife's Ring (Picture from his first paper)

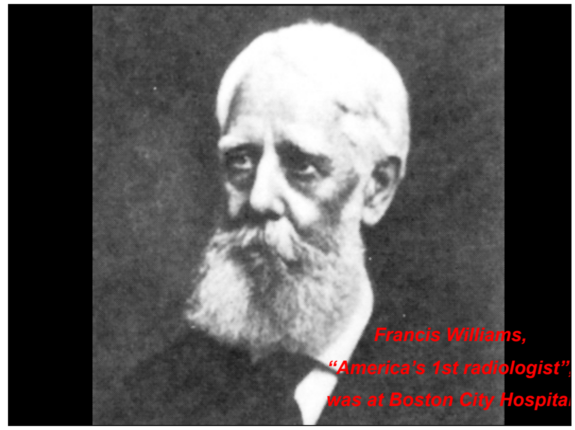


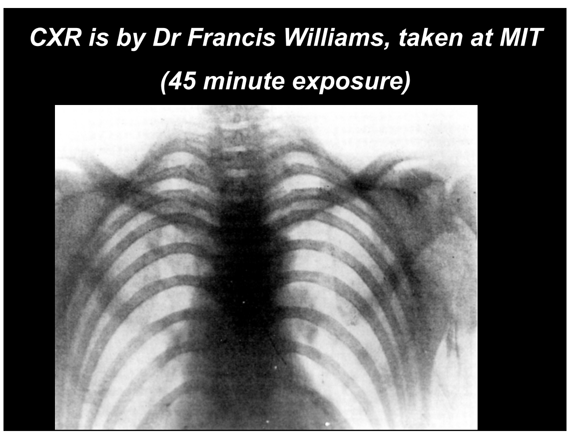
Another Figure from the Original Paper

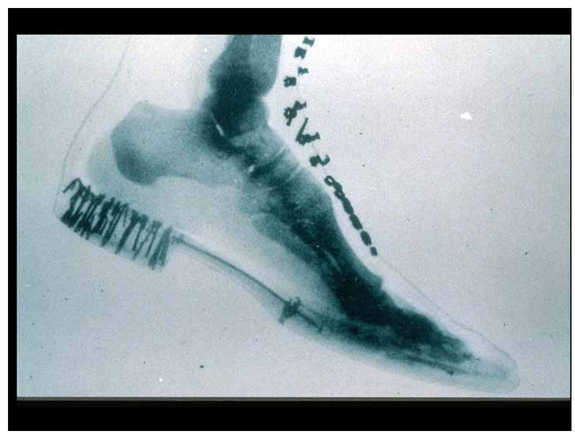


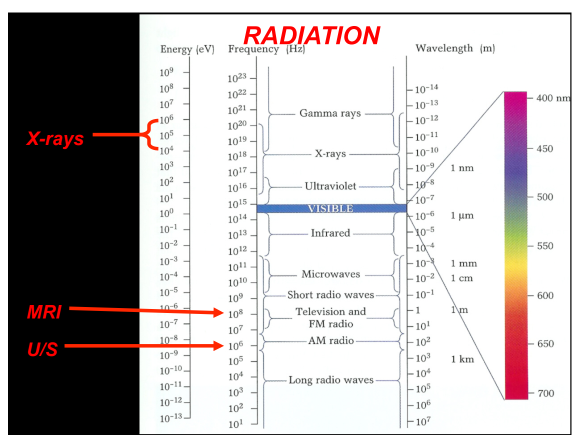
An X-ray image, taken about 8 years before Rontgen (taken in Philadelphia)


Eddie McCarthy's Colles fracture
VCT Lab
2006
1896

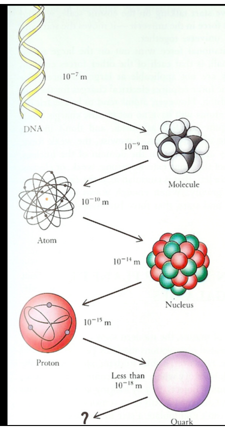

Francis Williams,
"America's 1st radiologist",
was at Boston City Hospita


CXR is by Dr Francis Williams, taken at MIT
(45 minute exposure)




RADIATION
X-rays
MRI
U/S
Energy [eV]
Frequency [Hz]
Wavelength [m]
Gamma rays
X-rays
Ultraviolet
VISIBLE
Infrared
Microwaves
Short radio waves
Television and FM radio
AM radio
Long radio waves
1 nm
1 µm
1 mm
1 cm
1 m
1 km
400 nm
450
500
550
600
650
700

X-ray interaction With matter



Three Classical types of "Radiation"

Alpha	(helium nuclei)
Beta	(electrons)
Gamma	(high energy electromagnetic waves)

Also Neutrons

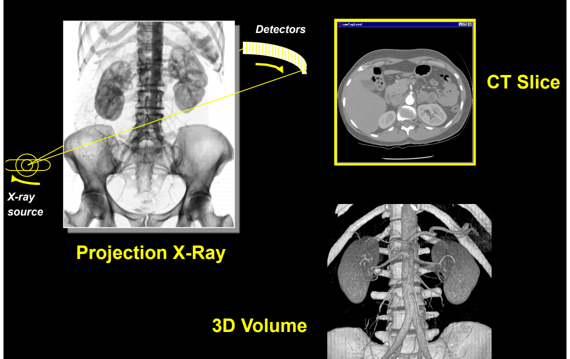
Types of Imaging

X-Rays	Plain radiography CT Fluoroscopy Angiography
γ-rays	Nuclear medicine Bone Scans SPECT PET
Radiofrequency	MRI
Sound waves	Ultrasound

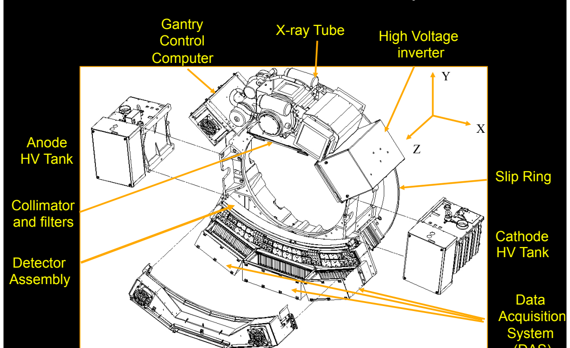
Organization

CT Physics Fundamentals	Novel Concepts	Future Directions
• Imaging chain • X-ray generation & filtration • Attenuation • Detection • Recon algorithms • Characterization • X-ray dose • CT artifacts	• 5 generations of scanners • Cardiac CT • Dual Energy CT • Flat-panel CT	• X-ray Source • Contrast Mechanism • Detectors and Photon Counting • Reconstruction Algorithms

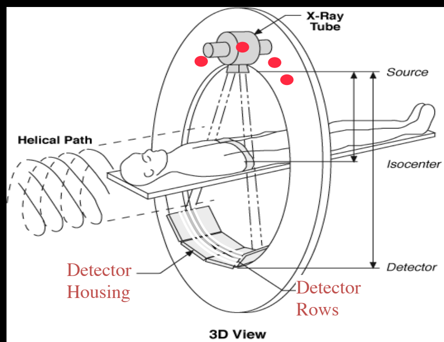
From X-Ray projections to CT Slices



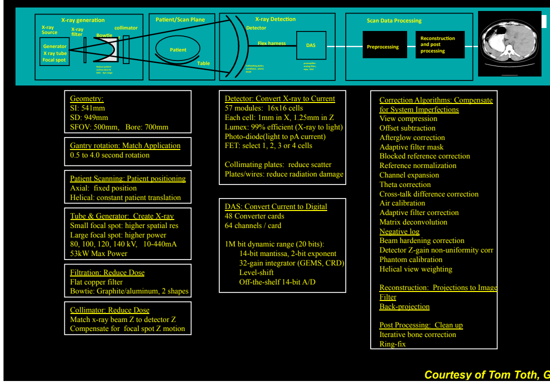
A 3rd Generation Gantry



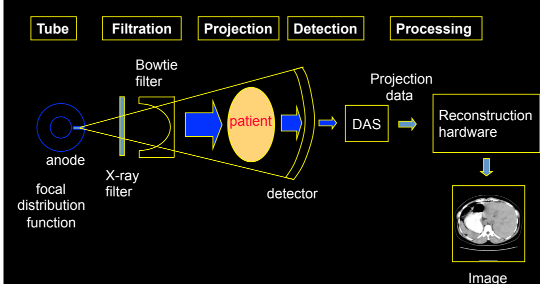
Simplified Gantry Model



CT Image Chain: God Lives in Details



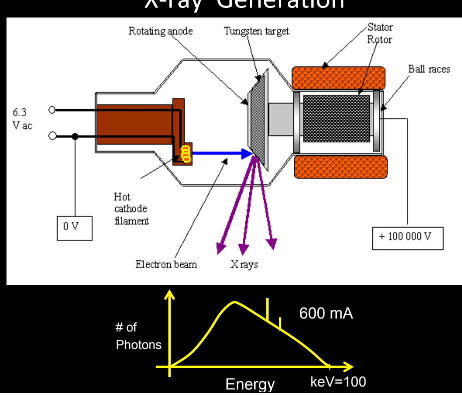
CT Image Chain



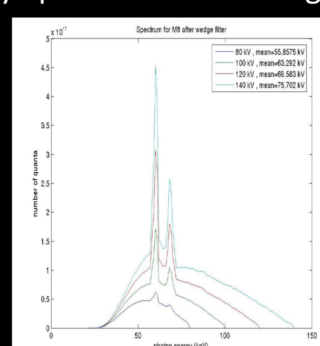
Overview of CT Physics

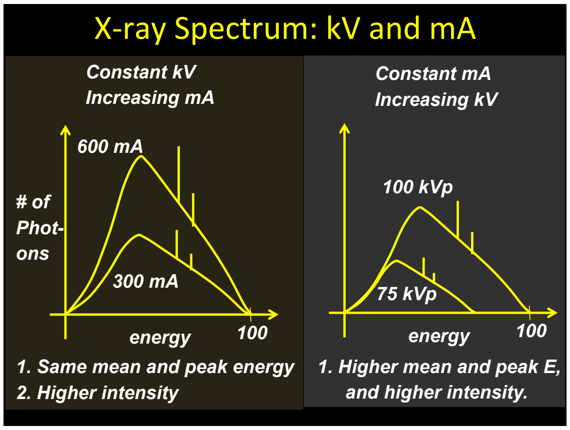
- CT imaging chain
- X-ray tube
  - X-ray generation
  - Filtration
  - Collimation
- Attenuation in patient
- X-ray detection and scan modes
- Reconstruction algorithms
- Characterization
  - Spatial resolution
  - Contrast resolution
  - Dose
- CT artifacts
- Five generations

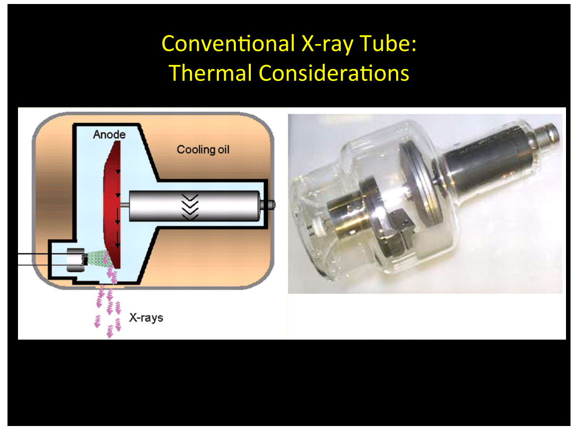
X-ray Generation

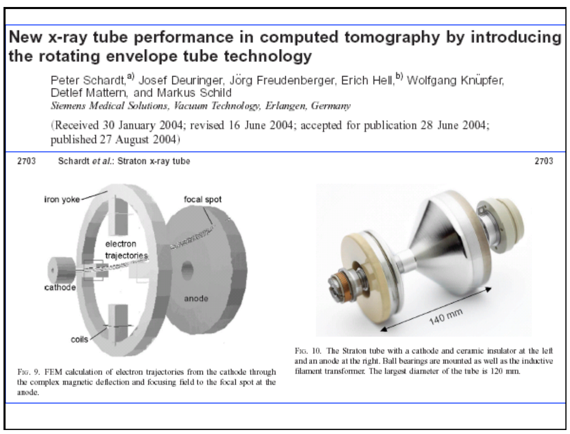


X-ray Spectrum after Wedge Filter








New x-ray tube performance in computed tomography by introducing the rotating envelope tube technology

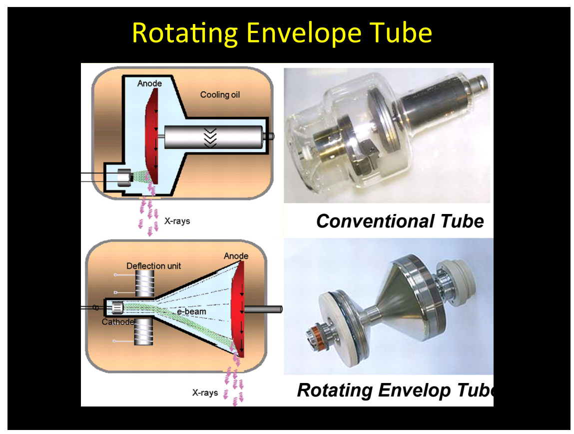
Peter Schardt,[a)] Josef Deuringer, Jörg Freudenberger, Erich Hell,[b)] Wolfgang Knüpfer, Detlef Mattern, and Markus Schild
Siemens Medical Solutions, Vacuum Technology, Erlangen, Germany

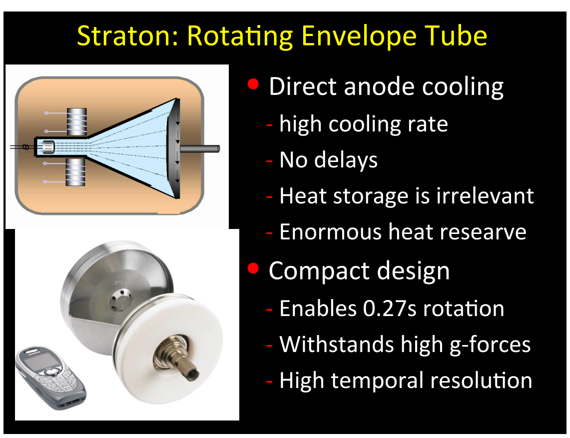
(Received 30 January 2004; revised 16 June 2004; accepted for publication 28 June 2004; published 27 August 2004)

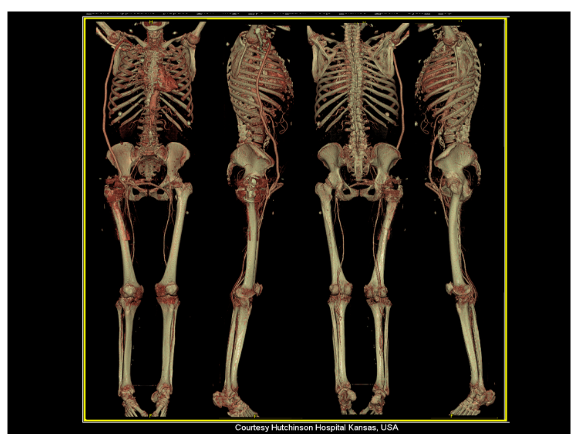
2703 Schardt *et al.*: Straton x-ray tube 2703

FIG. 9. FEM calculation of electron trajectories from the cathode through the complex magnetic deflection and focusing field to the focal spot at the anode.

FIG. 10. The Straton tube with a cathode and ceramic insulator at the left and an anode at the right. Ball bearings are mounted as well as the inductive filament transformer. The largest diameter of the tube is 120 mm.

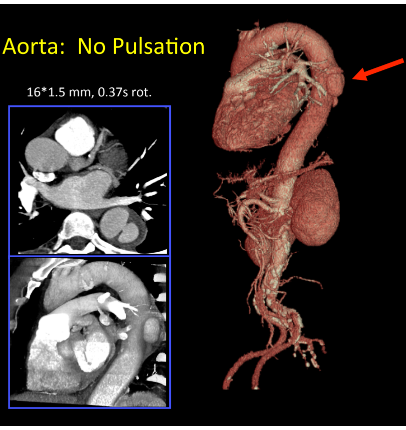




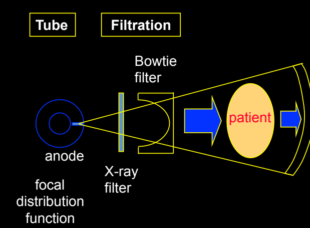


Gated Aorta: No Pulsation

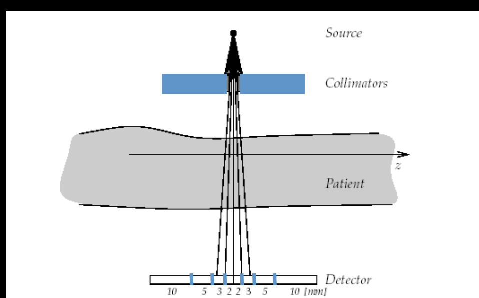
16*1.5 mm, 0.37s rot.



X-ray Filtration



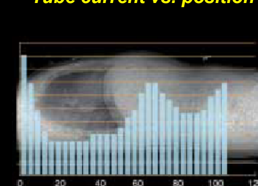
Collimation



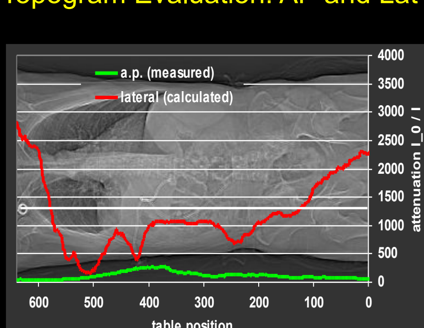
Tube Current Modulation: Z-axis

- X-ray absorption varies according to path length and tissue type.
- Constant mA is too low or too high.
- Modulate tube current according to patient size.
- Lower x-ray dose.
- Better image quality.

Tube current vs. position



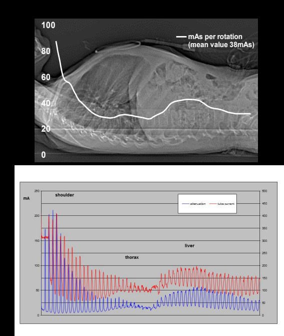
Topogram Evaluation: AP and Lat



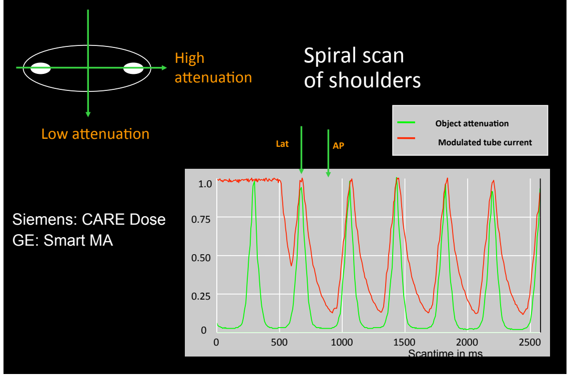
Real-Time Dose Modulation

Dose Reduction for Pediatric CT

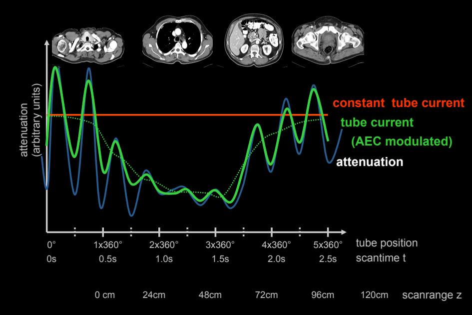
- Child, 6 years of age
- Standard:165 mAs
- Optimum image quality
- Minimum required dose (average 38 mAs).



Real-time mA Modulation: X-Y plane



Real-Time mA Modulation (XY and Z)



Real-Time Dose Modulation

- Dose saving up to 66% for adults
- Improved IQ: higher mAs where needed
- Simplified workflow: auto-adjustment
  - -Tech doesn't have to worry about proper mAs
- No over-dosing of pediatric patients *

* Kamel IR et al: Radiation dose reduction in CT of the pediatric pelvis. Radiology 1994; 190:683–687: *Only 43% of institutions adjust their CT scanning techniques when examining children.*

Take-home Points

Dose: kV vs mAs

- ↑mAs
  - More photons, same spectrum
  - ↑dose (~ linearly)
- ↑kV
  - More photons, wider spectrum
  - ↑dose (non-linear)

Filters needed to:

- Remove low energy photons
- Shape the beam

Tricks to reduce dose

- Smart mA
- Auto mA
- CareDose

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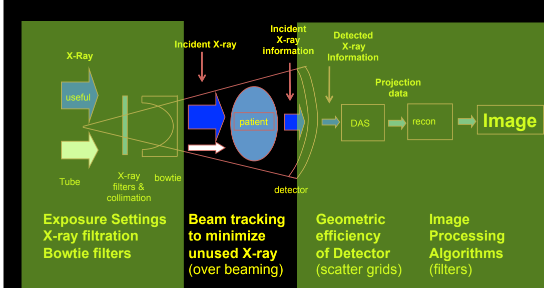
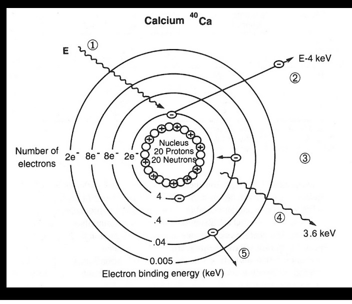
Projection and X-ray Attenuation



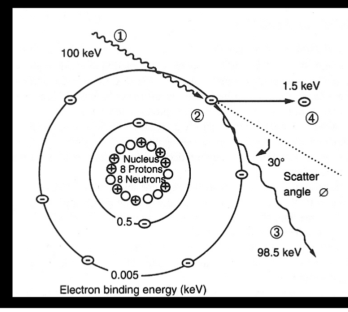
Major Photon Interactions

Photoelectric Effect: Bound electron absorbs all energy of incident photon



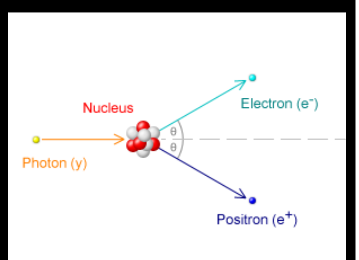
Major Photon Interactions

Compton Scattering: Photon scatters off single free/bound electron



Pair Production

- Low Energy
  - Photoelectric Effect
- Medium Energy
  - Compton Effect
- High Energy
  - Pair Production



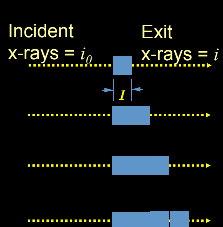
Minor Photon Interactions

- Pair Production
- Rayleigh Scattering
- Thomson Scattering
- Nuclear Resonant Scattering…

But what's really important is:

- Absorption (Photoelectric Effect)
- Scatter (Compton Scattering

X-ray Attenuation: Single Material



$$i = \frac{i_0}{\alpha}$$

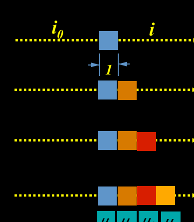
$$i = \frac{i_0}{\alpha^2}$$

$$i = \frac{i_0}{\alpha^3}$$

$$i = \frac{i_0}{\alpha^4}$$

In general: $i = i_0 \alpha^{-l} = i_0 e^{-\mu l}$

X-ray Attenuation: Multiple Materials



$$i = i_0 e^{-\mu_1 l}$$

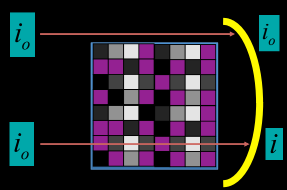
$$i = i_0 e^{-\mu_1 l} e^{-\mu_2 l}$$

$$i = i_0 e^{-\mu_1 l} e^{-\mu_2 l} e^{-\mu_3 l}$$

$$i = i_0 e^{-\mu_1 l} e^{-\mu_2 l} e^{-\mu_3 l} e^{-\mu_4 l}$$

In general: $i = i_o e^{-\Sigma \mu l}$

The Projection Image



$$i = i_o e^{-\Sigma\mu_i}$$

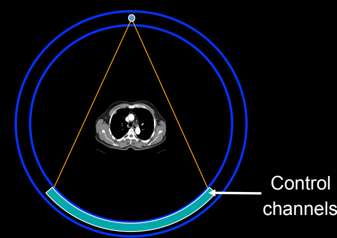
$$-\log\frac{i}{i_0} = \Sigma\mu_i$$

$$y = \Sigma\mu_i$$

Each projected pixel is SUM of individual attenuation coefficients.

Importance of Air Calibration

- Important to know I_0
- Each projection = ray sum
- Pt must be fully in fan-beam



$$i = i_o e^{-\Sigma\mu_i}$$

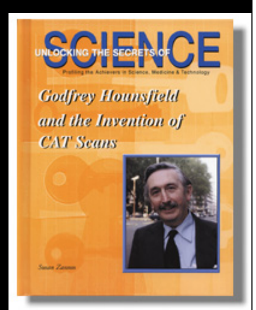
$$-\ln\frac{i}{i_0} = \Sigma\mu_i$$

$$y = \Sigma\mu_i$$

The CT Image

Map of μ values scaled in Hounsfield units (HU)

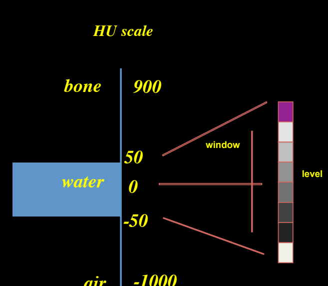
$$HU = \frac{\mu_x - \mu_w}{\mu_w} \times 1000$$



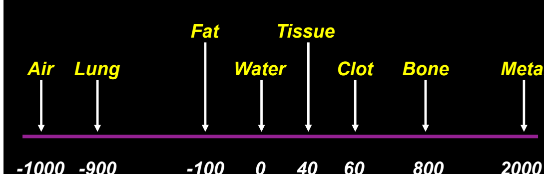
CT Image: A Matrix of μ Values

- Linear attenuation coefficient (μ)
- Probability: X-ray photon is scattered or absorbed
- Depends on:
  - atomic number and density
  - Photon energy
- μ is heavily manipulated to be a scalar.

Range of Human Tissue in HU



Hounsfield Units



Take-home Points

- Each projection = ray-sum of μ values.
- Each projection is internally calibrated.
- HU system is water centered.
- μ and HU are artificial quantities.

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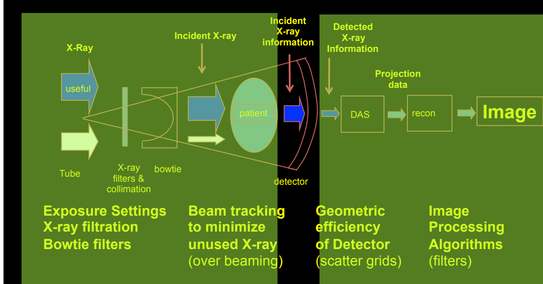
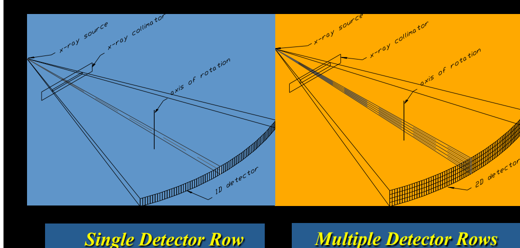
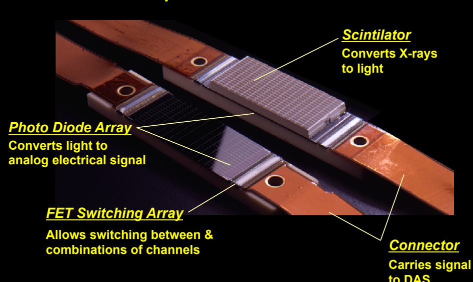
Detection Subsystem



Single to Multiple detector-row CT

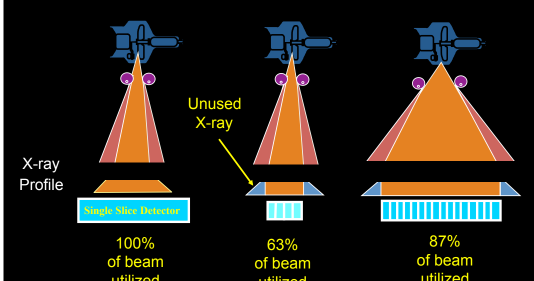


Anatomy of a Multi-slice Detector

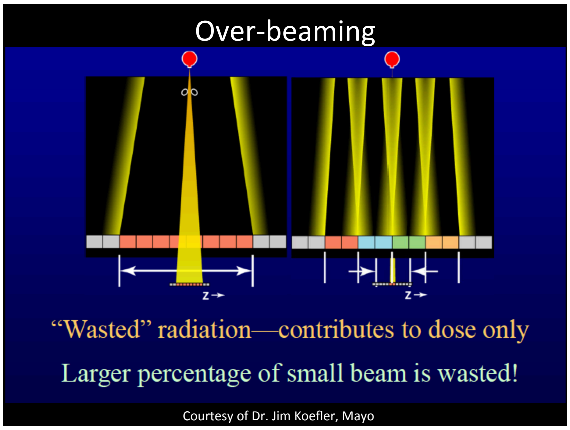


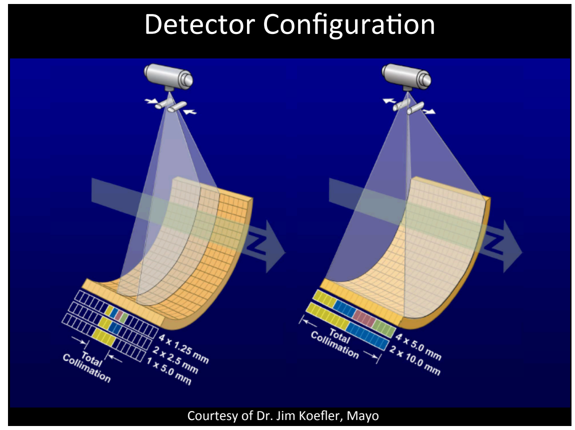
DAS - Data Acquisition System *(not shown)*
Converts analog signals to digital and begins reconstruction processing

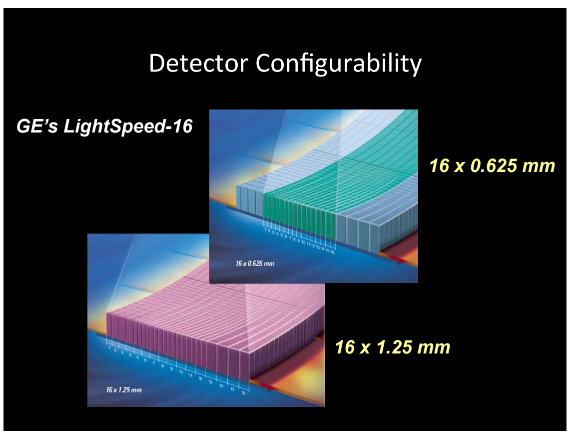
Multi-slice Z-axis Dose Efficiency

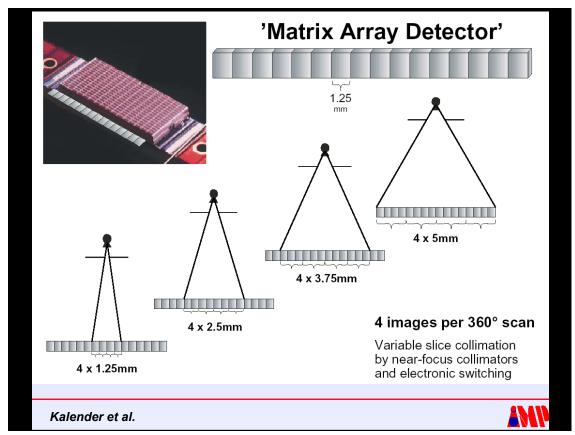


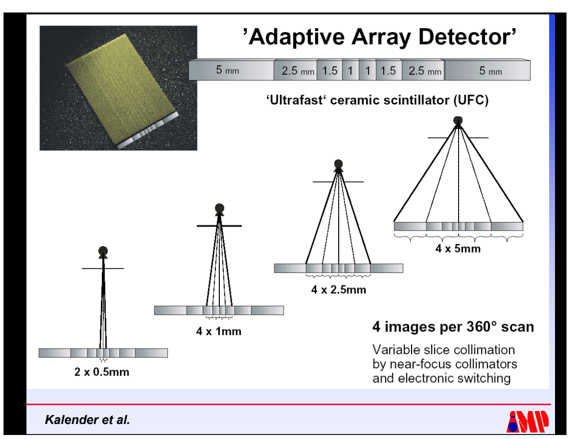
A longer detector length is more dose efficient

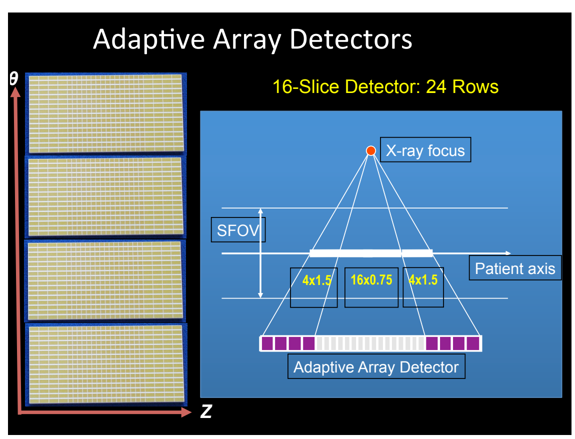

Over-beaming
“Wasted” radiation—contributes to dose only
Larger percentage of small beam is wasted!
Courtesy of Dr. Jim Koefler, Mayo


Detector Configuration
Total Collimation
4 x 1.25 mm
2 x 2.5 mm
1 x 5.0 mm
Total Collimation
4 x 5.0 mm
2 x 10.0 mm
Courtesy of Dr. Jim Koefler, Mayo


Detector Configurability
GE’s LightSpeed-16
16 x 0.625 mm
16 x 1.25 mm


’Matrix Array Detector’
1.25 mm
4 x 5mm
4 x 3.75mm
4 x 2.5mm
4 x 1.25mm
4 images per 360° scan
Variable slice collimation
by near-focus collimators
and electronic switching
Kalender et al.


’Adaptive Array Detector’
5 mm
2.5 mm
1.5
1
1
1.5
2.5 mm
5 mm
‘Ultrafast‘ ceramic scintillator (UFC)
4 x 5mm
4 x 2.5mm
4 x 1mm
2 x 0.5mm
4 images per 360° scan
Variable slice collimation
by near-focus collimators
and electronic switching
Kalender et al.

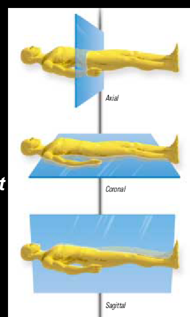

Adaptive Array Detectors
16-Slice Detector: 24 Rows
X-ray focus
SFOV
Patient axis
4x1.5
16x0.75
4x1.5
Adaptive Array Detector
θ
Z

Isotropic Voxel Size

0.625 x 0.625mm x 1.25 mm

0.625mm cube

- ***Voxel = smallest volume element***
- ***Isotropic voxel means same quality in axial, coronal and sagittal planes.***



GE Educational Brochure

Take-home Points

1. Multiple detector configurations
   - 4x1.25 mm (LightSpeed plus)
   - 8x1.25 mm (LightSpeed ultra)
   - 16x0.625 mm or 16x1.25 mm (LightSpeed 16)
   - 16x0.5 mm (Sensation 16, Siemens)
2. MSCT enables faster coverage
3. Isotropic Voxels
4. Dose efficiency increases with more slices

Scan Parameters

- Rotation time
- mA
- kV
- Scan Mode: Spiral vs. Helical
- Pitch
- Image Width
- Detector configuration
- Reconstruction Algorithm

Rotation Time

- Total scan time: proportional
- Dose: proportional
- Noise and low contrast resolution
  - Proportional to 1/square root(T)
- In general, you want to minimize rotation time and increase mA
- Timing considerations for IV contrast

Tube Current

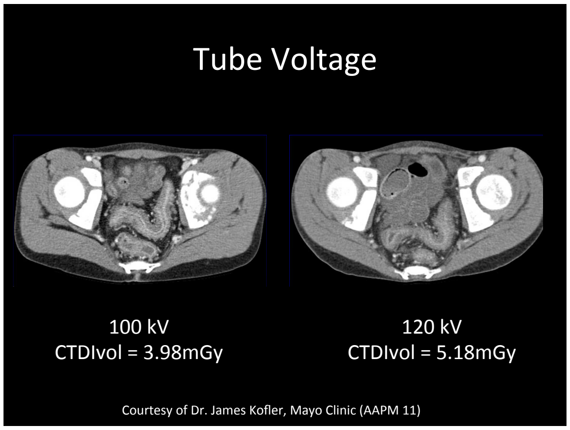
- Affects
  - Noise / Low contrast resolution
  - Dose (proportional)

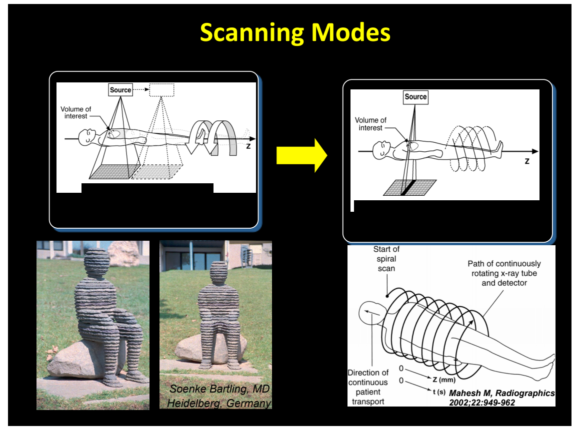
Note:

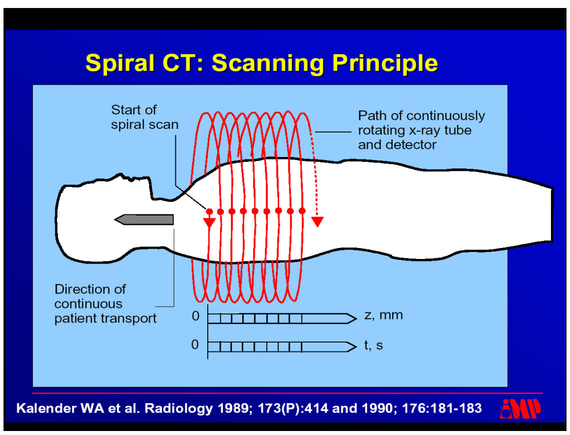
- mA near tube/generator limits can be problematic (especially when dose modulation is used)

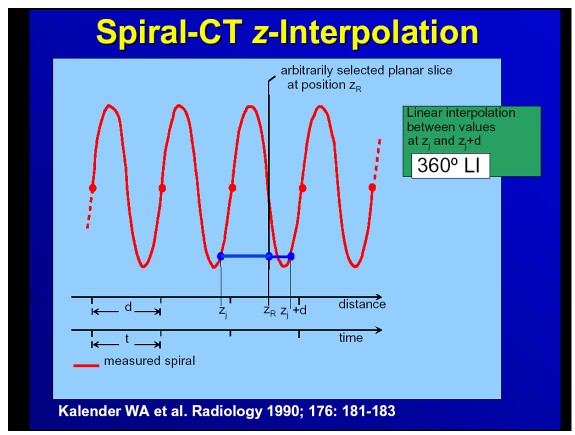
Tube Voltage

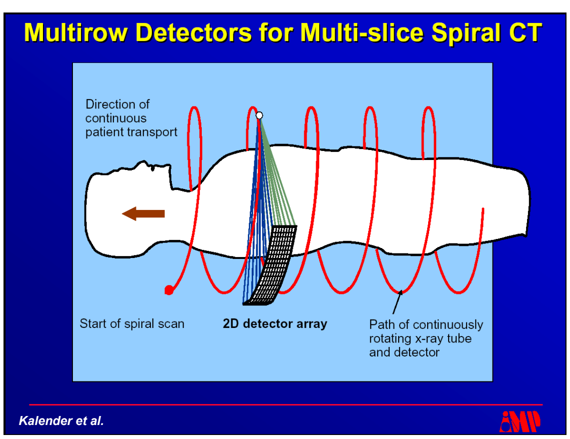
- Affects
  - Contrast resolution
  - Dose
- Note:
  - Optimum mA varies with kV
  - Bolus tracking thresholds different at different kVs

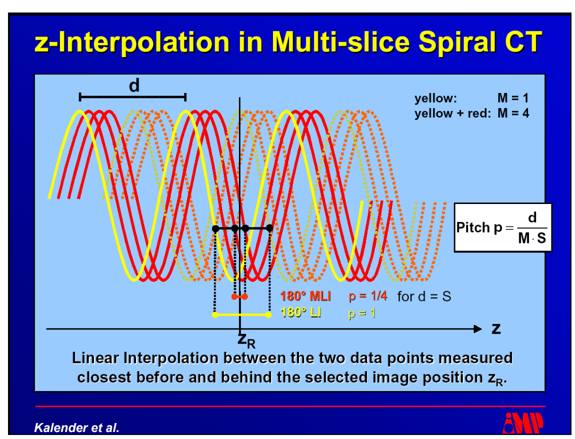

Tube Voltage
100 kV
CTDIvol = 3.98mGy
120 kV
CTDIvol = 5.18mGy
Courtesy of Dr. James Kofler, Mayo Clinic (AAPM 11)

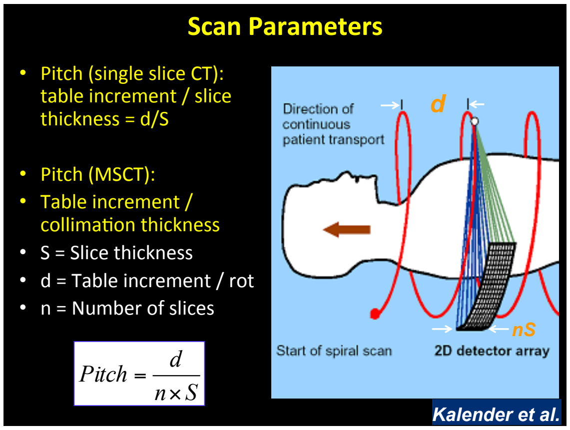

Scanning Modes
Source
Volume of interest
Start of spiral scan
Path of continuously rotating x-ray tube and detector
Direction of continuous patient transport
z (mm)
t (s)
Soenke Bartling, MD Heidelberg, Germany
Mahesh M, Radiographics 2002;22:949-962

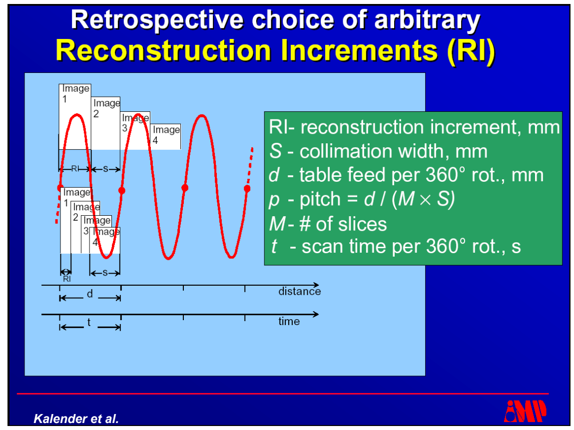

Spiral CT: Scanning Principle
Start of spiral scan
Path of continuously rotating x-ray tube and detector
Direction of continuous patient transport
0
z, mm
0
t, s
Kalender WA et al. Radiology 1989; 173(P):414 and 1990; 176:181-183

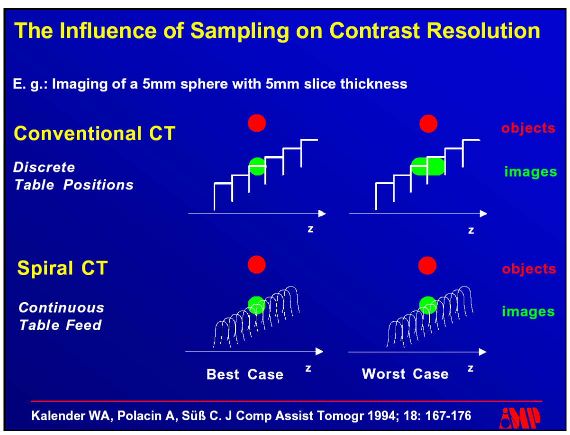

Spiral-CT z-Interpolation
arbitrarily selected planar slice at position z_R
Linear interpolation between values at z_j and z_j+d
360º LI
d
z_j
z_R
z_j+d
distance
t
time
measured spiral
Kalender WA et al. Radiology 1990; 176: 181-183

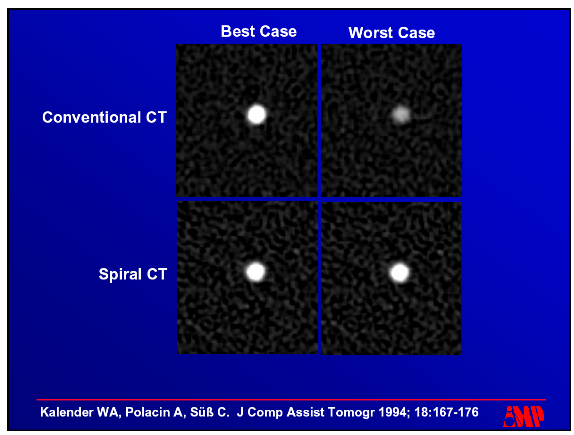

Multirow Detectors for Multi-slice Spiral CT
Direction of continuous patient transport
Start of spiral scan
2D detector array
Path of continuously rotating x-ray tube and detector
Kalender et al.

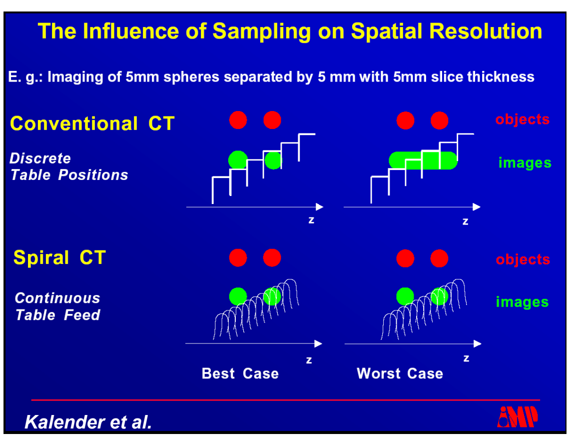

z-Interpolation in Multi-slice Spiral CT
d
yellow: M = 1
yellow + red: M = 4
Pitch p = $\frac{d}{M \cdot S}$
180º MLI
p = 1/4
for d = S
180º LI
p = 1
z_R
z
Linear Interpolation between the two data points measured closest before and behind the selected image position z_R.
Kalender et al.

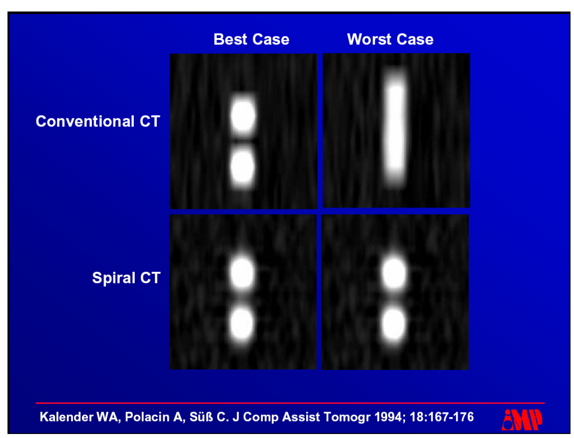

Scan Parameters
Pitch (single slice CT): table increment / slice thickness = d/S
Pitch (MSCT):
Table increment / collimation thickness
S = Slice thickness
d = Table increment / rot
n = Number of slices
$Pitch = \frac{d}{n \times S}$
Direction of continuous patient transport
d
nS
Start of spiral scan
2D detector array
Kalender et al.


Retrospective choice of arbitrary
Reconstruction Increments (RI)
RI- reconstruction increment, mm
S - collimation width, mm
d - table feed per 360° rot., mm
p - pitch = d / (M × S)
M - # of slices
t - scan time per 360° rot., s
distance
time
Kalender et al.


The Influence of Sampling on Contrast Resolution
E. g.: Imaging of a 5mm sphere with 5mm slice thickness
Conventional CT
Discrete Table Positions
Spiral CT
Continuous Table Feed
objects
images
Best Case
Worst Case
Kalender WA, Polacin A, Süß C. J Comp Assist Tomogr 1994; 18: 167-176


Best Case
Worst Case
Conventional CT
Spiral CT
Kalender WA, Polacin A, Süß C. J Comp Assist Tomogr 1994; 18:167-176


The Influence of Sampling on Spatial Resolution
E. g.: Imaging of 5mm spheres separated by 5 mm with 5mm slice thickness
Conventional CT
Discrete Table Positions
Spiral CT
Continuous Table Feed
objects
images
Best Case
Worst Case
Kalender et al.

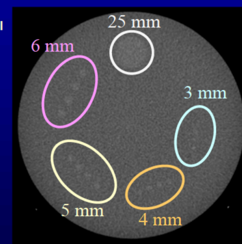

Best Case
Worst Case
Conventional CT
Spiral CT
Kalender WA, Polacin A, Süß C. J Comp Assist Tomogr 1994; 18:167-176

Pitch

- Affects
  - Total scan time
  - Noise / Low contrast resolution
  - Dose

Pitch

Pitch	$CTDI_{vol}$
0.562	162



Variable pitch.

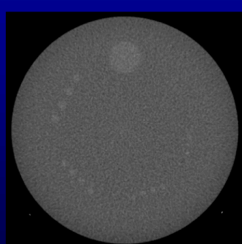
All other parameters constant.

Pitch: 0.562
$CTDI_{vol}$: 162 mGy

Courtesy of Dr. James Kofler, Mayo Clinic (AAPM 11)

Pitch

Pitch	$CTDI_{vol}$
0.562	162



Variable pitch.

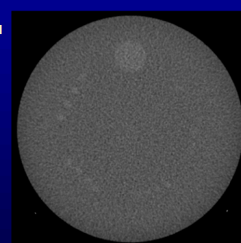
All other parameters constant.

Pitch: 0.562
$CTDI_{vol}$: 162 mGy

Courtesy of Dr. James Kofler, Mayo Clinic (AAPM 11)

Pitch

Pitch	$CTDI_{vol}$
0.562	162
0.938	97



Variable pitch.

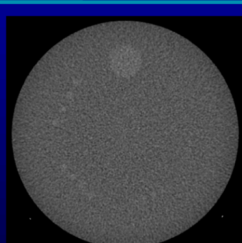
All other parameters constant.

Pitch: 0.938
$CTDI_{vol}$: 97 mGy

Courtesy of Dr. James Kofler, Mayo Clinic (AAPM 11)

Pitch

Pitch	$CTDI_{vol}$
0.562	162
0.938	97
1.375	66



Variable pitch.

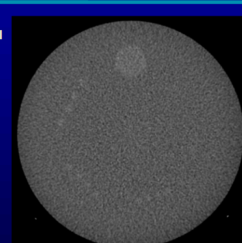
All other parameters constant.

Pitch: 1.375
$CTDI_{vol}$: 66 mGy

Courtesy of Dr. James Kofler, Mayo Clinic (AAPM 11)

Pitch

Pitch	$CTDI_{vol}$
0.562	162
0.938	97
1.375	66
1.75	52



Variable pitch.

All other parameters constant.

Pitch: 1.75
$CTDI_{vol}$: 52 mGy

Courtesy of Dr. James Kofler, Mayo Clinic (AAPM 11)

Slice Thickenss

- Affects Noise and Low contrast Resolution
- Does not affect dose if changed retrospectively
- Can dramatically increase mA and dose if you try to compensate for increase noise in thinner slices.

Slice Thickness

$$\text{Noise} \propto \frac{1}{\sqrt{\#\ \text{Photons}}}$$

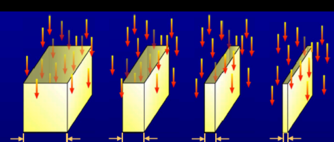


Image (mm):	5	2.5	1.25	0.625
Rel. Noise:	100%	141%	200%	283%
Req. mAs (for = noise):	100%	200%	400%	800%

- Better z-resolution (less partial vol. averaging)
- Increased image noise
- *Potential* for increased radiation dose

Courtesy of Dr. James Kofler, Mayo Clinic (AAPM 11)

Slice Thickness

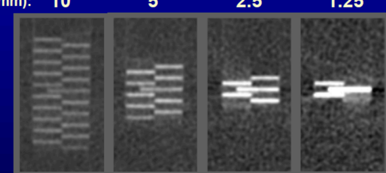


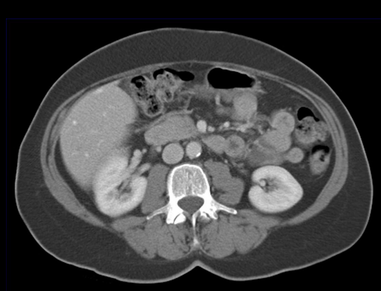
Image (mm):	10	5	2.5	1.25
Noise (HU):	2.93	3.84	5.89	7.82

Thinner images => less partial volume effect

Only image thickness varied, all other parameters are identical

Courtesy of Dr. James Kofler, Mayo Clinic (AAPM 11)

Slice Thickness (10 mm)

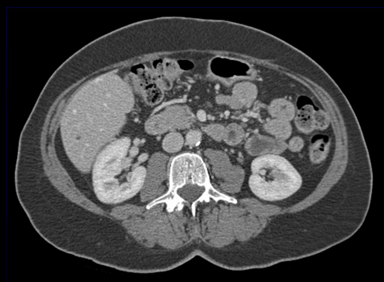


Courtesy of Dr. James Kofler, Mayo Clinic (AAPM 11)

Slice Thickness (5 mm)

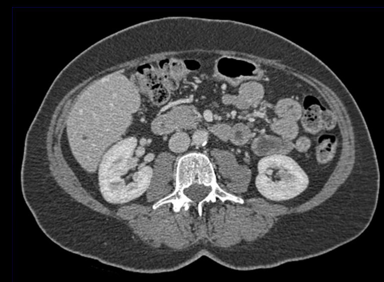
Courtesy of Dr. James Kofler, Mayo Clinic (AAPM 11)

Slice Thickness (2 mm)



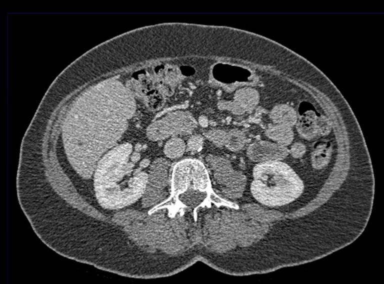
Courtesy of Dr. James Kofler, Mayo Clinic (AAPM 11)

Slice Thickness (1 mm)



Courtesy of Dr. James Kofler, Mayo Clinic (AAPM 11)

Slice Thickness (0.6 mm)



Courtesy of Dr. James Kofler, Mayo Clinic (AAPM 11)

Take-home Points

1. Spiral => continuous scanning, shorter time.
2. Images can be reconstructed:
   - In overlapped fashion.
   - At any arbitrary location.
3. No significant difference in image quality.
4. 3-D resolution is improved by spiral CT!!!
5. The lower the pitch, the higher the dose.
6. More detector rows mean:
   - shorter scan time,
   - lower dose,
   - more patient comfort,
   - better image quality.