Fundamentals of Cone-Beam CT Imaging

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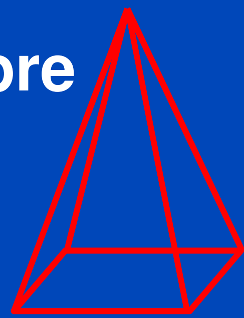
DEUTSCHES KREBSFORSCHUNGSZENTRUM IN DER HELMHOLTZ-GEMEINSCHAFT

Learning Objectives

- To understand the principles of volumetric image formation with flat detectors.
- To understand the difference between CBCT and MSCT.
- To learn about reconstruction techniques and image processing.
- To become acquainted with the important image quality parameters.

Terminology Cone-Beam CT

- The shape of the x-ray ensemble depends on the pre patient collimation and can be approximated by
  - a cone if the detector is a circle (e.g. an image intensifier)
  - a pyramid if the detector is a rectangle (e.g. a flat detector)
  - a distorted pyramid if the detector is an arc (e.g. a clinical CT detector)



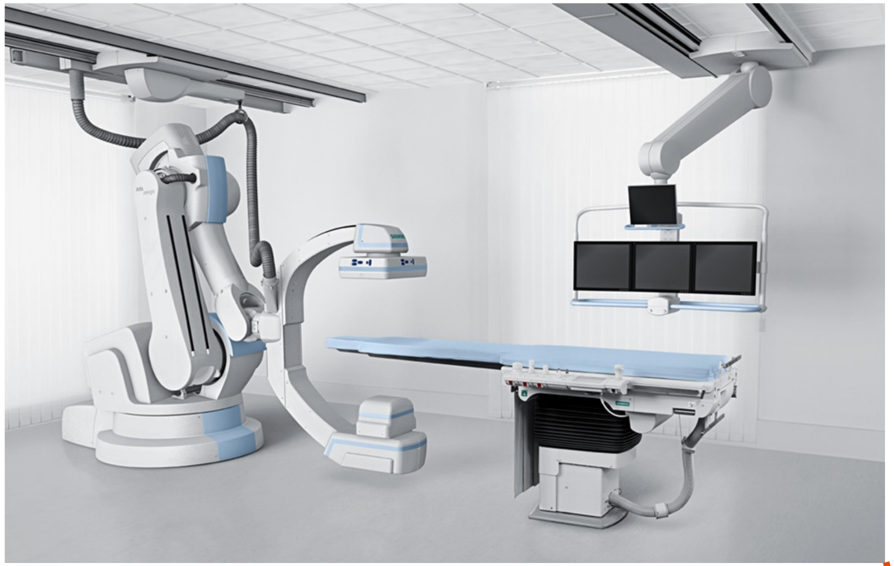
- Cone-beam CT =
  - a CT with many detector rows?
  - a CT equipped with flat detectors?
  - a CT that requires a volumetric reconstruction!
- Flat detector =
  - indirect converting, based on TFT (amorph. Si) or CMOS (cryst. Si)
  - a detector of low aspect ratio (number of columns ≈ number of rows)
- Often used synonymously:
  - CT = clinical CT = diagnostic CT = MSCT = multi slice CT
  - CBCT = cone-beam CT = FDCT = flat detector CT (non diagnostic)

Clinical CT

Clinical CT detector inside

e.g. Definition Flash dual source spiral cone-beam CT scanner, Siemens Healthcare, Forchheim, Germany.

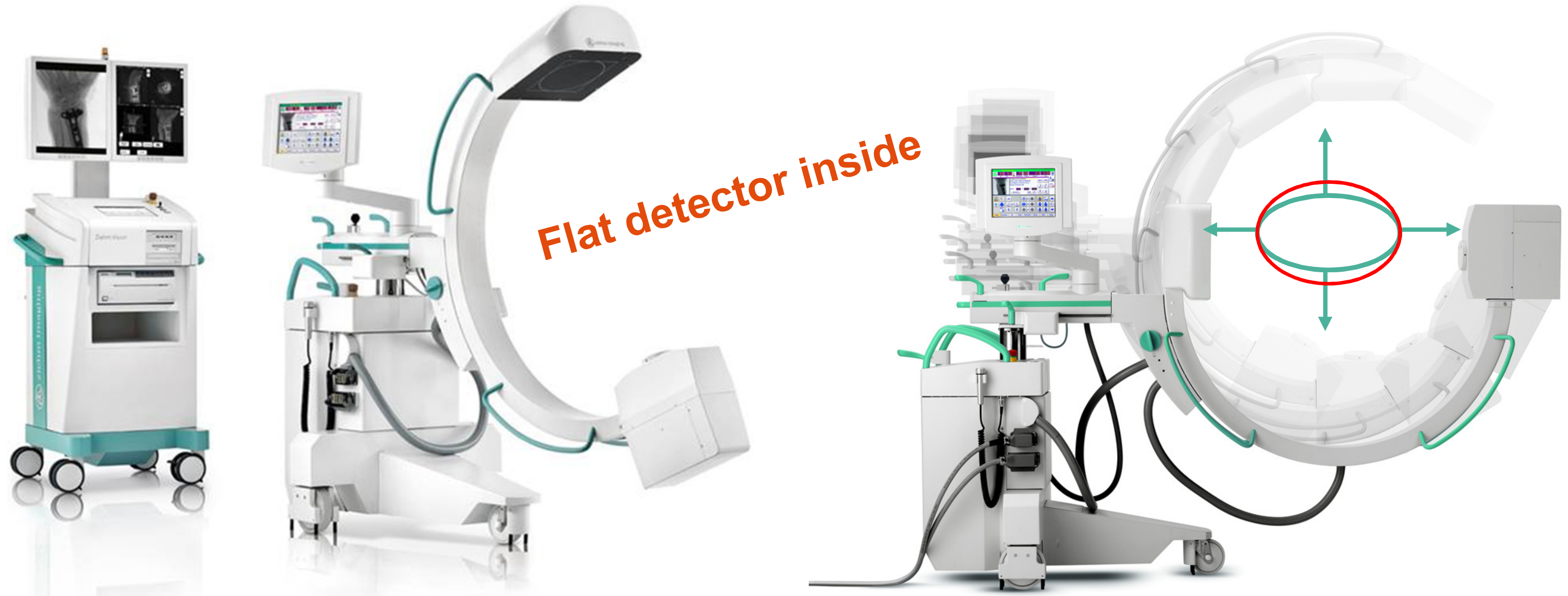
Fixed C-Arm CT



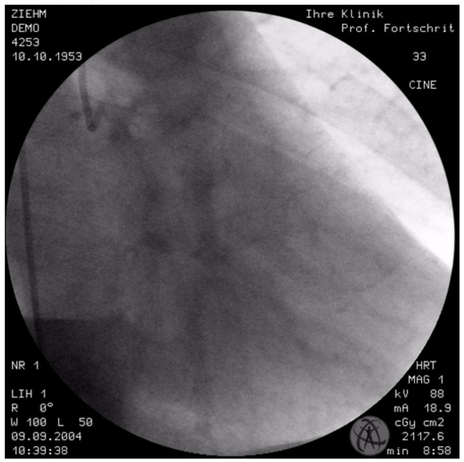
Flat detector inside

e.g. floor-mounted Artis Zeego or ceiling-mounted Artis Zee, Siemens Healthcare, Forchheim, Germany

Mobile C-Arm CT



e.g. Vision FD Vario 3D, Ziehm Imaging GmbH, Nürnberg, Germany



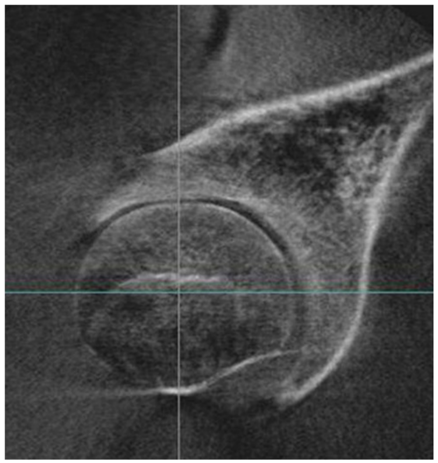
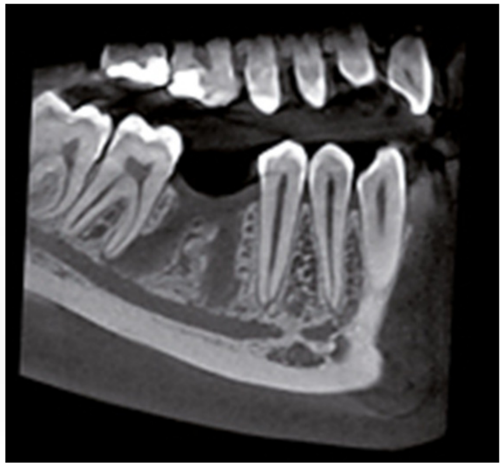


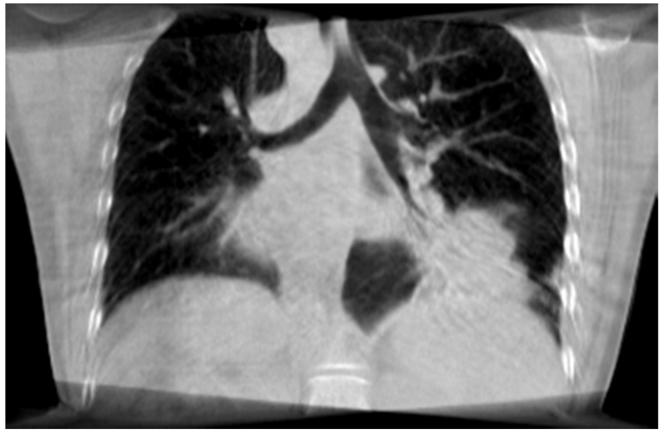
Image courtesy by Ziehm Imaging

Dental Volume Tomography (DVT)



e.g. Orthophos XG 3D, Sirona Dental Systems GmbH, Bensheim, Germany

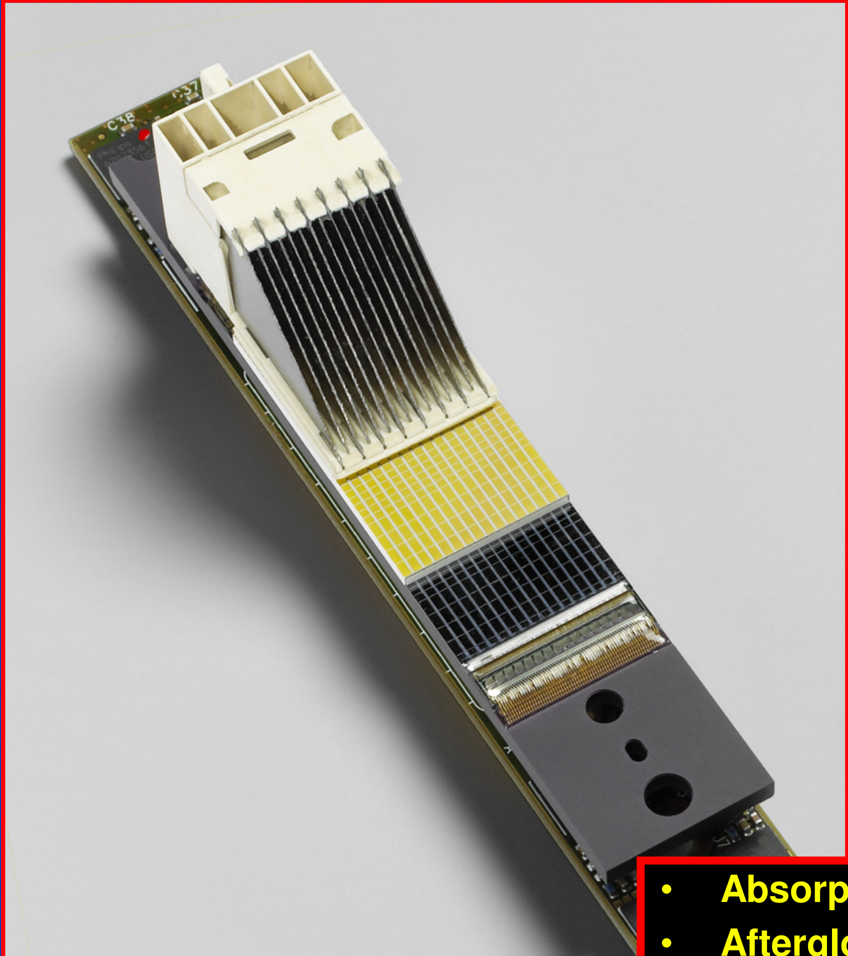
CBCT Guidance for Radiation Therapy



e.g. TrueBeam, Varian Medical Systems, Palo Alto, CA, USA

Detector Technology

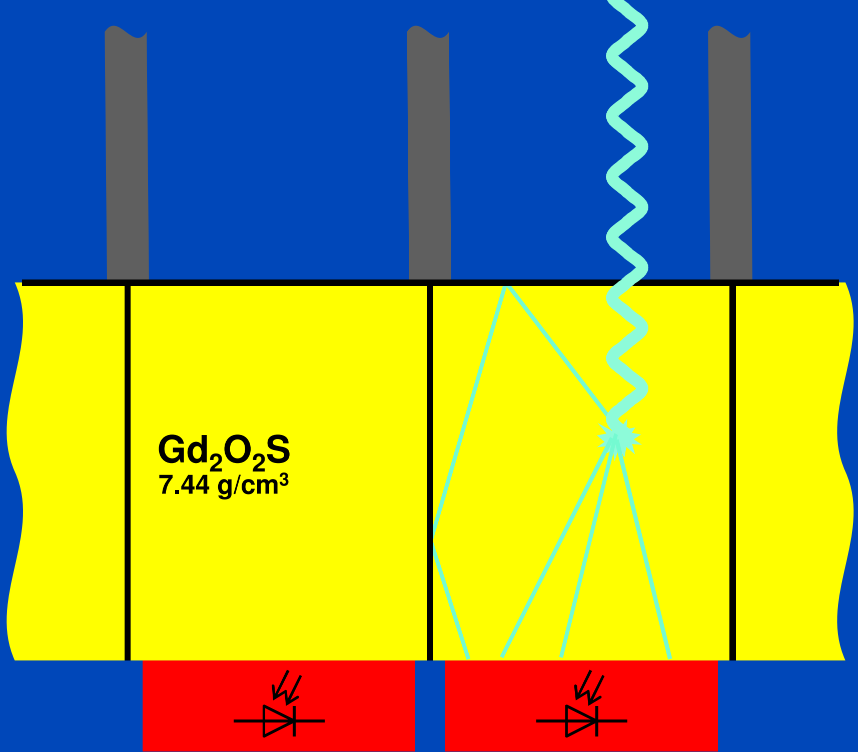
Clinical CT Detector



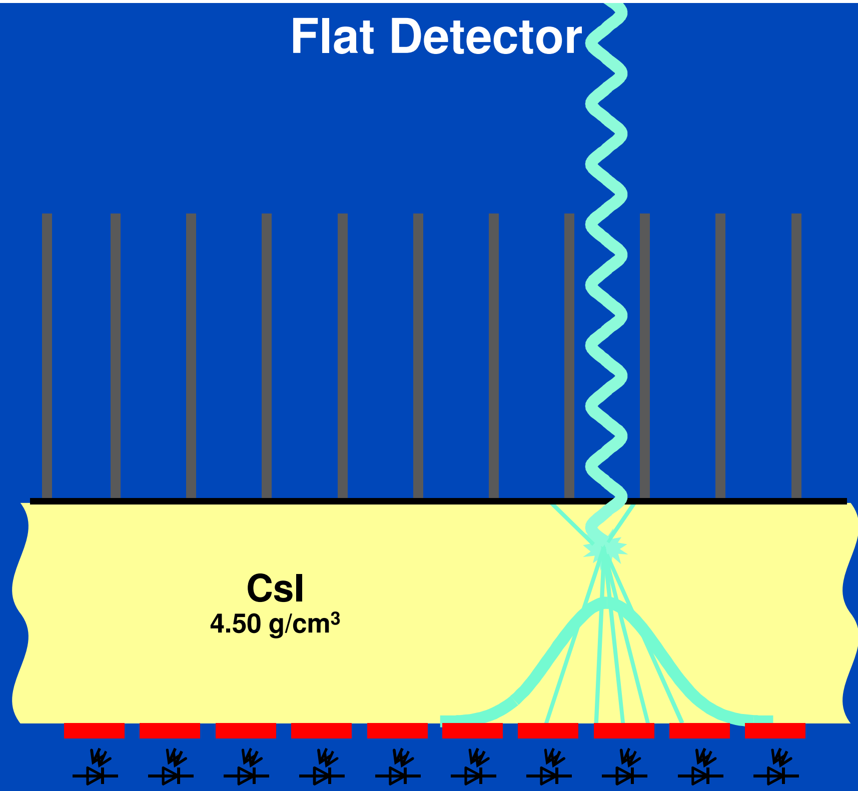
Flat Detector

- Absorption efficiency
- Afterglow
- Dynamic range
- Cross-talk
- Framerate
- Scatter grid

Clinical CT Detector



Flat Detector



Clinical CT Detector

- Anti-scatter grids are aligned to the detector pixels
- Anti-scatter grids reject scattered radiation
- Detector pixels are of about 1.2 mm size
- Detector pixels are structured, reflective coating maximizes light usage and minimizes cross-talk
- Thick scintillators improve dose usage
- Gd_2O_2S is a high density scintillator with favourable decay times
- Individual electronics, fast read-out (5 kHz)
- Very high dynamic range (10^7) can be realized

Flat Detector

- Anti-scatter grids are not aligned to the detector pixels
- The benefit of anti-scatter grids is unclear
- Detector pixels are of about 0.2 mm size
- Detector pixels are unstructured, light scatters to neighboring pixels, significant cross-talk
- Thick scintillators decrease spatial resolution
- CsI grows columnar and suppresses light scatter to some extent
- Row-wise readout is rather slow (25 Hz)
- Low dynamic range ($<10^3$), long read-out paths

Dose Efficiency of Flat Detectors

	Clinical CT (120 kV)			Flat Detector CT (120 kV)			Micro CT (60 kV)		
Material	Gd_2O_2S			CsI			CsI		
Density	7.44 g/cm^3			4.5 g/cm^3			4.5 g/cm^3		
Thickness	1.4 mm			0.6 mm			0.3 mm		
Manufacturer	Siemens			Varian			Hamamatsu		
Water Layer	0 cm	20 cm	40 cm	0 cm	20 cm	40 cm	0 cm	4 cm	8 cm
Photons absorbed	98.6%	97.7%	96.7%	80.0%	69.8%	62.2%	85.3%	85.6%	85.8%
Energy absorbed	94.5%	91.4%	88.7%	66.6%	55.4%	48.3%	67.1%	65.2%	64.2%

Absorption values are relative to a detector of infinite thickness.

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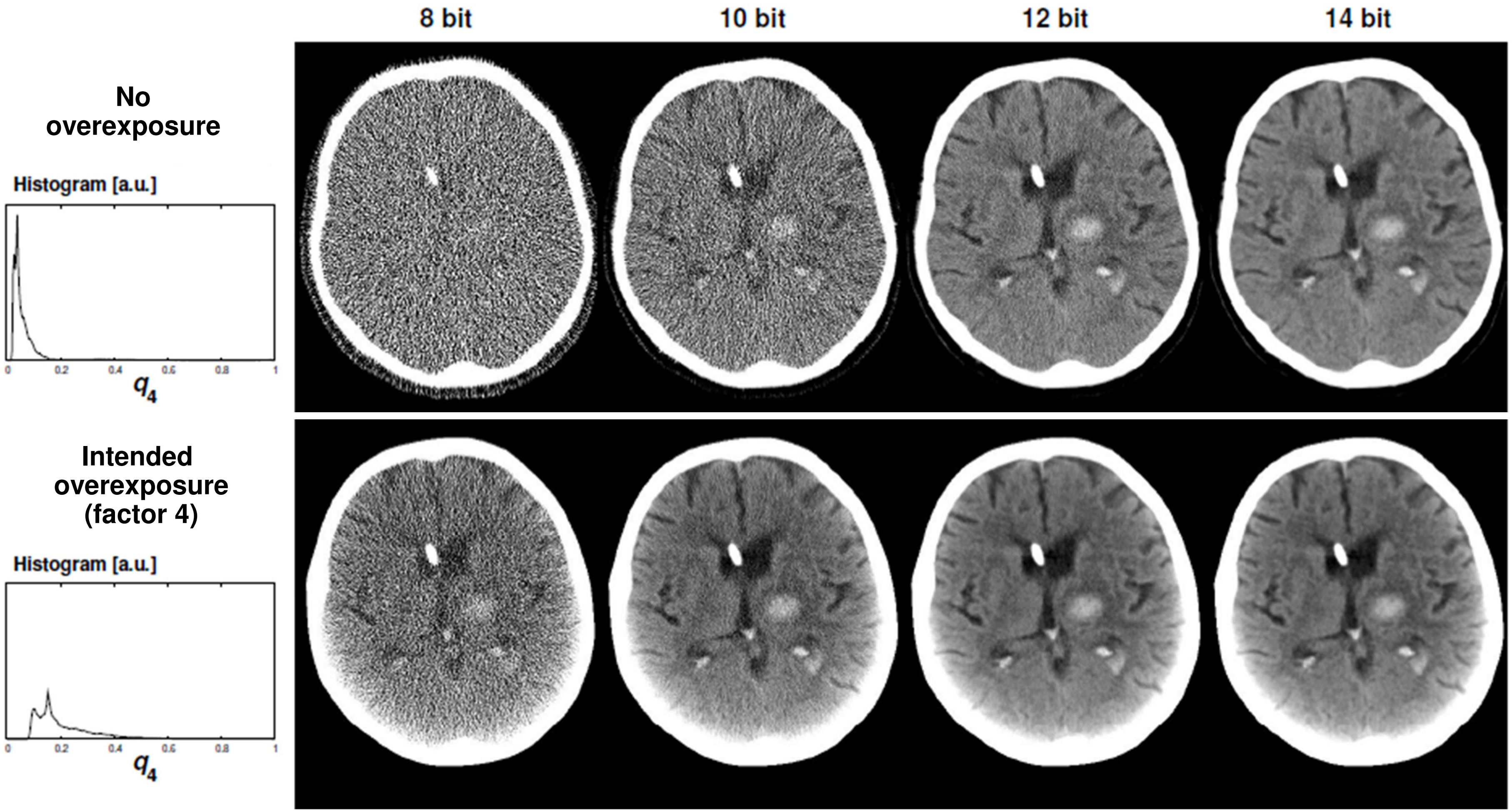
Dynamic Range in Flat Detectors

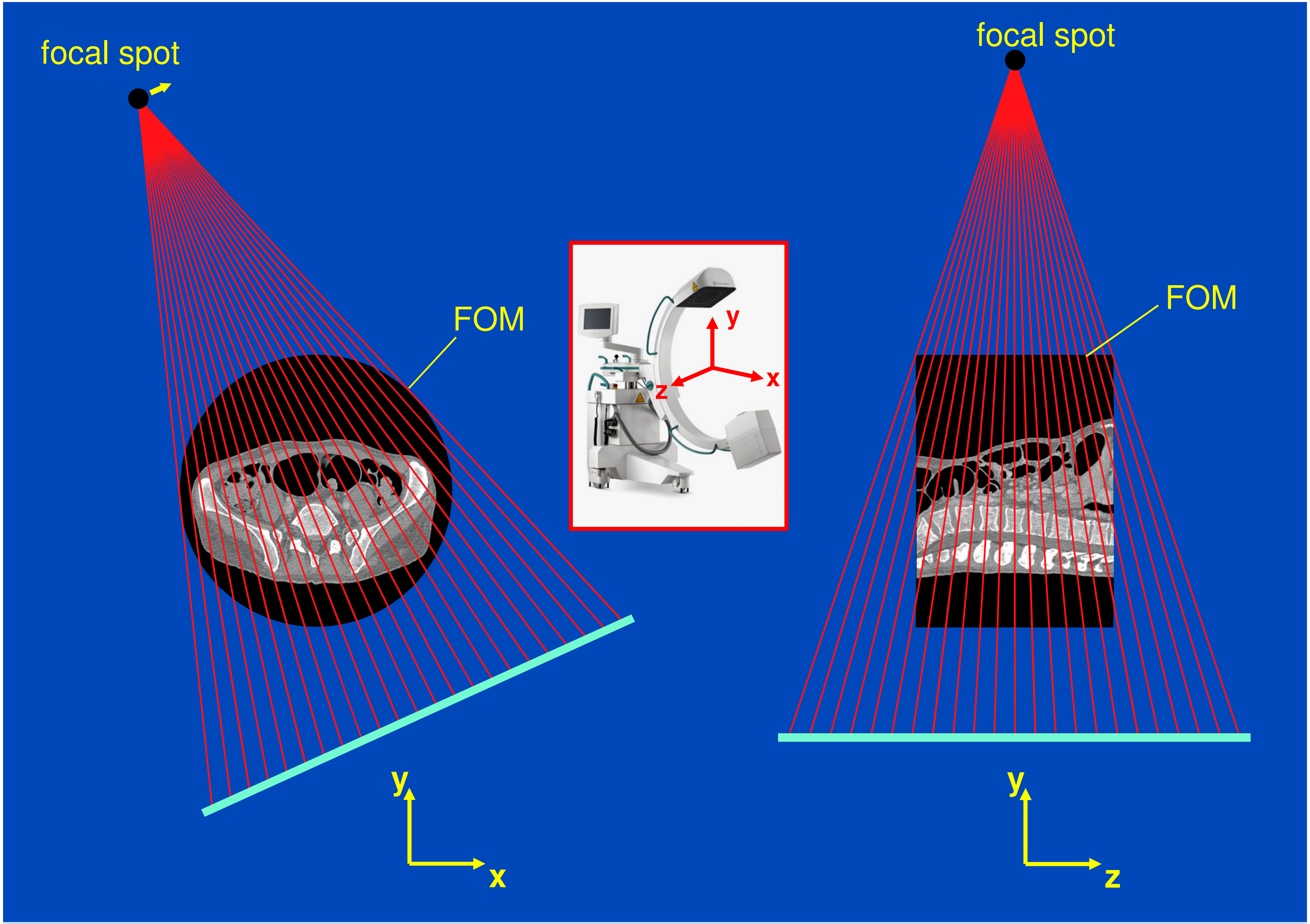
	Saturation-to-noise range			X-ray exposure range				Digital range	
	Electronic noise (ADU)	Saturation signal (ADU)	Dynamic range	Quantum limited exposure (μR)	Saturation exposure (μR)	Dynamic range	Eff. bit depth (bits)	Quantization range	Eff. bit depth (bits)
No binning, gain 2	A1	B1	B1/A1	A2	B2	C2=B2/A2	D2=lb(C2)	B1:1	lb(B1)
Dynamic gain switching	5.32	80500	15100	2.75	3550	**1291**	**10.3**	80500:1	16.3
0.5 pF fixed	5.32	14500	2700	2.75	595	**216**	**7.8**	14500:1	13.8
4 pF fixed	3.57	14800	4150	35.7	4200	**118**	**6.9**	14800:1	13.8
2x2 binning, gain 1									
Dual gain readout	4.33	80100	18500	1.00	1800	**1800**	**10.8**	80100:1	16.3
Dynamic gain switching	4.37	84200	19300	1.03	2062	**2002**	**11.0**	84200:1	16.4
0.5 pF fixed	4.37	14300	3300	1.03	311	**302**	**8.2**	14300:1	13.8
4 pF fixed	3.14	14800	4700	15.6	2104	**135**	**7.1**	14800:1	13.8
0.5 pF fixed, gain 2 (fluoroscopy mode)	7.25	12900	1700	0.71	125	**176**	**7.5**	12900:1	13.6

Table 2 4030CB dynamic range in available imaging modes

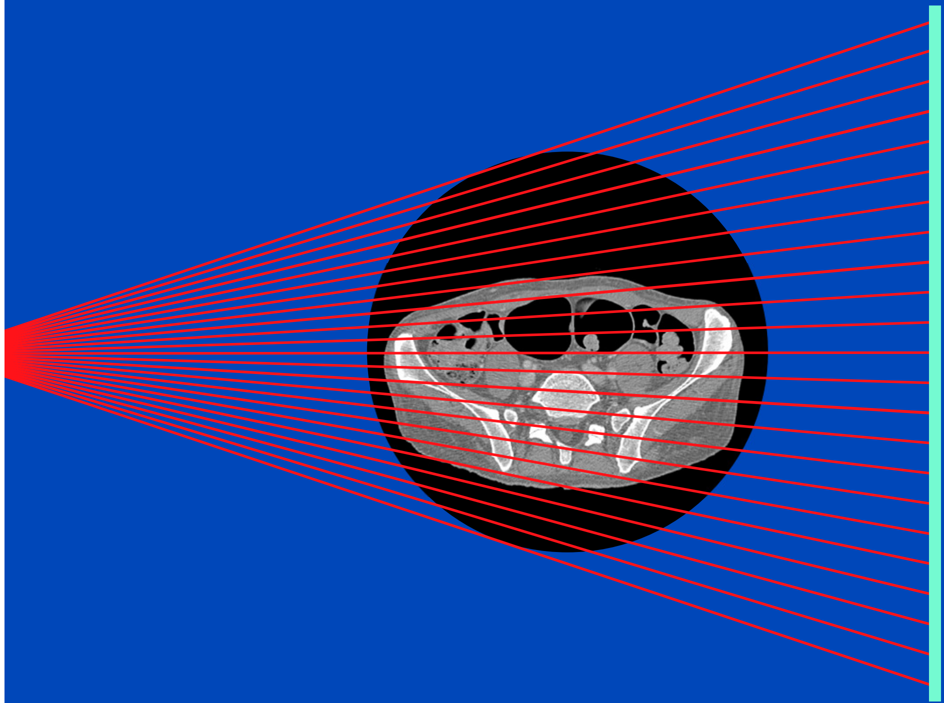
A2 is defined as the exposure where QuantumNoise=ElectronicNoise.

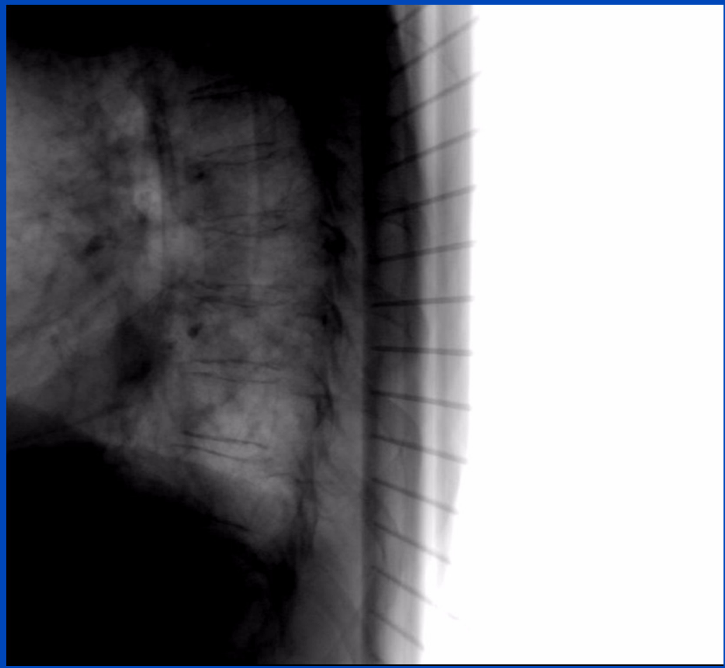
Table taken from [Roos et al. "Multiple gain ranging readout method to extend the dynamic range of amorphous silicon flat panel imagers," *SPIE Medical Imaging Proc.*, vol. 5368, pp. 139-149, 2004]. Additional values were added, for convenience.


8 bit
10 bit
12 bit
14 bit
No overexposure
Histogram [a.u.]
0
0.2
0.4
0.6
0.8
1
q_4
Intended overexposure (factor 4)
Histogram [a.u.]
0
0.2
0.4
0.6
0.8
1
q_4



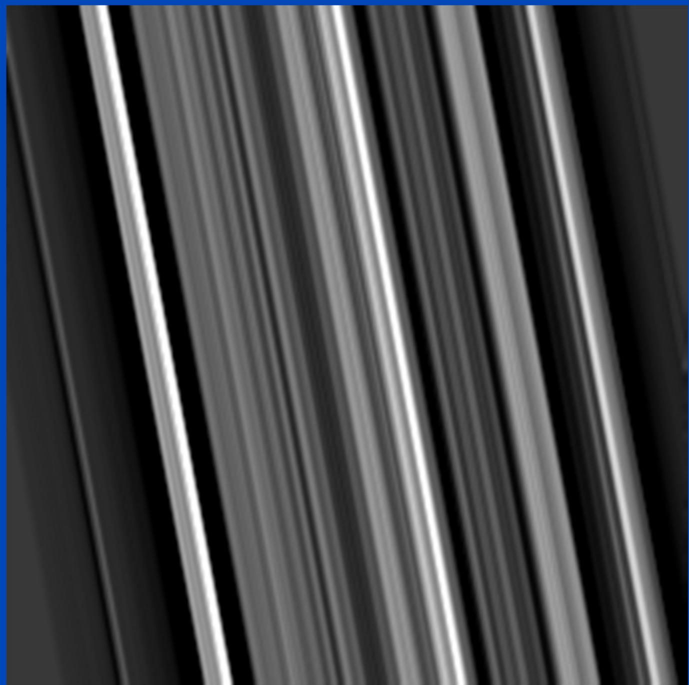
Detector: 1000×1000 to 4000×4000 elements, typically



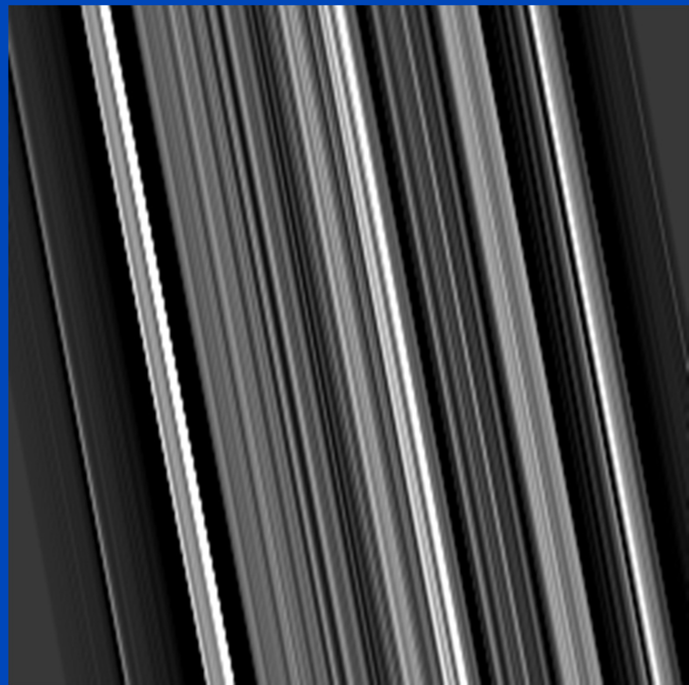


Filtered Backprojection (FBP)

1. Filter projection data with the reconstruction kernel.
2. Backproject the filtered data into the image:



Smooth

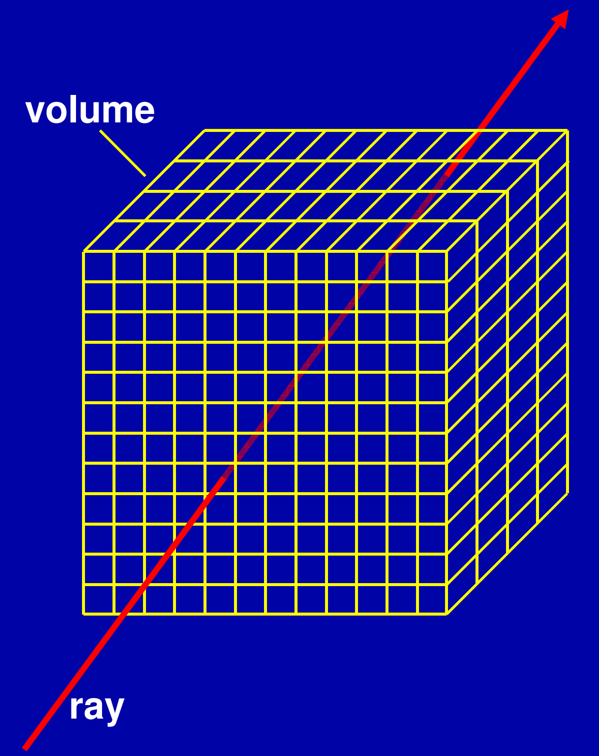


Standard

Reconstruction kernels balance between spatial resolution and image noise.

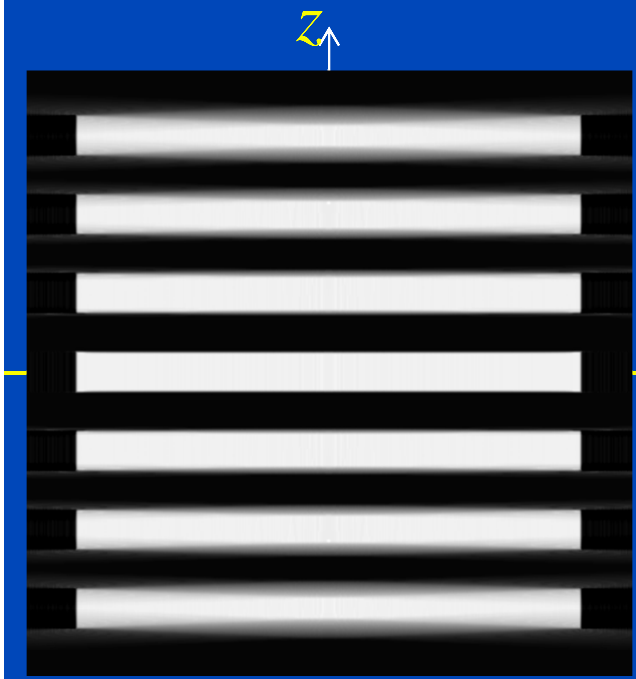
Feldkamp-Type Reconstruction

- **Approximate**
- **Similar to 2D reconstruction:**
  - row-wise filtering of the rawdata
  - followed by backprojection
- **True 3D volumetric backprojection along the original ray direction**

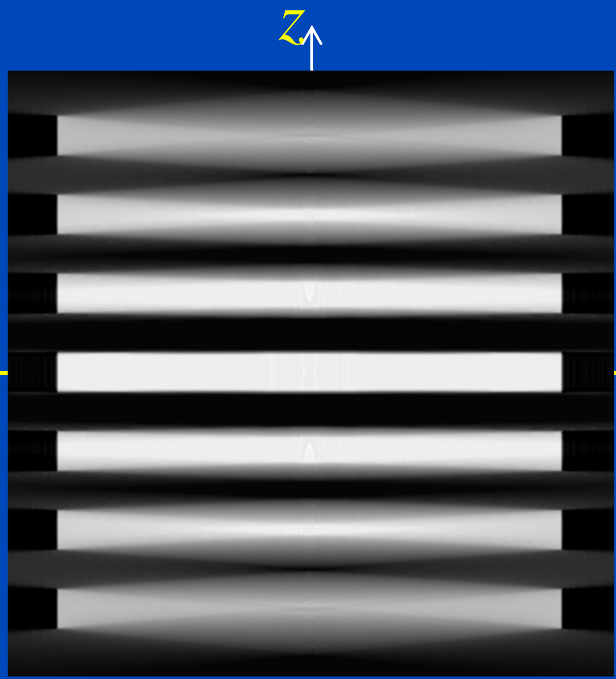


3D backprojection

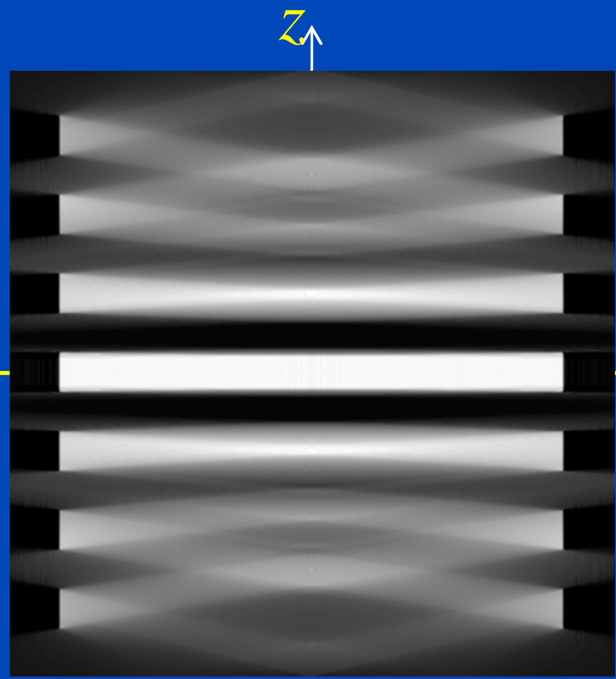
Cone-Beam Artifacts



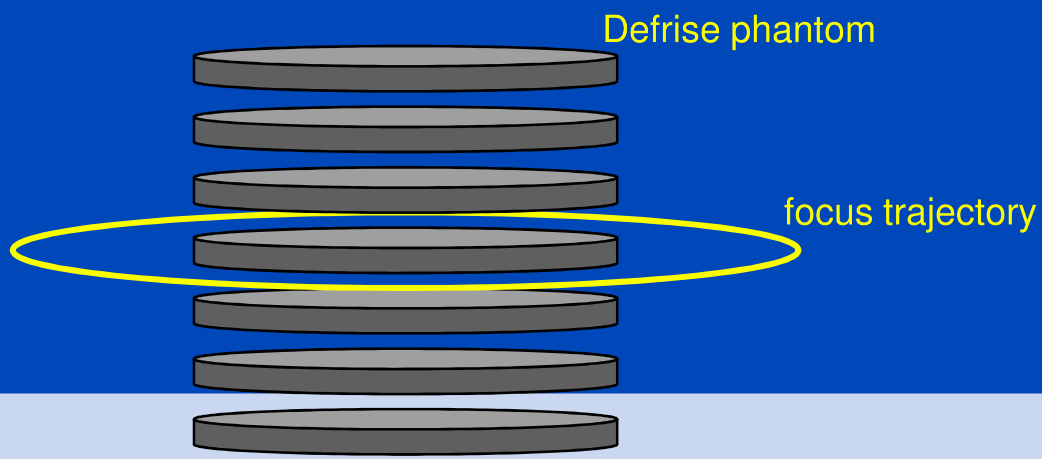
Cone-angle $\Gamma = 6°$



Cone-angle $\Gamma = 14°$

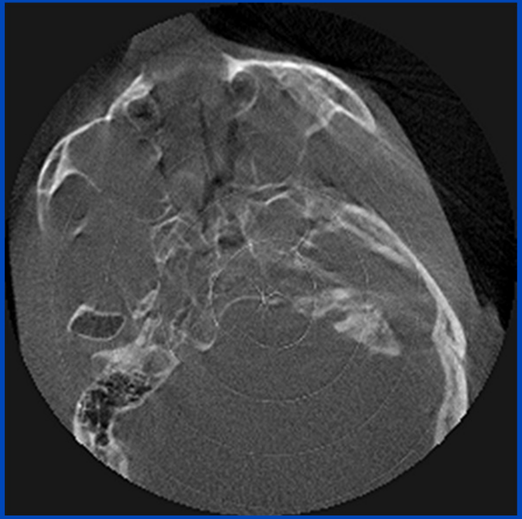


Cone-angle $\Gamma = 28°$

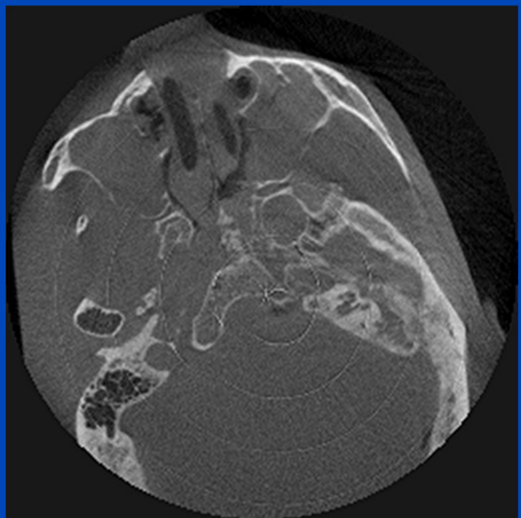


Data and Image Processing

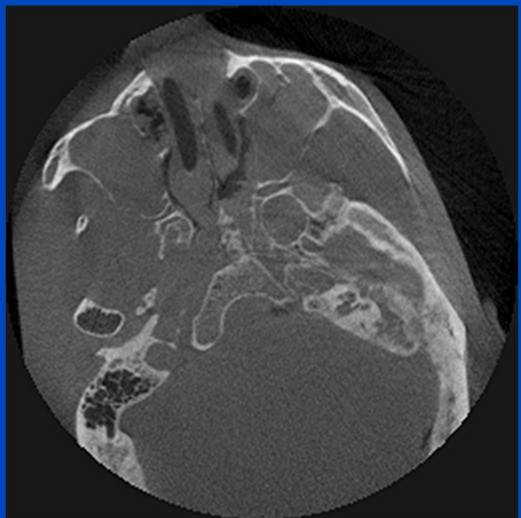
Uncorrected



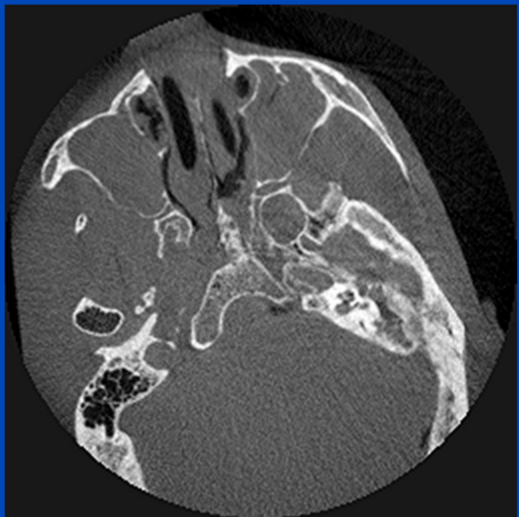
With Geometric Calibration

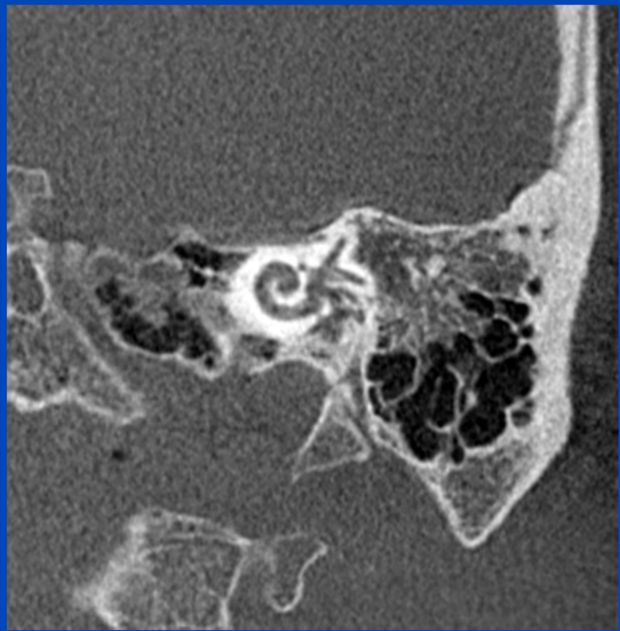


With Detector Calibration

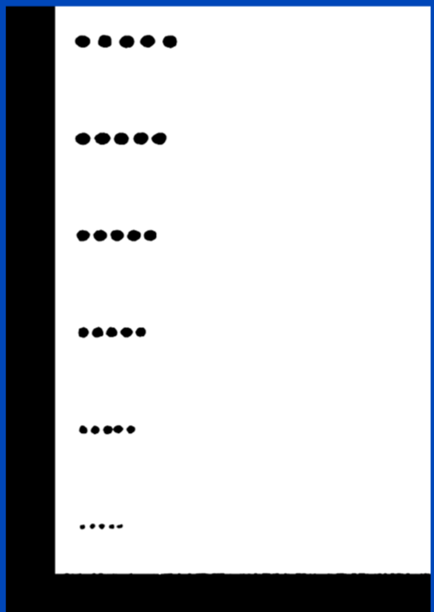


With Scatter and Beam Hardening Correction

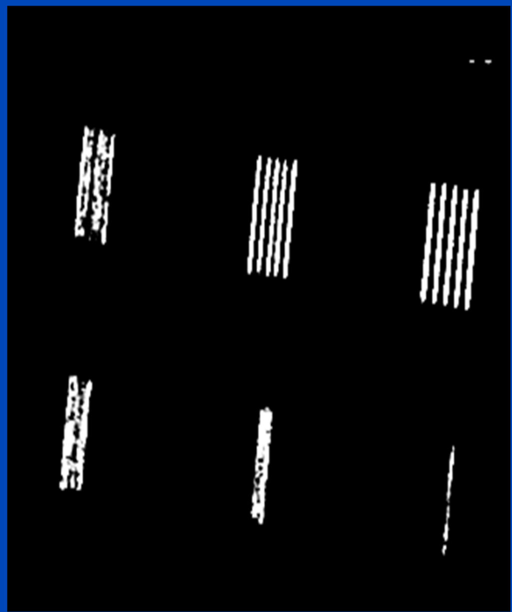




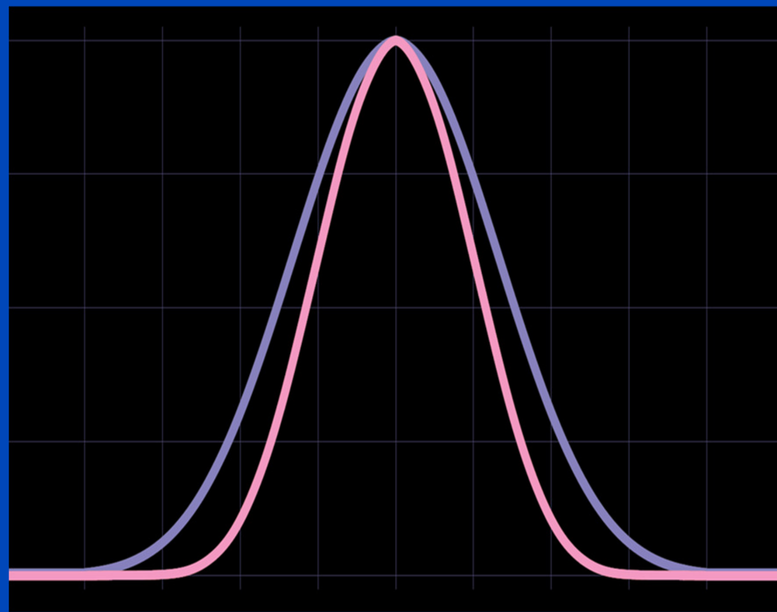
Spatial Resolution



Method 1

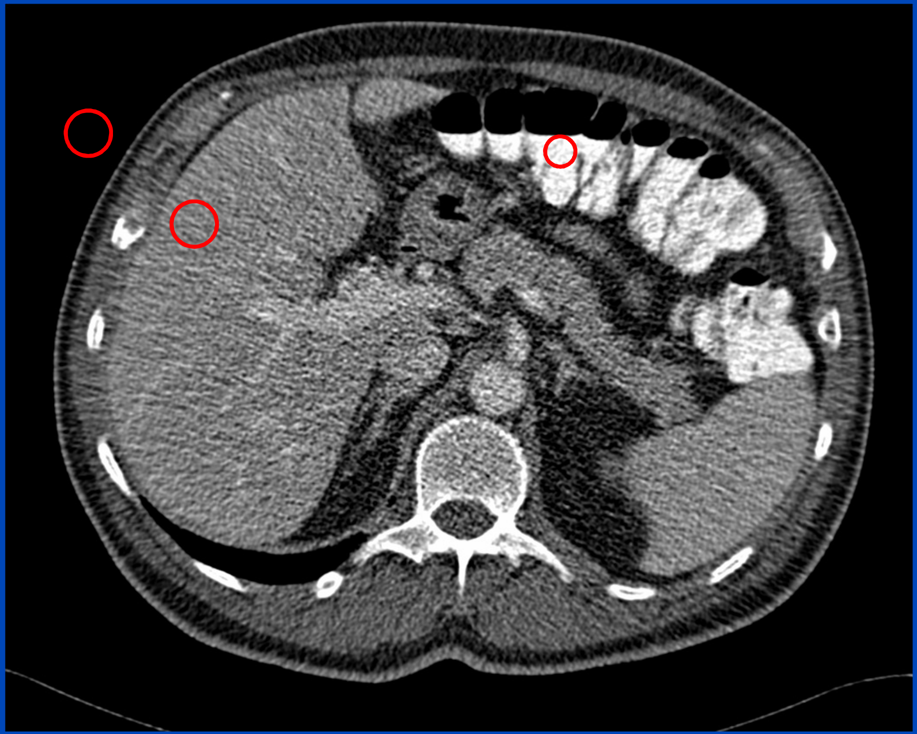


Method 2



Method 3

Image Noise



150 HU / 600 HU

Air ROI: μ = -995 HU, σ = 31 HU
Soft tissue ROI: μ = 148 HU, σ = 59 HU
Iodine ROI: μ = 423 HU, σ = 62 HU

Dependencies of IQ and Dose

- **Image quality is determined by spatial resolution and contrast resolution (image noise)**
- **Image noise σ decreases with the square-root of dose**

$$\sigma^2 = \text{Noise}^2 \propto \frac{1}{\text{Dose}} \propto \frac{1}{\text{mAs}_{\text{eff}}}$$

- **Dose increases with the fourth power of the spatial resolution for a given object and image noise**

$$\underbrace{\left(\frac{\sigma}{\mu}\right)^2}_{\substack{\text{Noise relative to} \\ \text{the background} \\ (= 1/\text{SNR})}} \propto \frac{e^{\mu 2R} + 1}{\mu^2 \underbrace{\Delta x^4}_{\substack{\text{Fourth power of} \\ \text{the spatial} \\ \text{resolution}}}}$$

Noise relative to the background (= 1/SNR)

Fourth power of the spatial resolution

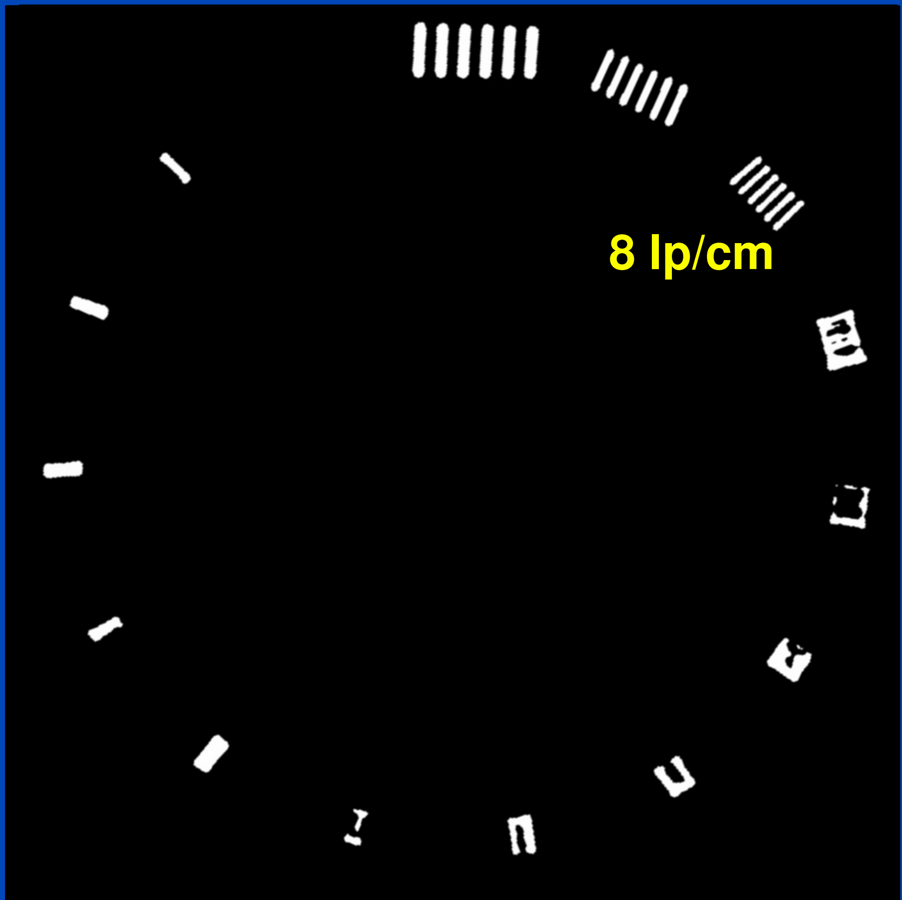
Always Relate SNR and CNR to Unit Dose!

- SNR and CNR are useless for comparisons if these are not taken at the same dose or if SNR and CNR are not normalized to unit dose.
- The terms SNRD and CNRD are used for SNR normalized to unit dose and CNR normalized to unit dose, respectively.

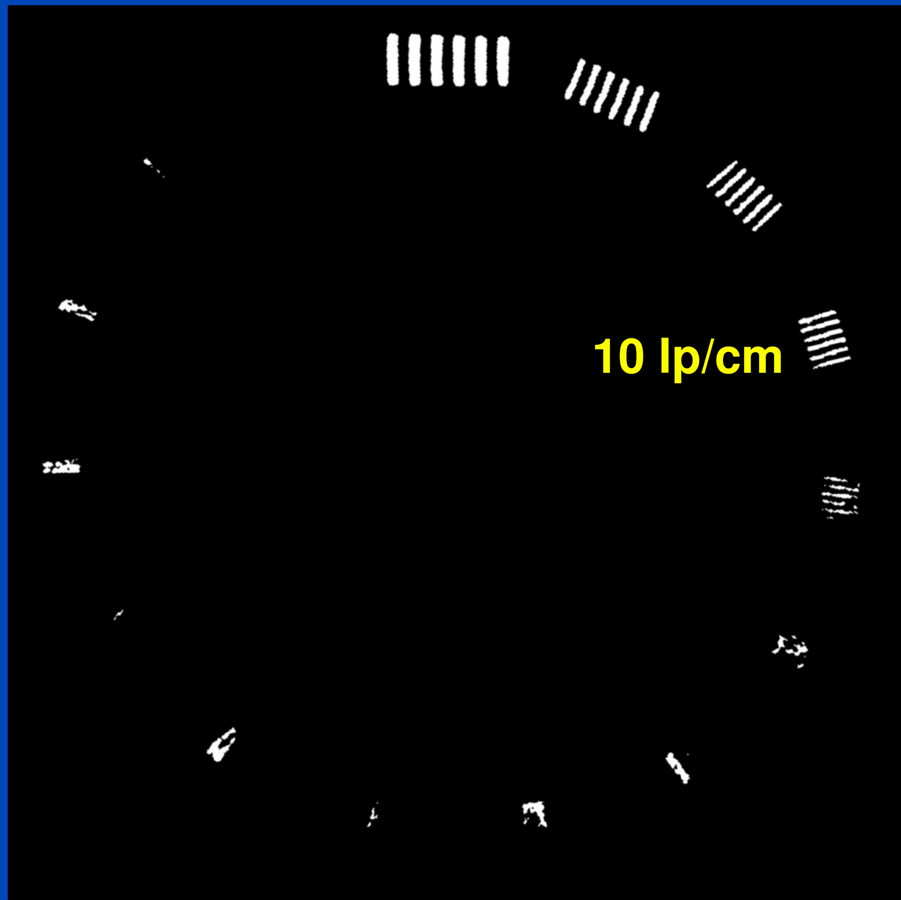
$$SNRD = \frac{\text{Signal}}{\text{Noise}\sqrt{\text{Dose}}} = \frac{SNR}{\sqrt{\text{Dose}}}$$

$$CNRD = \frac{\text{Contrast}}{\text{Noise}\sqrt{\text{Dose}}} = \frac{CNR}{\sqrt{\text{Dose}}}$$

Clinical CT vs. Flat Detector CT

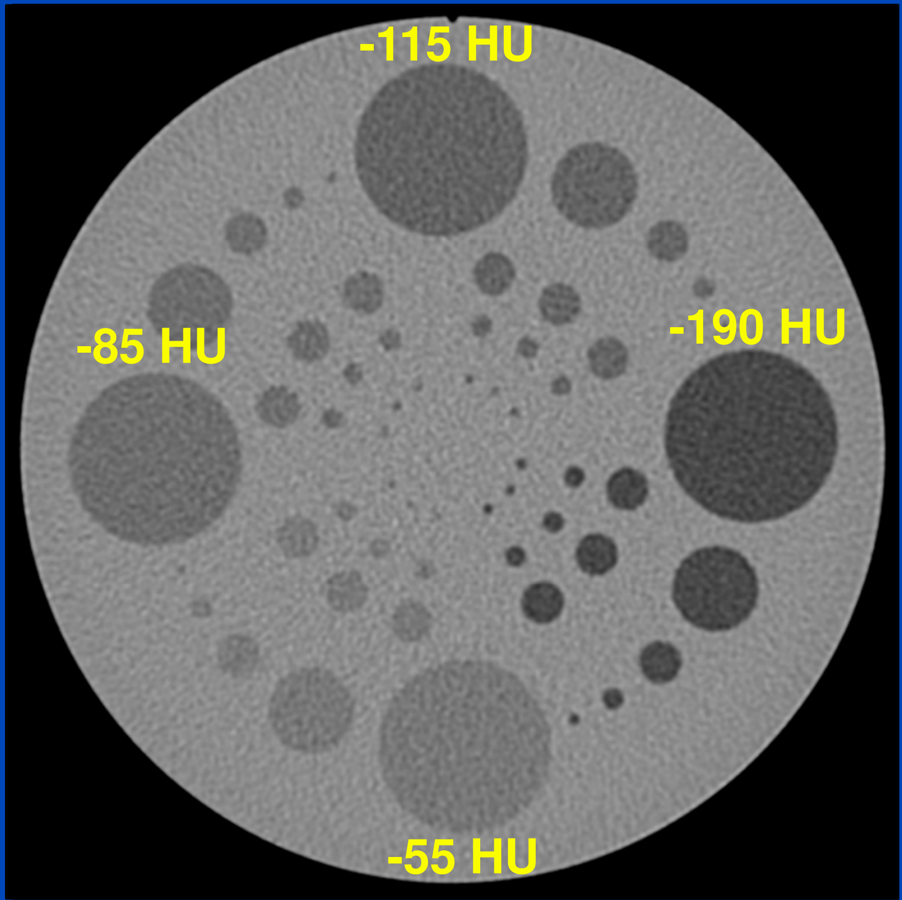


Clinical CT, Standard Kernel

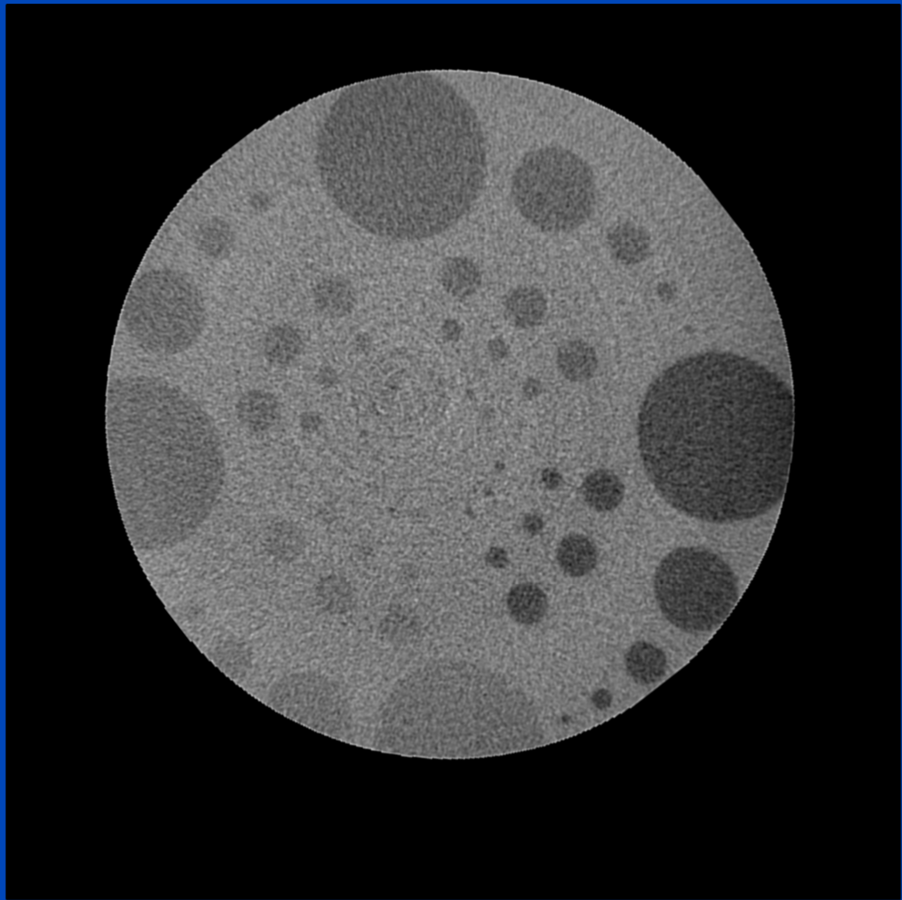


Flat Detector CT, 2×2 Binning

Clinical CT vs. Flat Detector CT

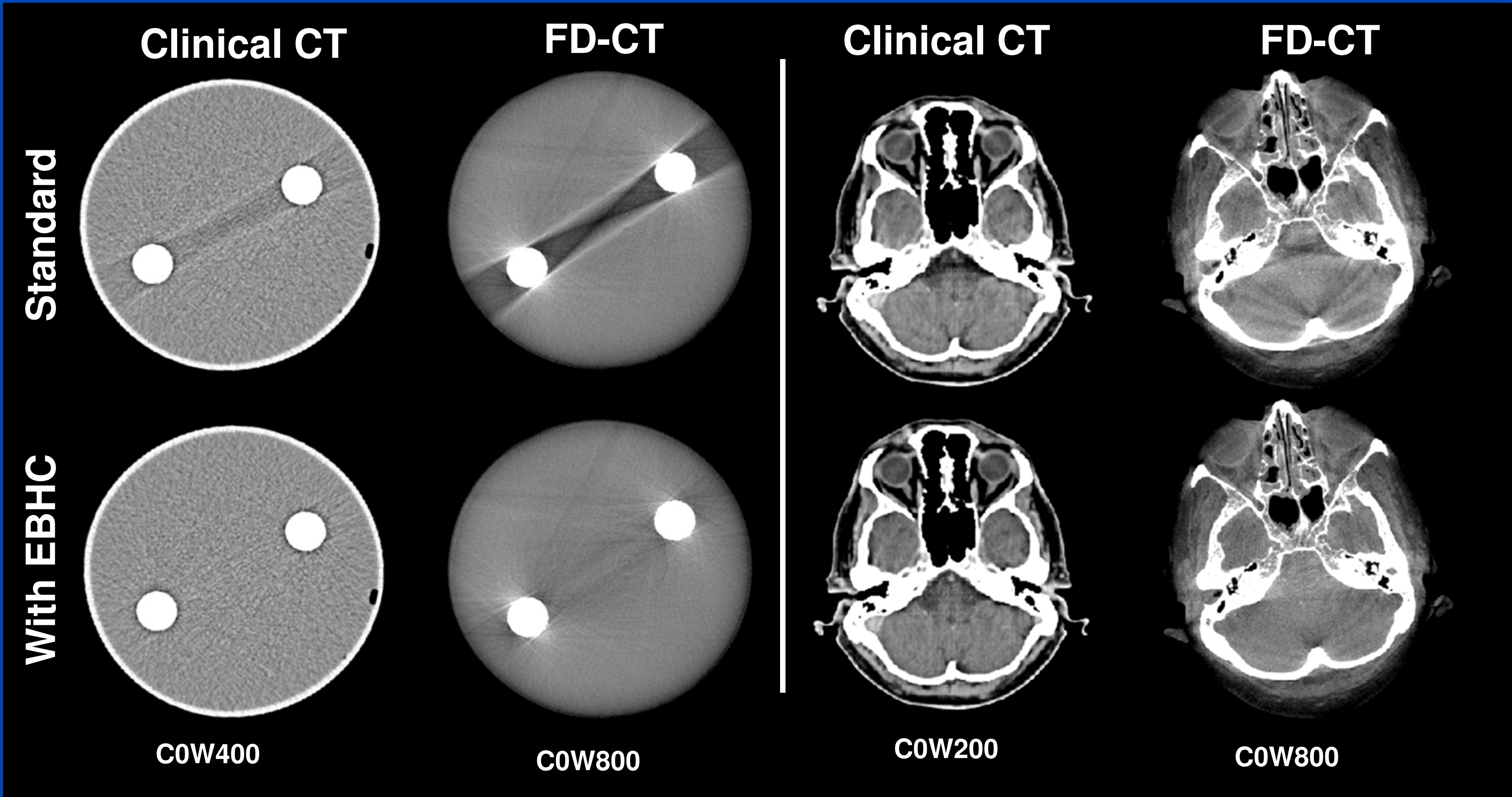


Clinical CT, Standard Kernel
C = 0 HU, *W* = 700 HU



Flat Detector CT, 2×2 Binning

Clinical CT vs. FD-CT



Siemens Somatom Definition vs. Siemens Axiom Artis

Clinical vs. Flat Detector CT

	Clinical CT	Flat Detector CT
Spatial resolution	0.5 mm	0.2 mm
Contrast	3 HU	30 HU
Dynamic range	≈ 20 bit	≈ 10 bit
Dose efficiency	≈ 90%	≈ 50%
Lowest rotation time	0.28 s	3 s
Temporal resolution	0.07 s	3 s
Frame rate	≈ 6000 fps	≈ 30 fps
X-ray power	100 – 120 kW	5 – 25 kW

Summary

- Flat detector CT image reconstruction is typically based on the Feldkamp filtered backprojection algorithm.
- Apart from a higher spatial resolution, flat detector-based cone-beam CT image quality is inferior to clinical CT image quality.
- The high spatial resolution (100 to 200 µm) and the good form factor (small, light weight) of flat detectors justifies their existence for several highly important medical applications (see presentations of Dr. Grass and Dr. Horner)


Thank You!
marc.kachelriess@dkfz.de
This presentation will soon be available at www.dkfz.de/ct.