

Fundamentals of Cone-Beam CT Imaging

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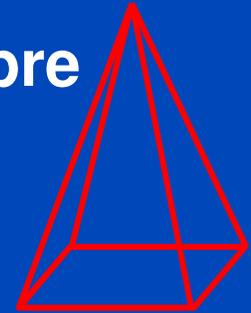
DEUTSCHES
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IN DER HELMHOLTZ-GEMEINSCHAFT

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 \approx number of rows)
- Often used synonymously:
 - CT = clinical CT = diagnostic CT = multi slice CT (MSCT)
 - CBCT = cone-beam CT = flat detector CT (FDCT)

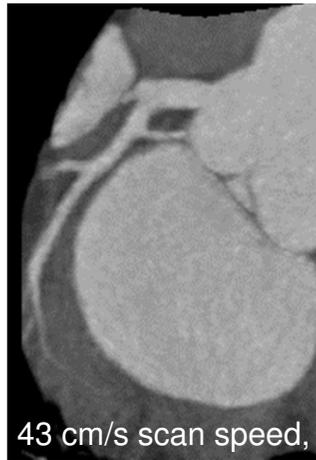


Clinical CT



Clinical CT detector inside

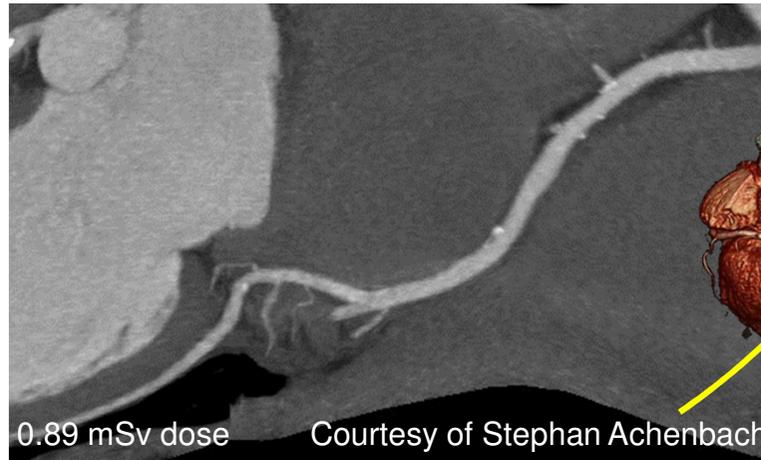
e.g. Definition Flash dual source spiral cone-beam CT scanner, Siemens Healthcare, Forchheim, Germany.



43 cm/s scan speed,



247 ms scan time, 70 ms temp. res.,

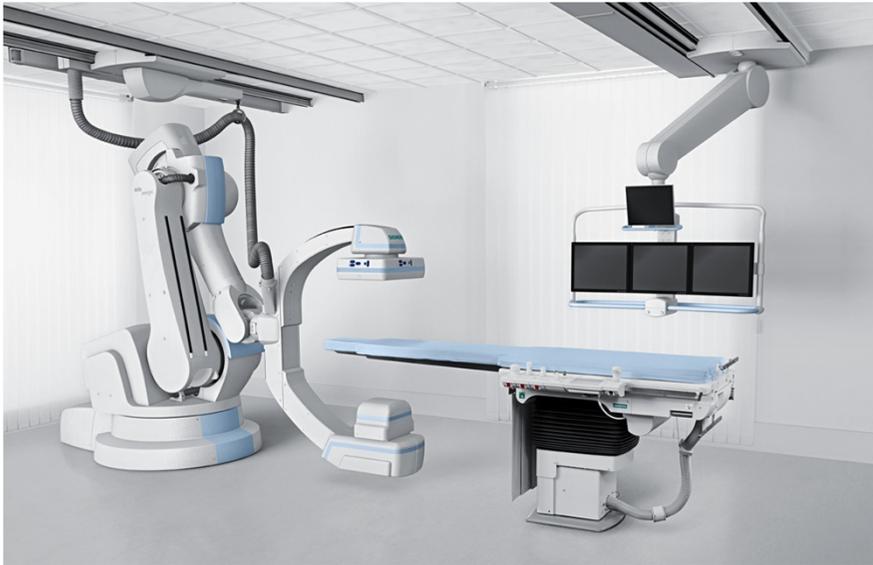


0.89 mSv dose

Courtesy of Stephan Achenbach

Image courtesy by Siemens Healthcare

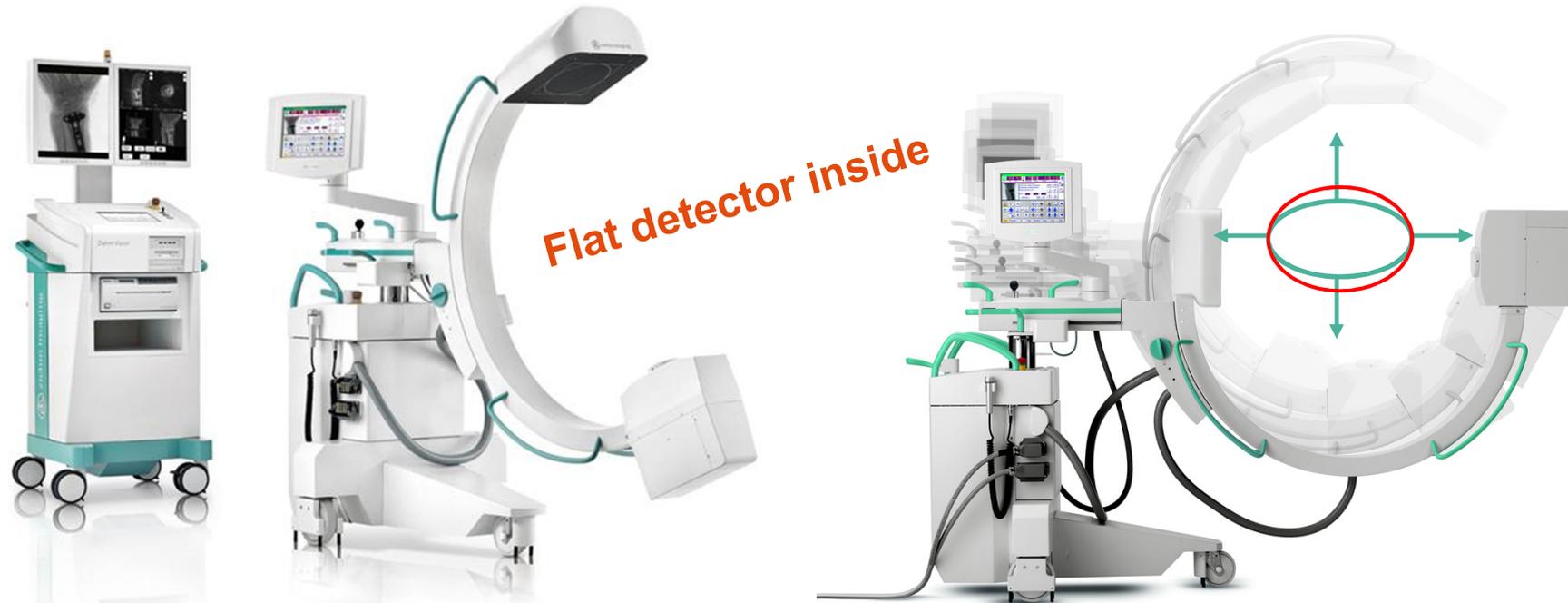
Fixed C-Arm CT



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

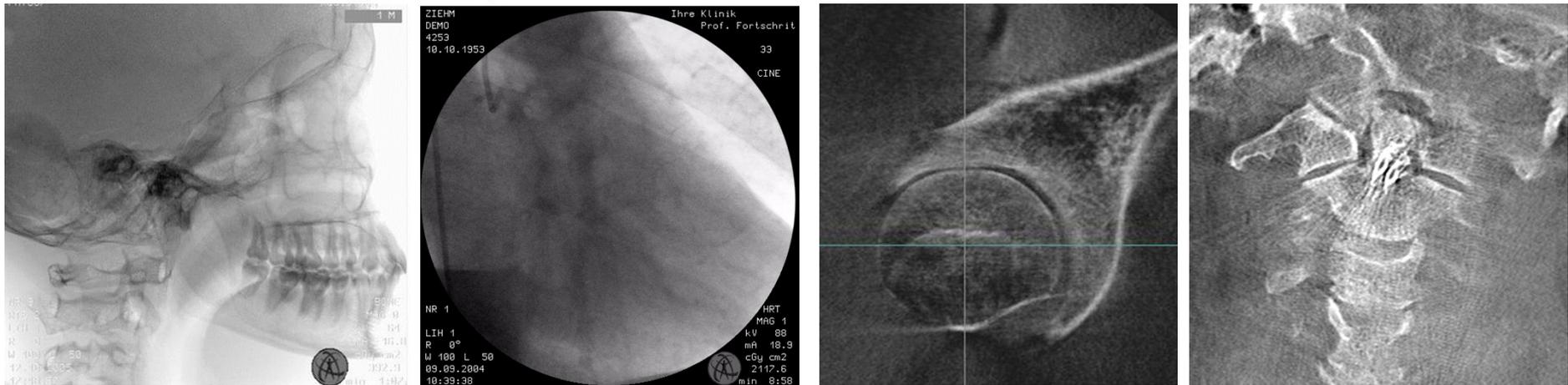
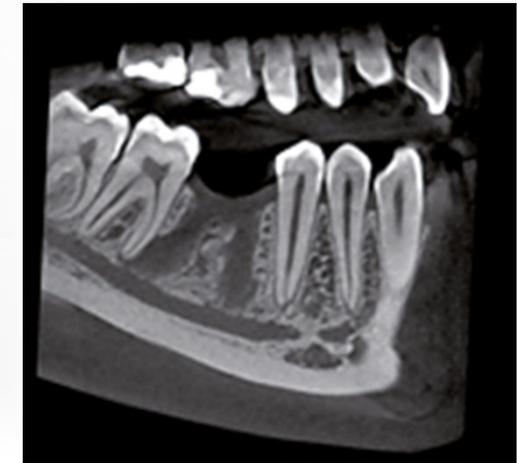


Image courtesy by Ziehm Imaging

Dental Volume Tomography (DVT)



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

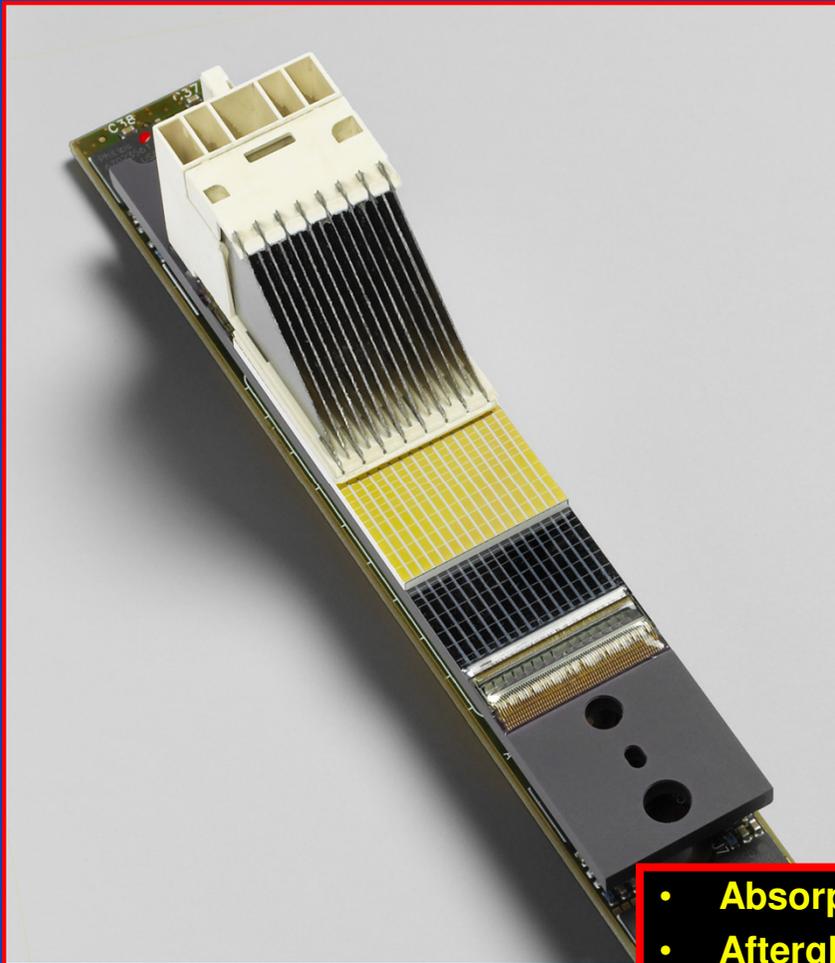
CBCT Guidance for Radiation Therapy



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

Detector Technology

Clinical CT Detector

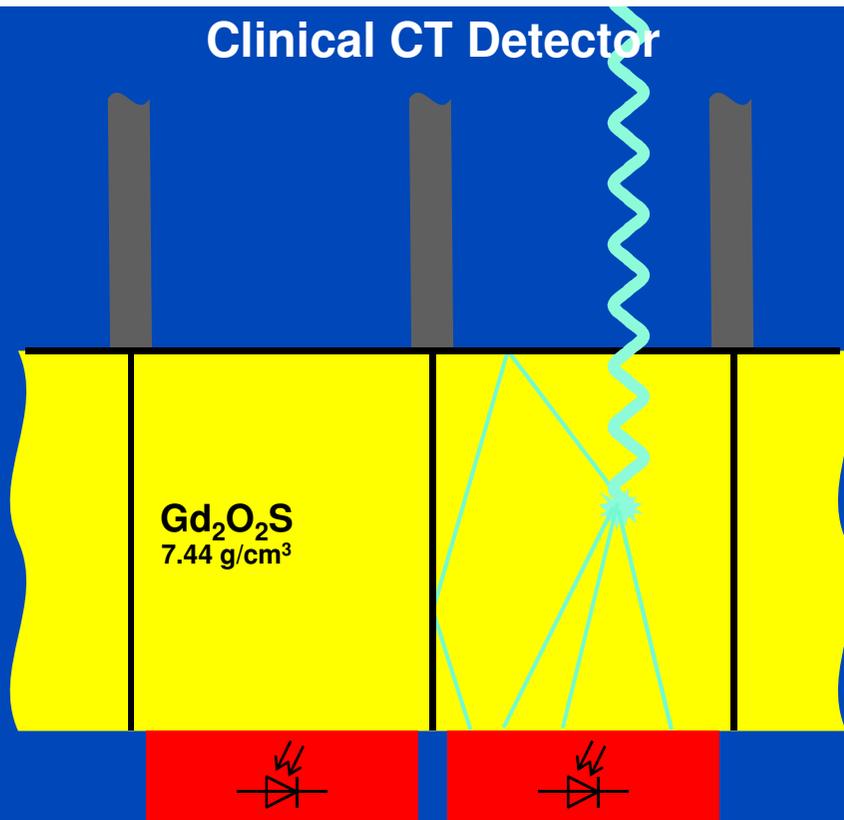


Flat Detector



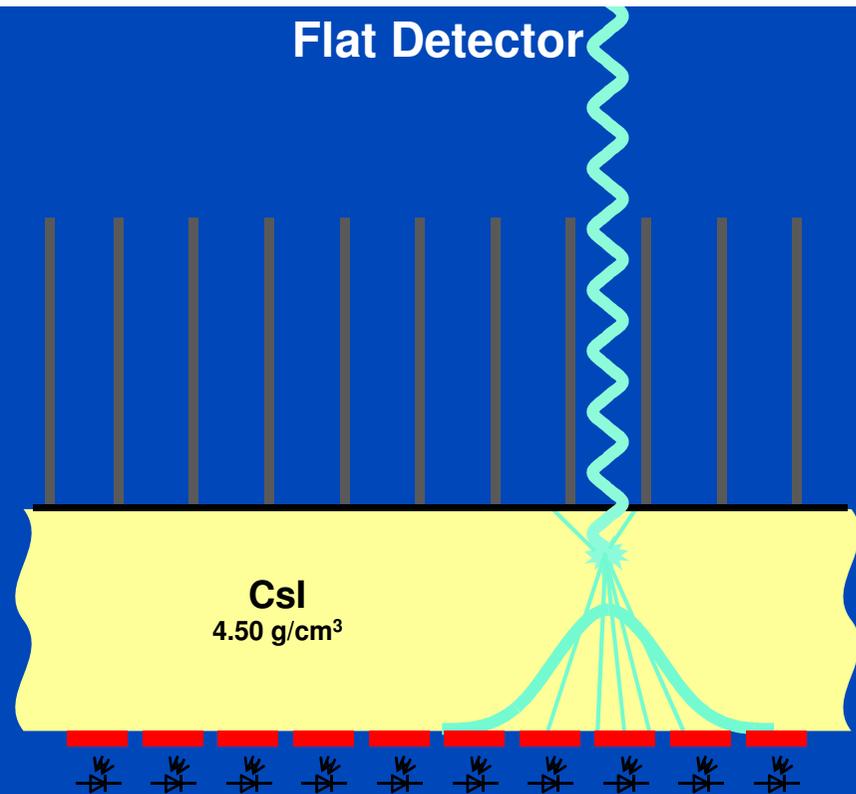
- Absorption efficiency
- Afterglow
- Dynamic range
- Cross-talk
- Framerate
- Scatter grid

Clinical CT Detector



- Anti-scatter grids are aligned to the detector pixels
- Anti-scatter grids reject scattered radiation
- Detector pixels are of about 1 mm size
- Detector pixels are structured, reflective coating maximizes light usage and minimizes cross-talk
- Thick scintillators improve dose usage
- $\text{Gd}_2\text{O}_2\text{S}$ 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 ₂ O ₂ S			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.

Dynamic Range in Flat Detectors

	<u>Saturation-to-noise range</u>			<u>X-ray exposure range</u>			Eff. bit depth (bits)	<u>Digital range</u>	
	Electronic noise (ADU)	Saturation signal (ADU)	Dynamic range	Quantum limited exposure (μR)	Saturation exposure (μR)	Dynamic range		Quantization range	Eff. bit depth (bits)
<u>No binning, gain 2</u>	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
<u>2x2 binning, gain 1</u>									
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

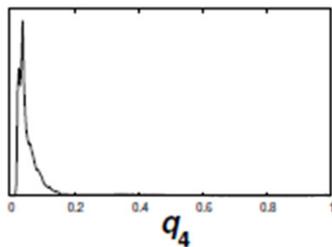
A2 is defined as the exposure where Quantum Noise=ElectronicNoise.



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.

No
overexposure

Histogram [a.u.]

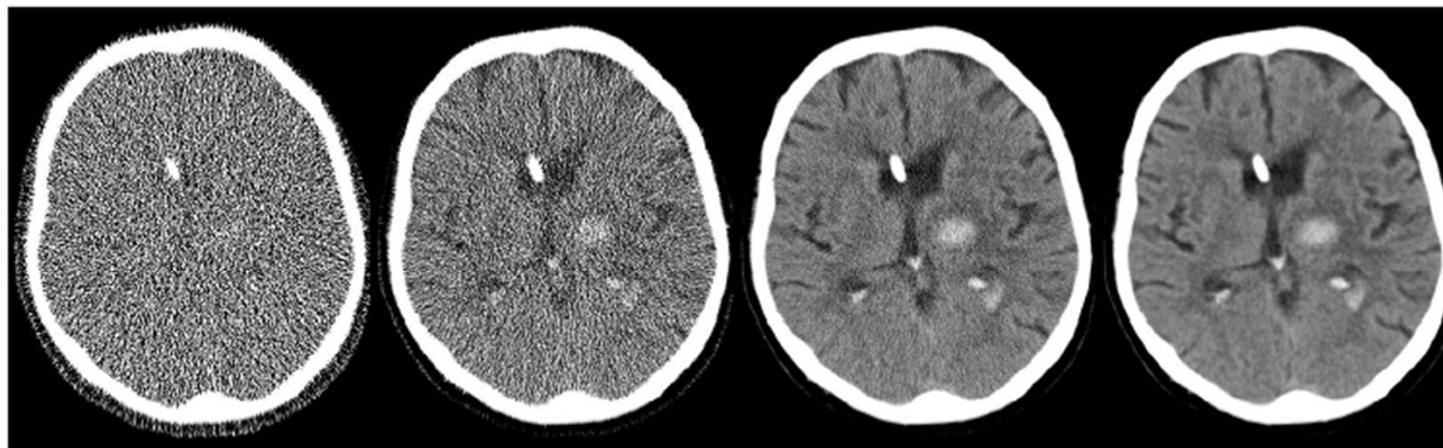


8 bit

10 bit

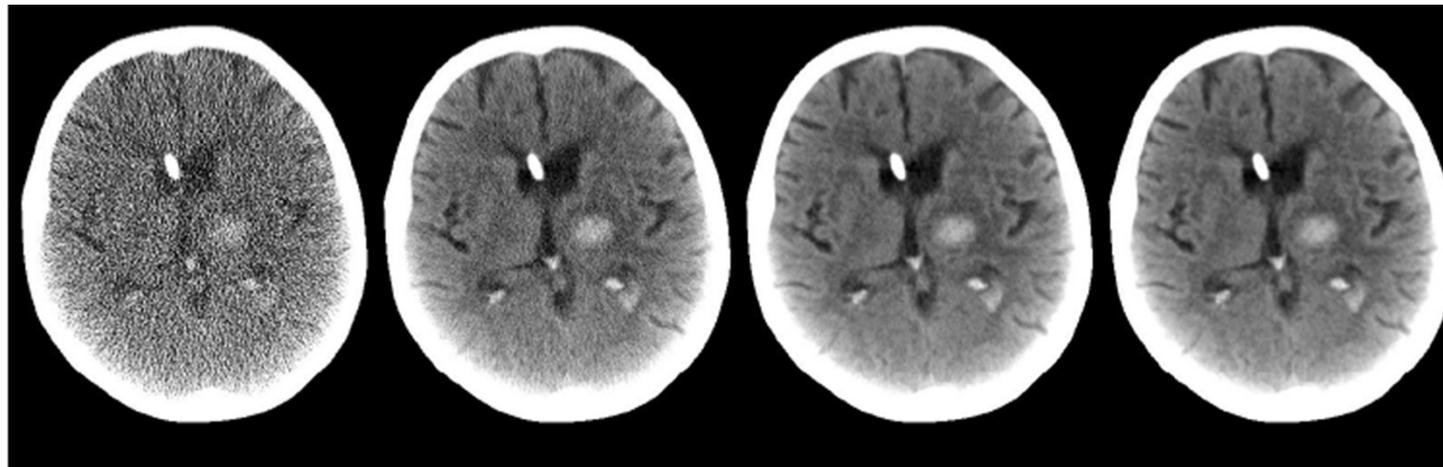
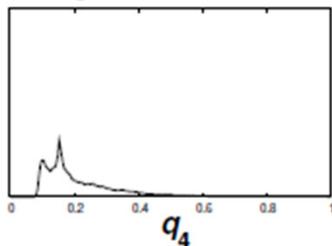
12 bit

14 bit

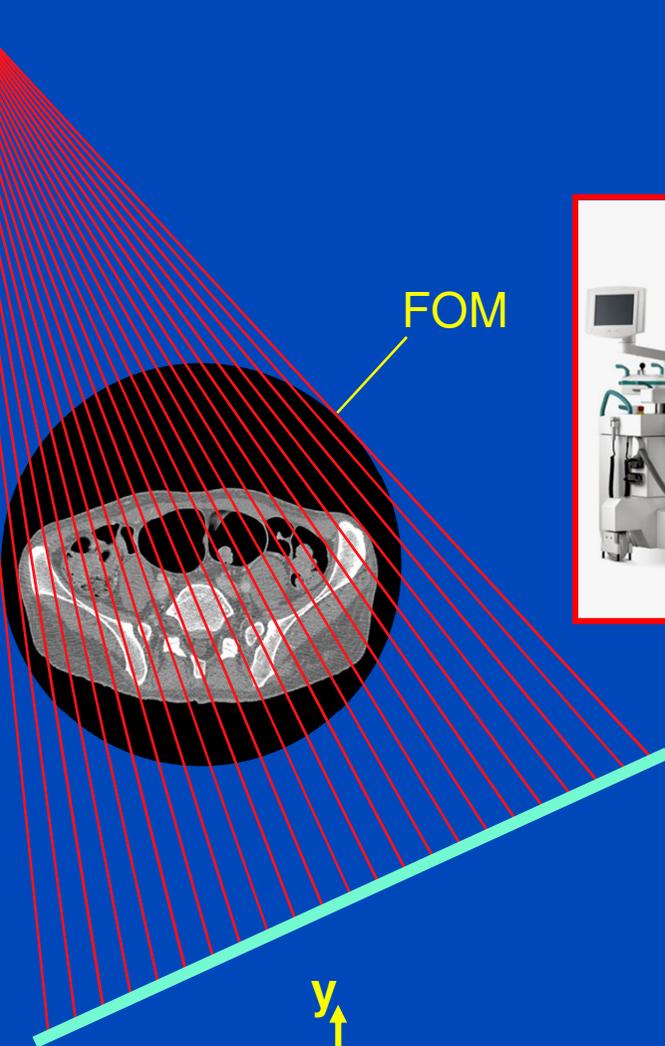


Intended
overexposure
(factor 4)

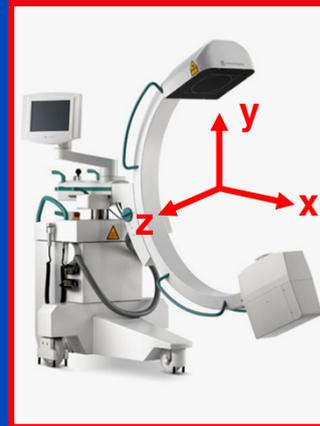
Histogram [a.u.]



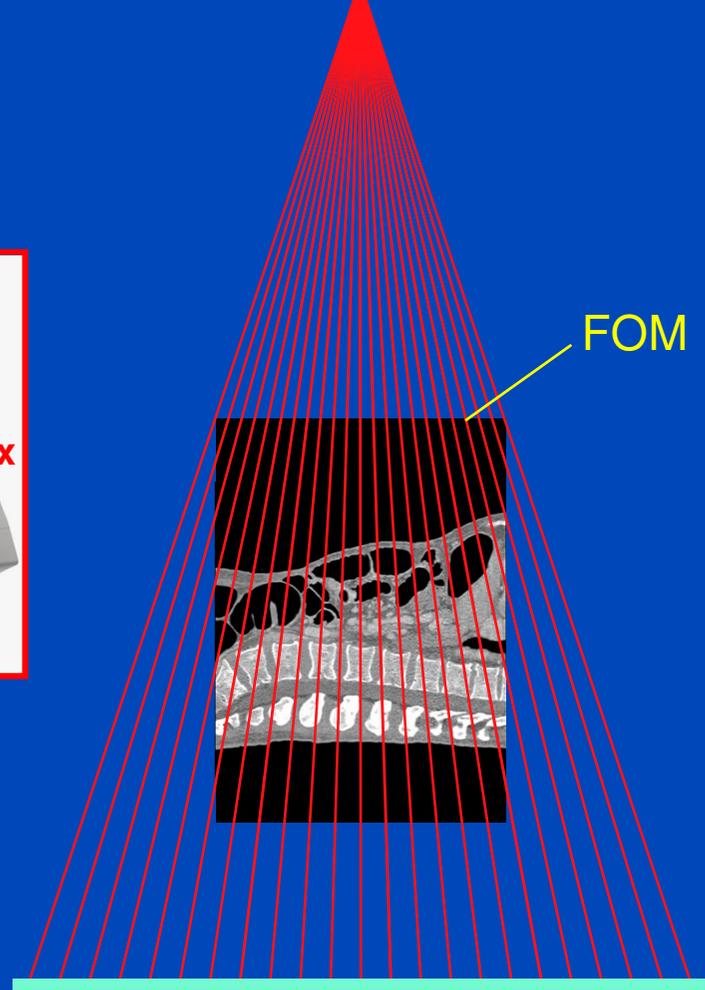
focal spot



FOM

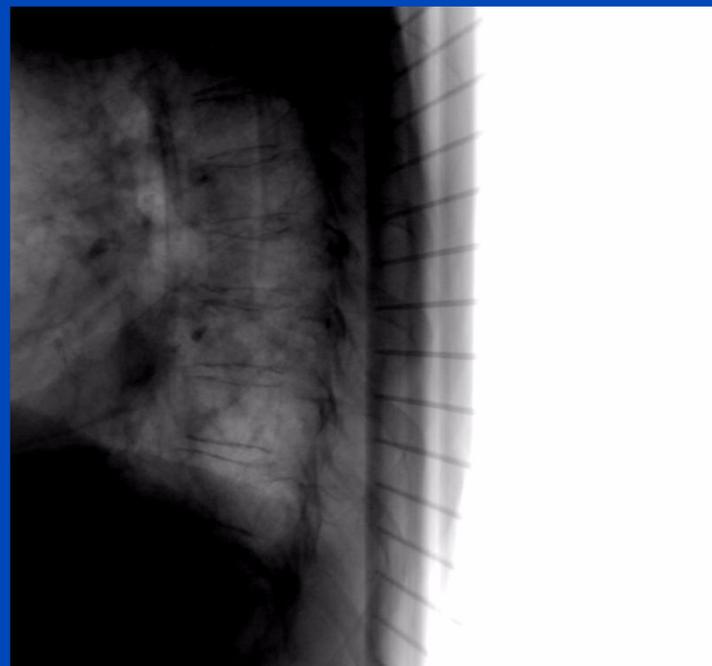
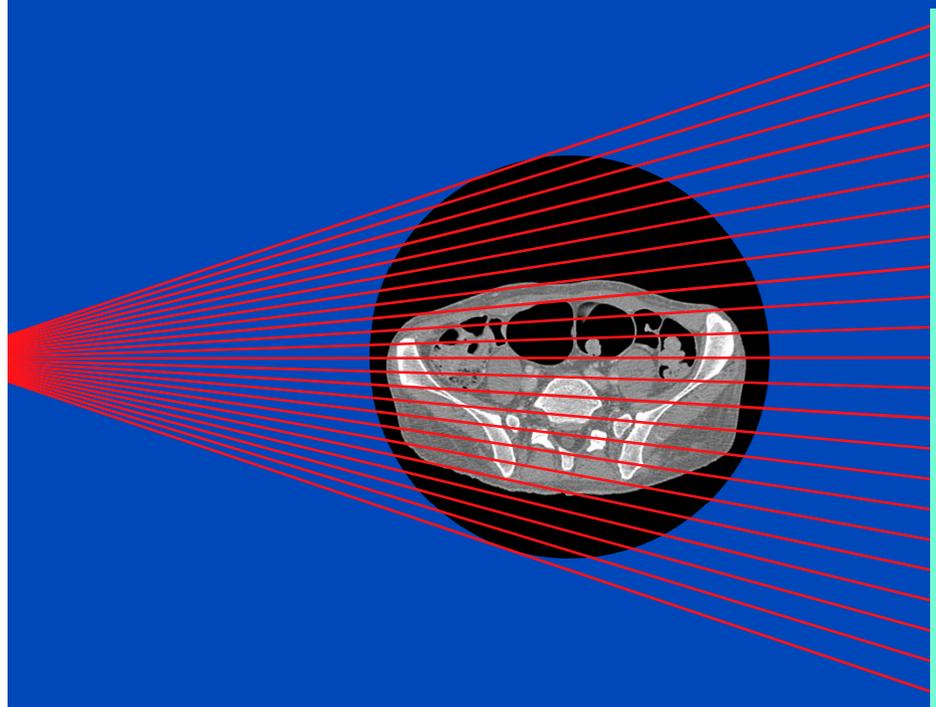


focal spot



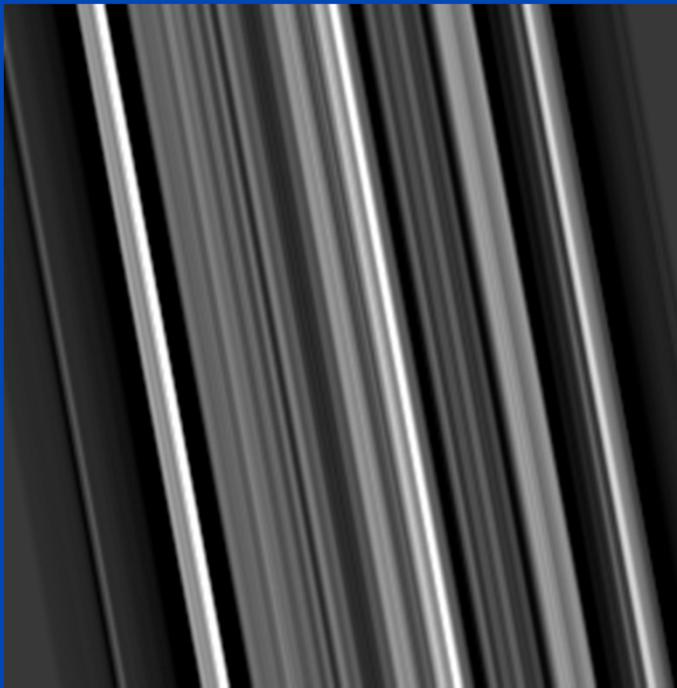
FOM

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

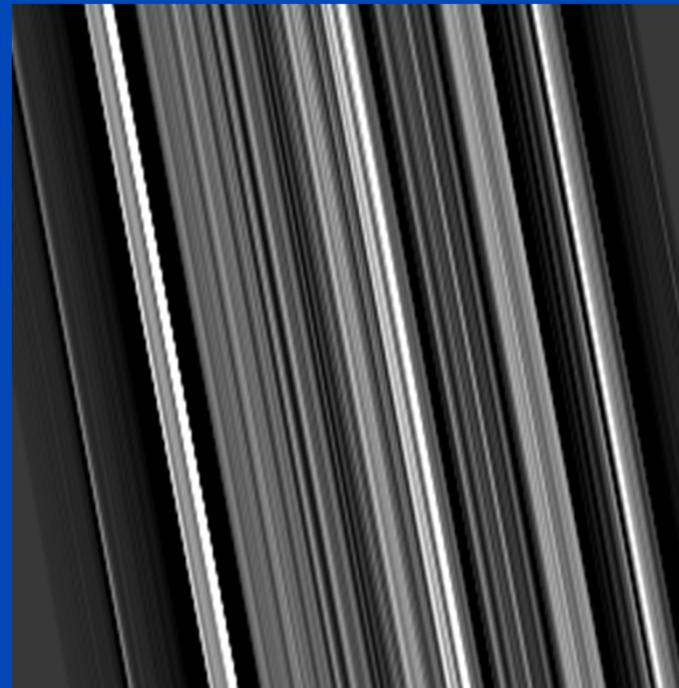


Filtered Backprojection (FBP)

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



Smooth

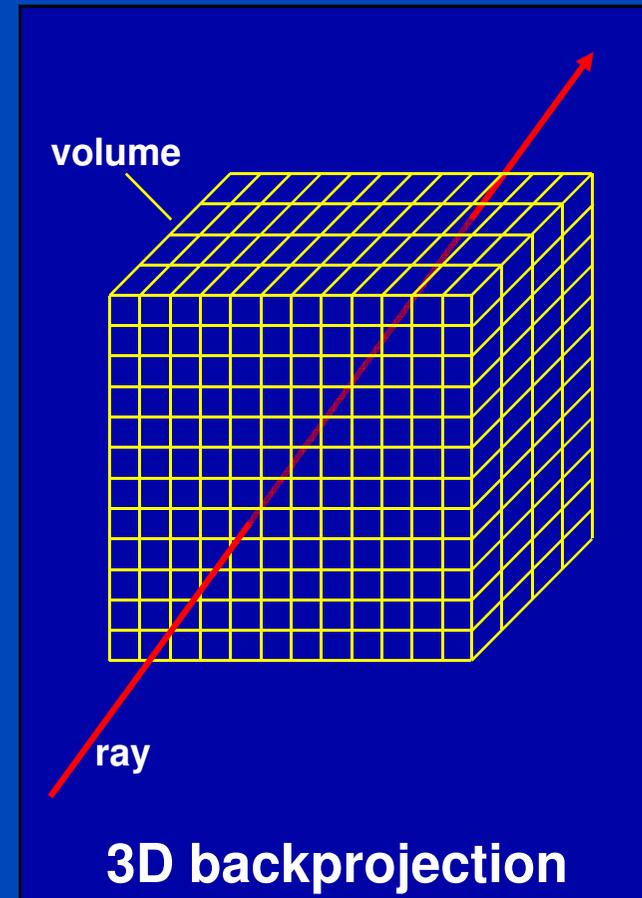


Standard

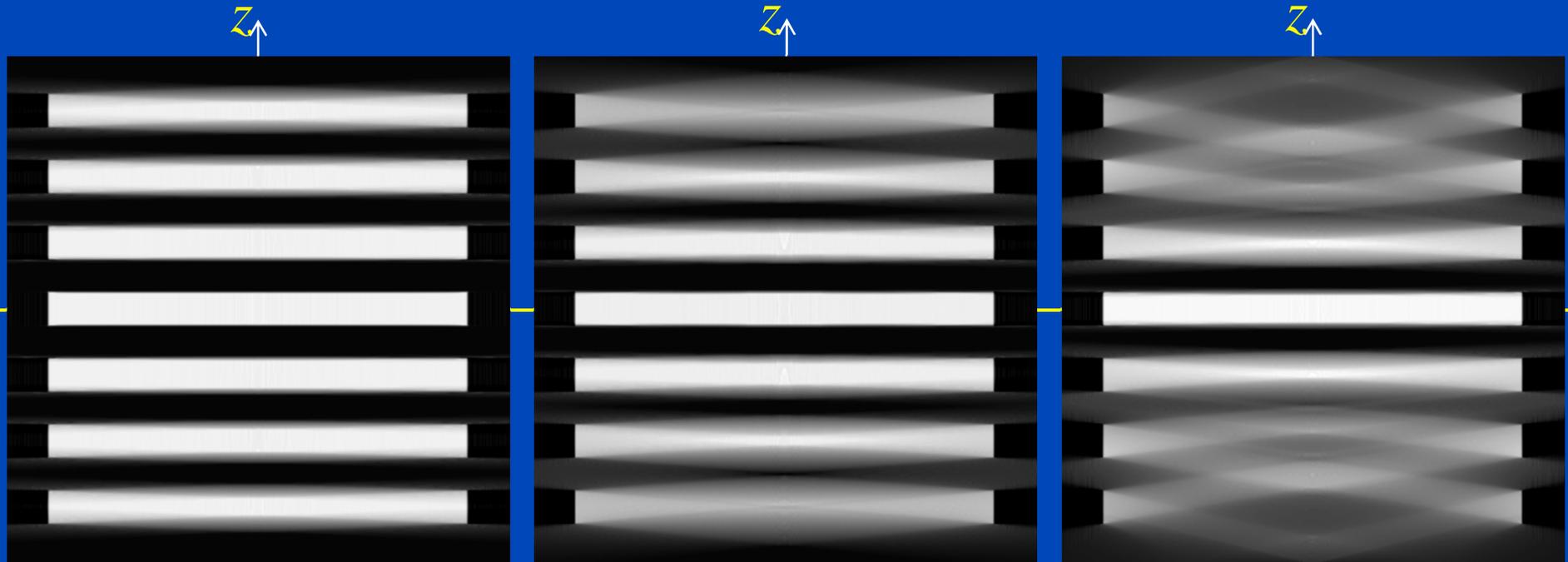
Reconstruction kernels balance between spatial resolution and image noise.

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



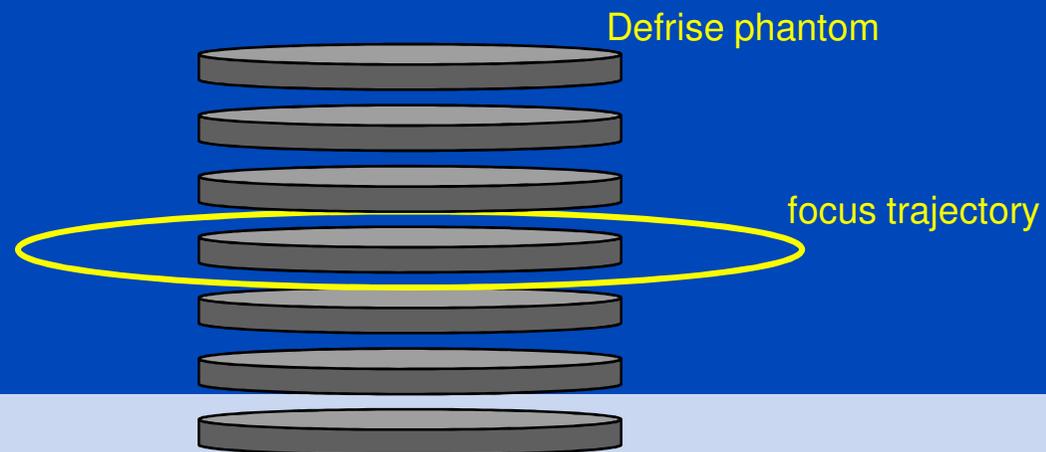
Cone-Beam Artifacts



Cone-angle $\Gamma = 6^\circ$

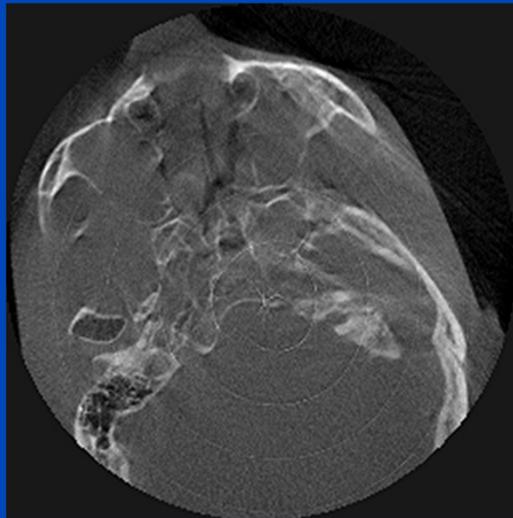
Cone-angle $\Gamma = 14^\circ$

Cone-angle $\Gamma = 28^\circ$



Data Processing and Image Quality

Uncorrected



With Geometric Calibration

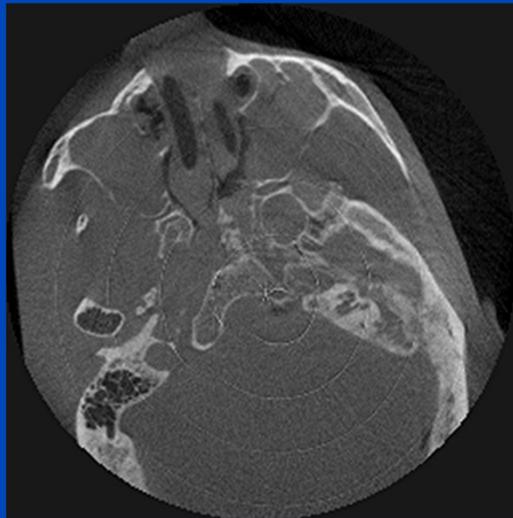


Image courtesy of Dr. Ludwig Ritschl, Ziehm Imaging GmbH, Nürnberg, Germany.

With Detector Calibration

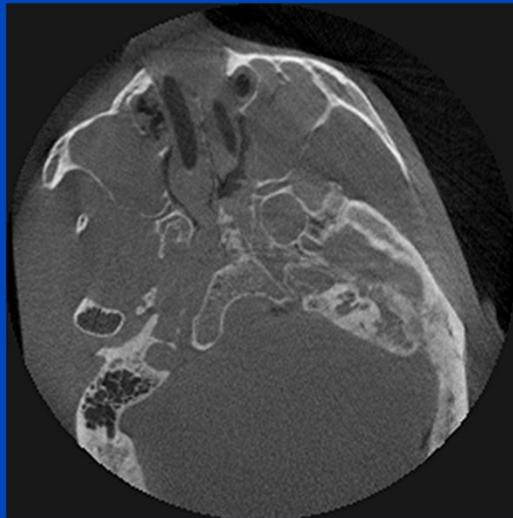


Image courtesy of Dr. Ludwig Ritschl, Ziehm Imaging GmbH, Nürnberg, Germany.

With Scatter and Beam Hardening Correction

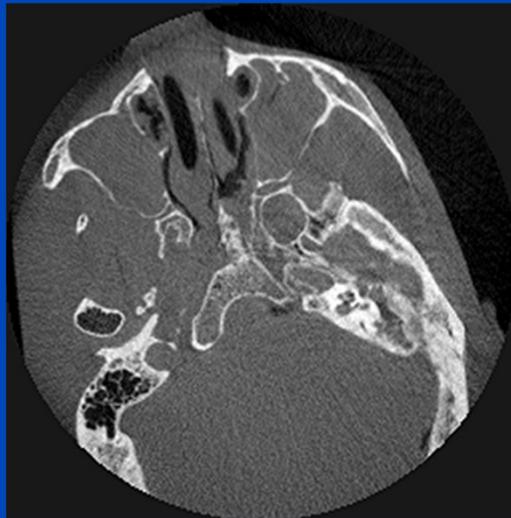


Image courtesy of Dr. Ludwig Ritschl, Ziehm Imaging GmbH, Nürnberg, Germany.

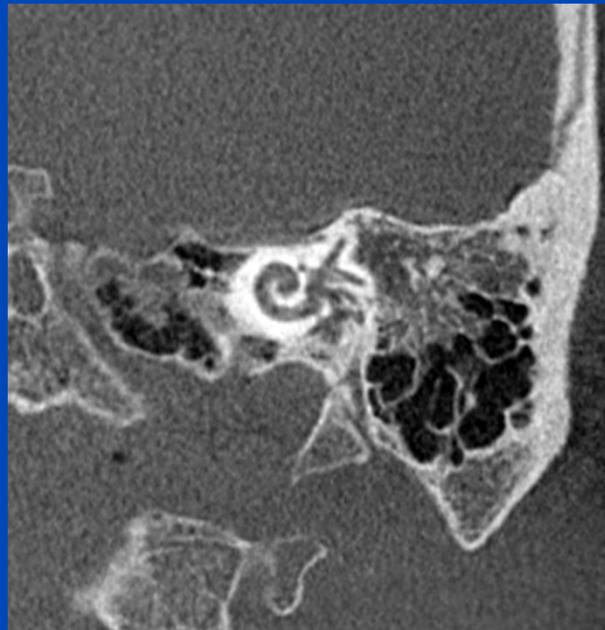


Image courtesy of Dr. Ludwig Ritschl, Ziehm Imaging GmbH, Nürnberg, Germany.

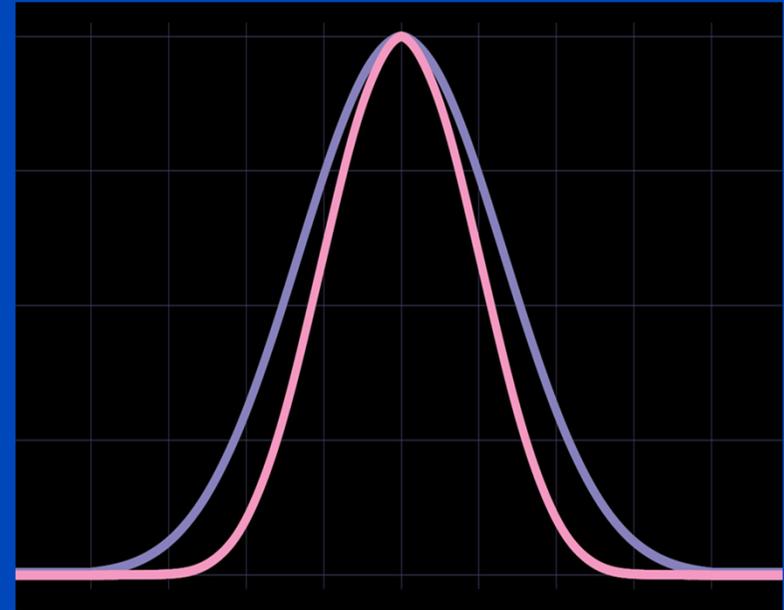
Spatial Resolution



Method 1

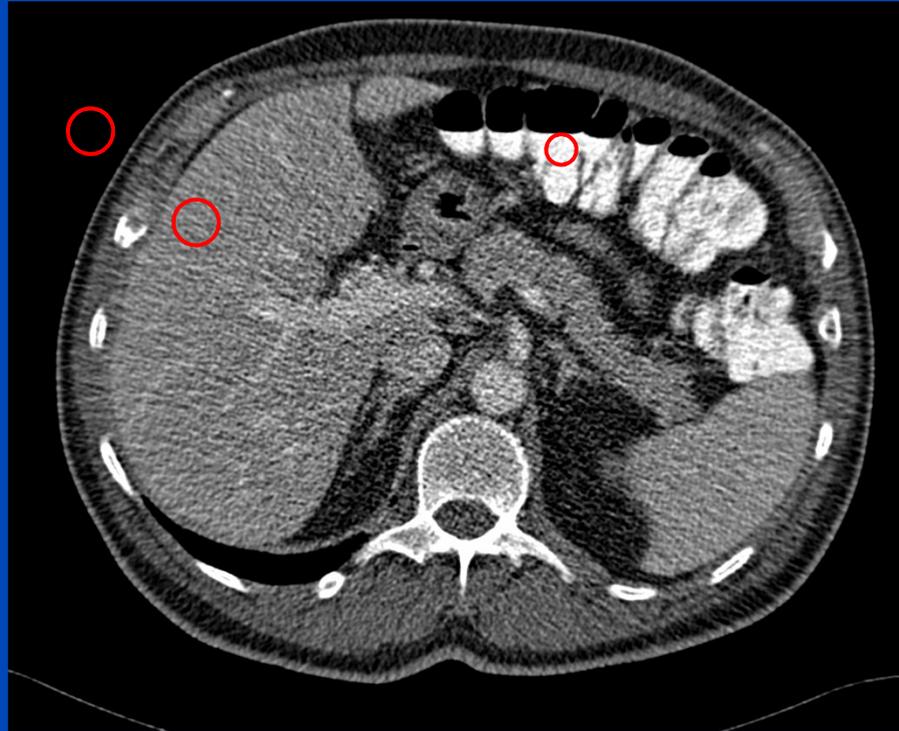


Method 2



Method 3

Image Noise



150 HU / 600 HU

Air ROI: $\mu = -995$ HU , $\sigma = 31$ HU
Soft tissue ROI: $\mu = 148$ HU , $\sigma = 59$ HU
Iodine ROI: $\mu = 423$ HU , $\sigma = 62$ 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

$$\left(\frac{\sigma}{\mu}\right)^2 \propto \frac{e^{\mu 2R} + 1}{\mu^2 \Delta x^4}$$

Noise relative to
the background
(= 1/SNR)

Fourth power of
the spatial
resolution

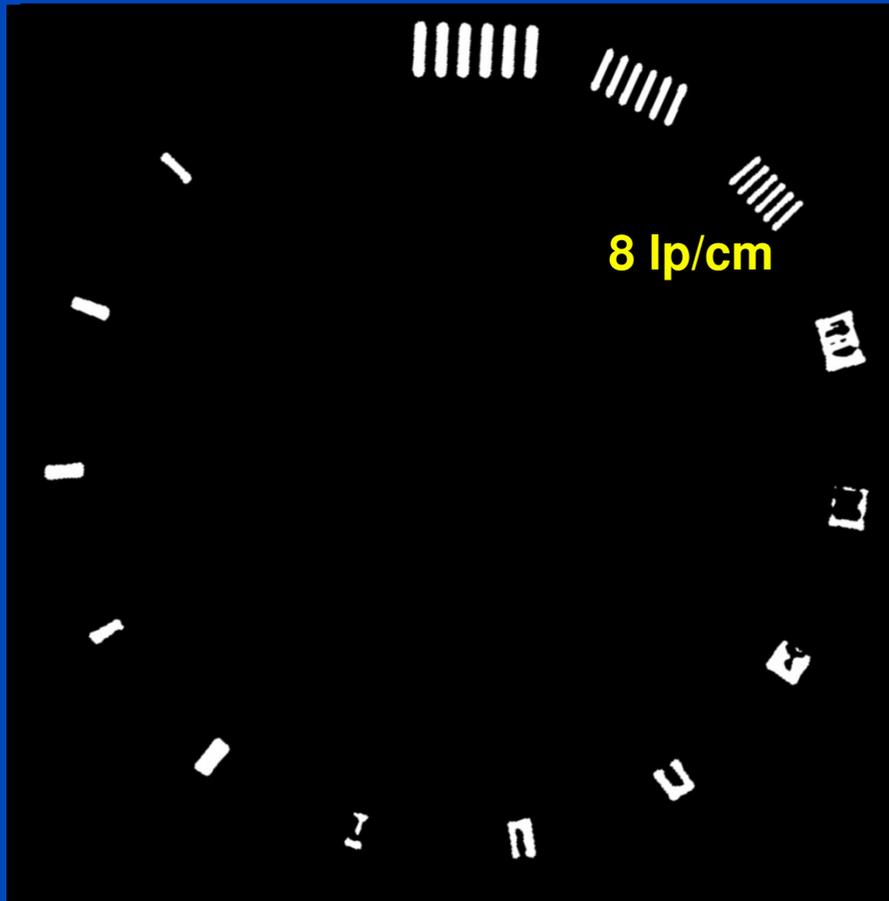
Always Relate SNR and CNR to Unit Dose!

- 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.

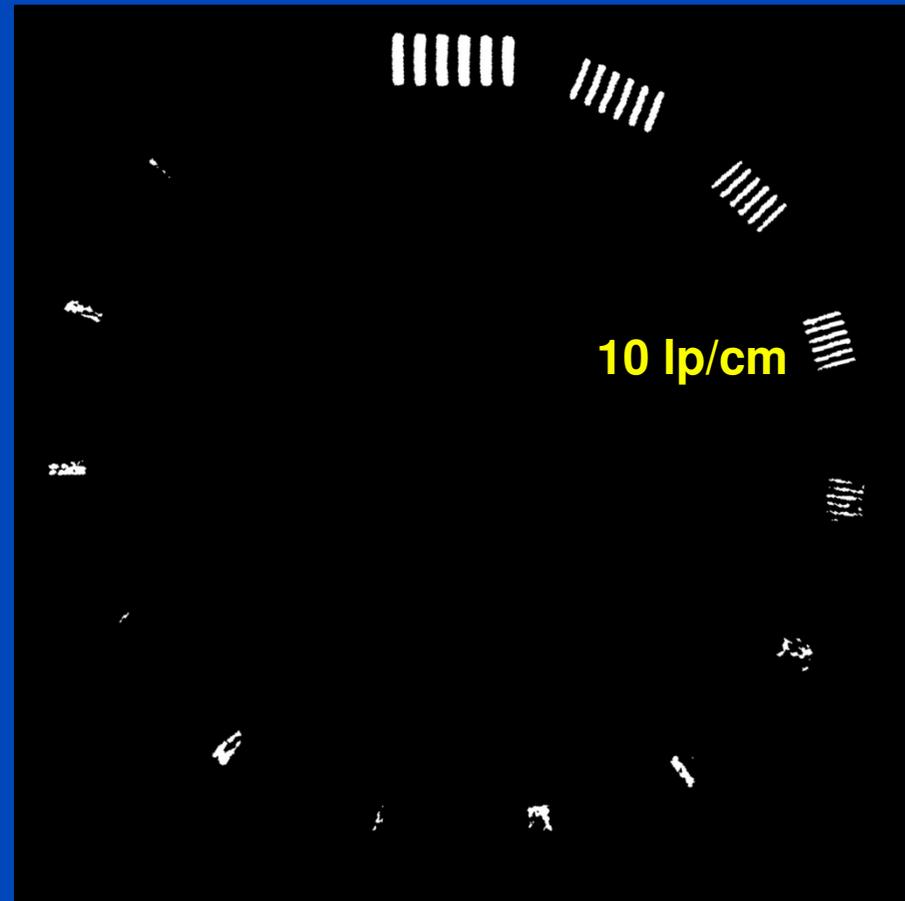
$$SNRD = \frac{\text{Signal}}{\text{Noise}\sqrt{\text{Dose}}} = \frac{SNR}{\sqrt{\text{Dose}}}$$

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

Clinical CT vs. Flat Detector CT

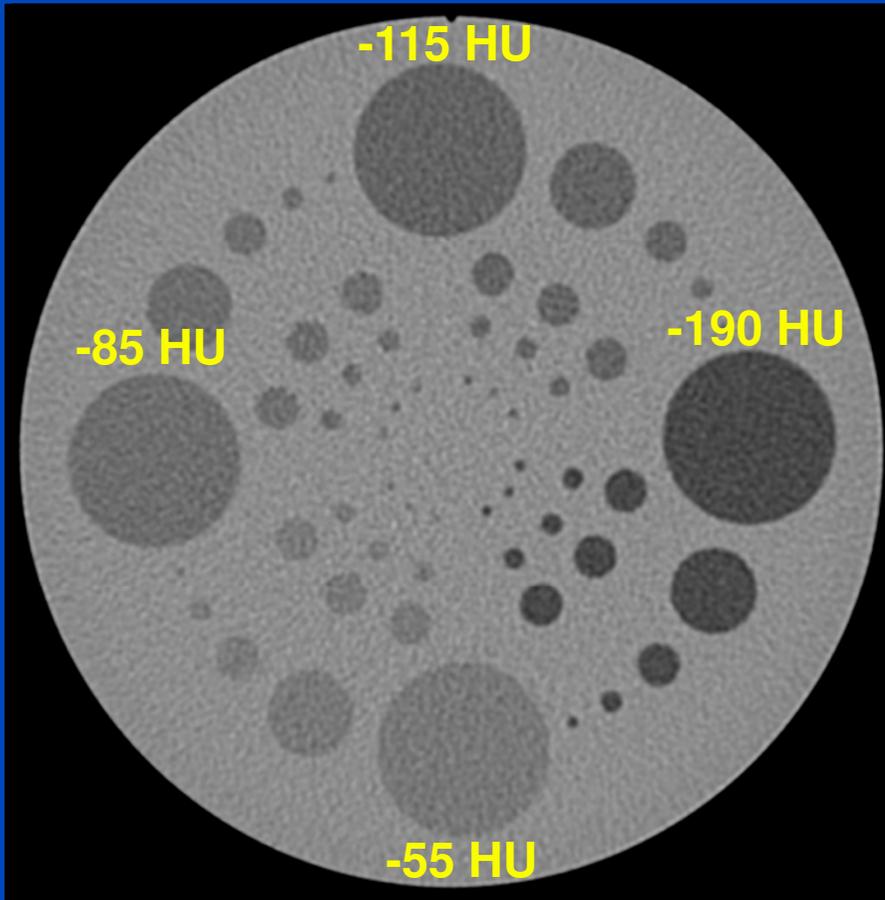


Clinical CT, Standard Kernel

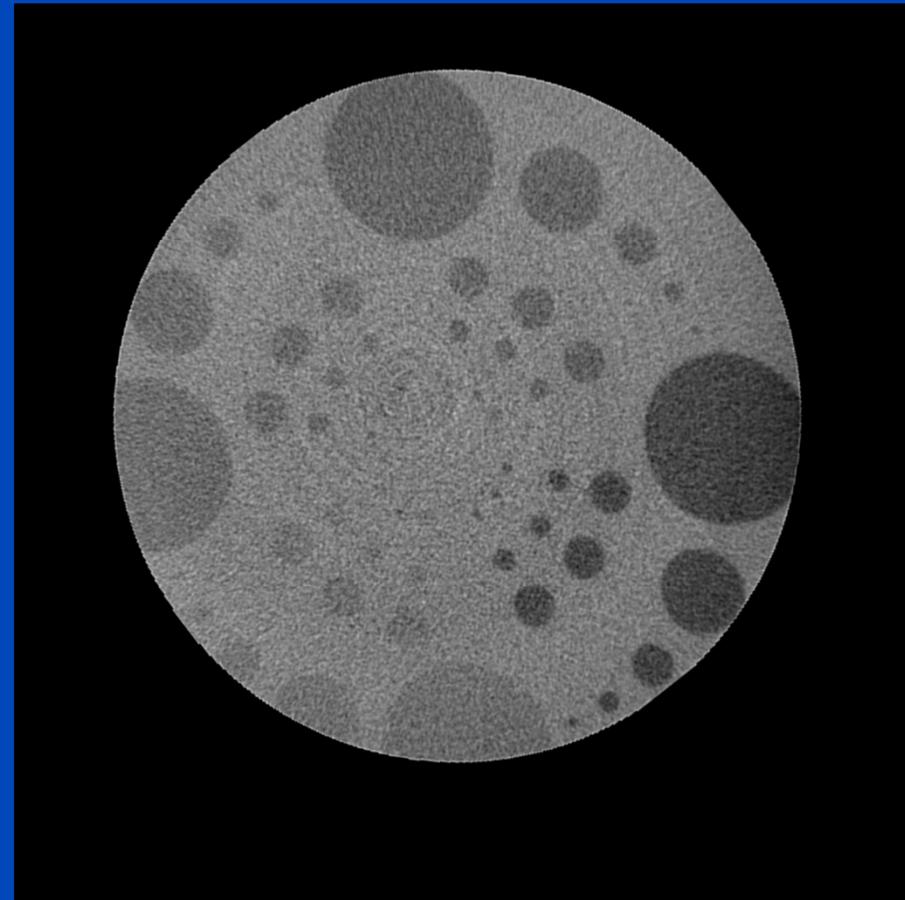


Flat Detector CT, 2x2 Binning

Clinical CT vs. Flat Detector CT

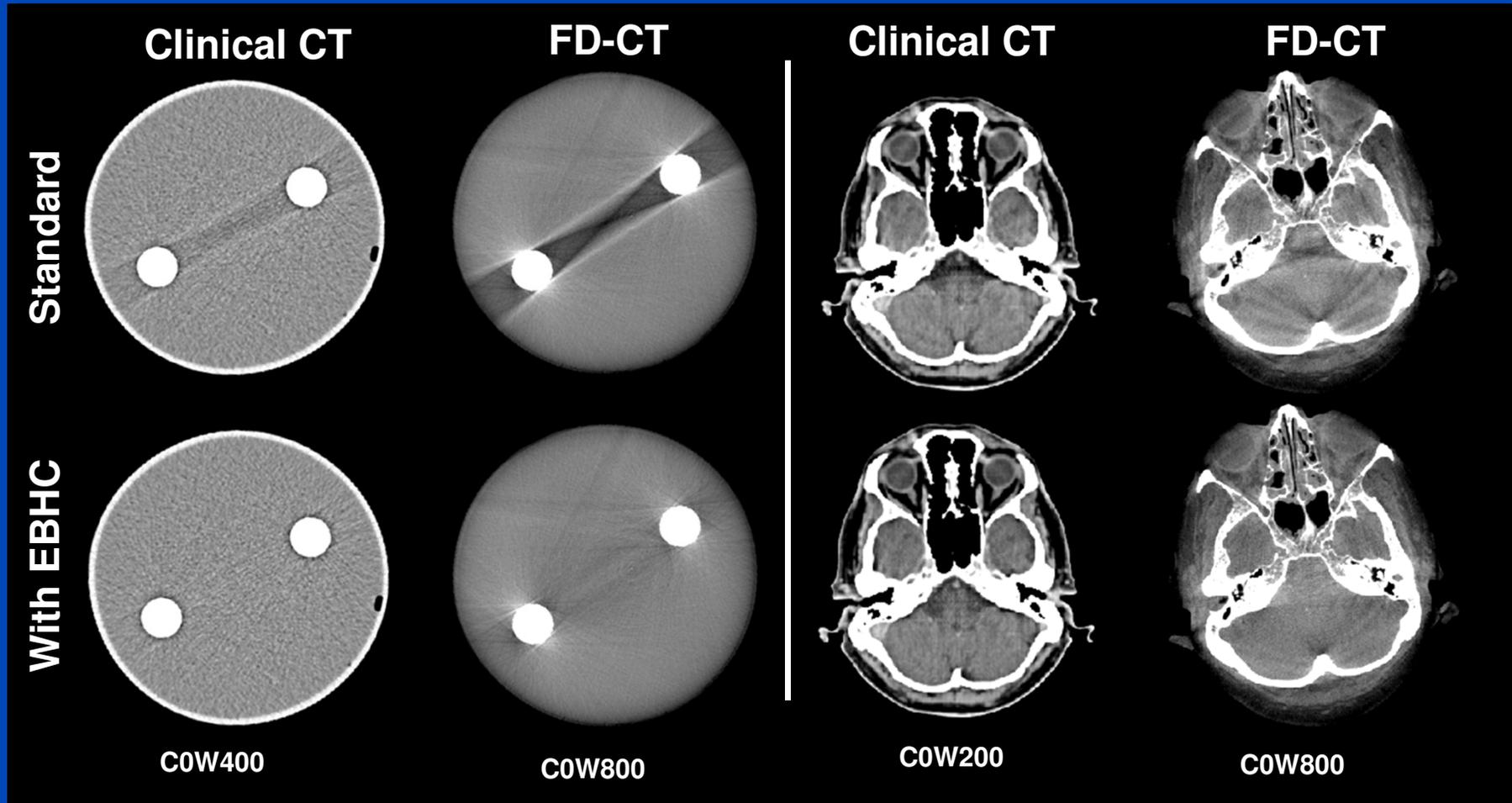


Clinical CT, Standard Kernel
 $C = 0 \text{ HU}$, $W = 700 \text{ HU}$



Flat Detector CT, 2x2 Binning

Clinical CT vs. FD-CT



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	≈ 5000 fps	≈ 25 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!



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This presentation will soon be available at www.dkfz.de/ct.