CT Technology: Clinical and Preclinical CT

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DEUTSCHES
KREBSFORSCHUNGSZENTRUM
IN DER HELMHOLTZ-GEMEINSCHAFT

Is CT a Molecular Imaging Modality?

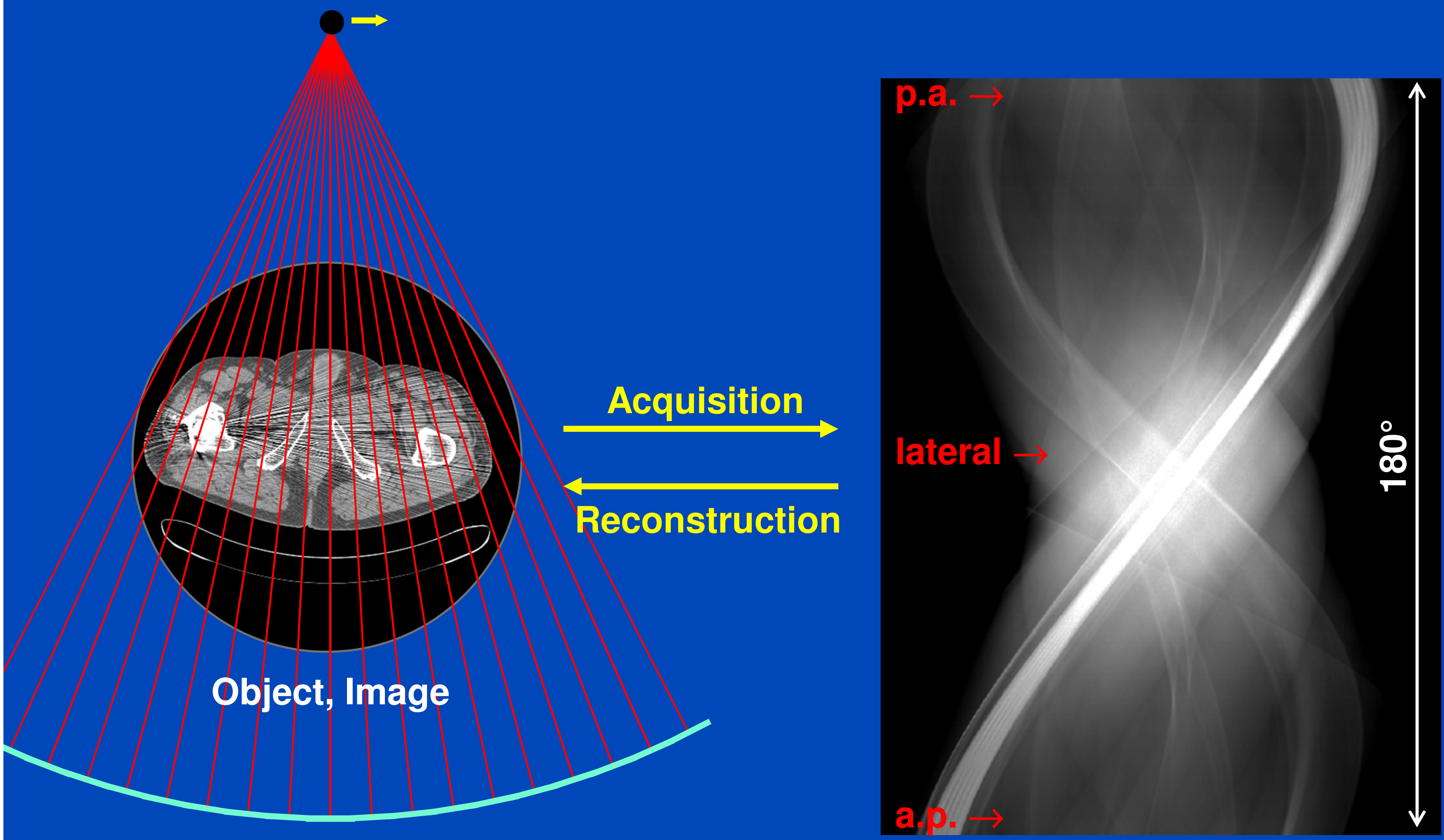
Imaging Modality	Molecular Sensitivity	Reference
PET	10^{-11}-10^{-12} mol/L	1
SPECT	10^{-10}-10^{-11} mol/L	1
Bioluminescence Imaging	10^{-9}-10^{-11} mol/L	2
Ultrasound	10^{-8} mol/L	3
MRI	10^{-3}-10^{-5} mol/L	1
CT	10^{-3} mol/L	4

1 C. S. Levin, “New Imaging Technologies to Enhance the Molecular Sensitivity of Positron Emission Tomography,“ Proc. IEEE 96(3), 439-467 (2008).

2 D. S. Wang, M. D. Dake, J. M. Park, and M. D. Kuo, “Molecular Imaging: A Primer for Interventionalists and Imagers,” J. Vasc. Interv. Radiol. 17, 1405-1423 (2006).

3 G. Schmitz, “Ultrasonic imaging of molecular targets,” Basic Res. Cardiol. 103, 174-181 (2008).

4 L. Fass, “Imaging and cancer: A review,“ Molecular Oncology 2, 115-152 (2008).



Sinogram, Rawdata

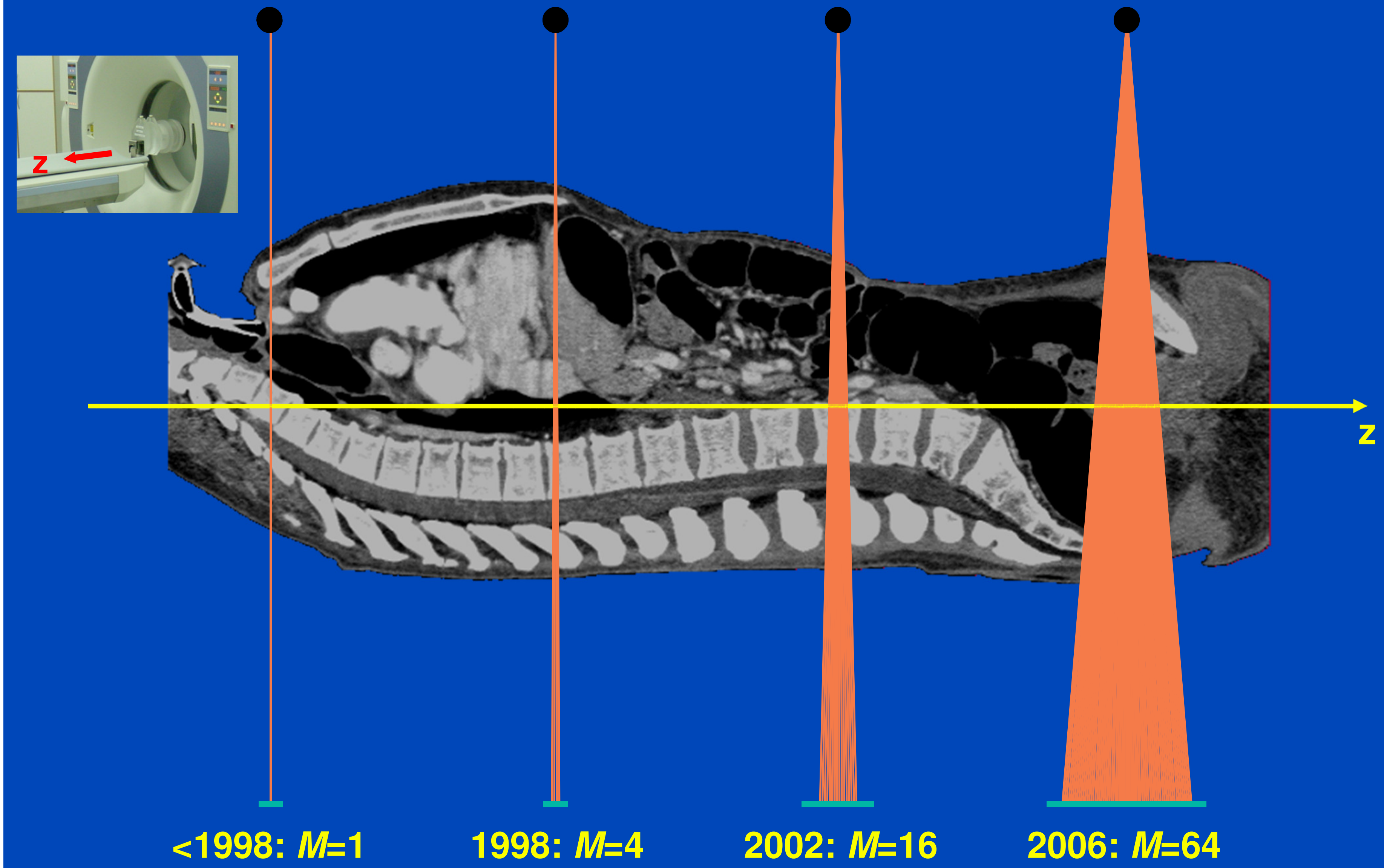
GE Revolution CT

Philips IQon Spectral CT

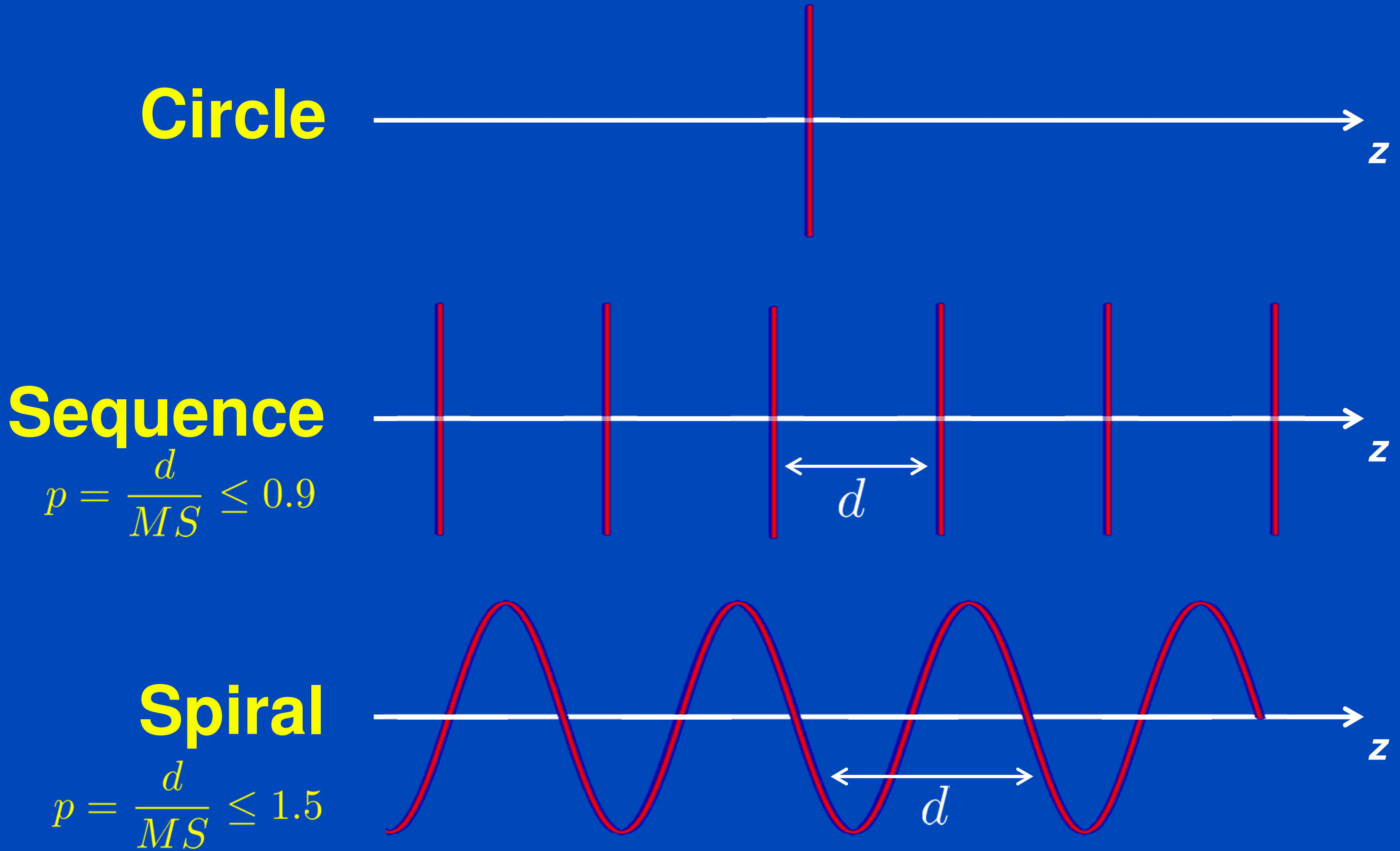
Siemens Somatom Force

Toshiba Aquilion ONE Vision

Axial Geometry (z-Direction)



Scan Trajectories



$$p = \frac{d}{MS} \leq 0.9$$

$$p = \frac{d}{MS} \leq 1.5$$

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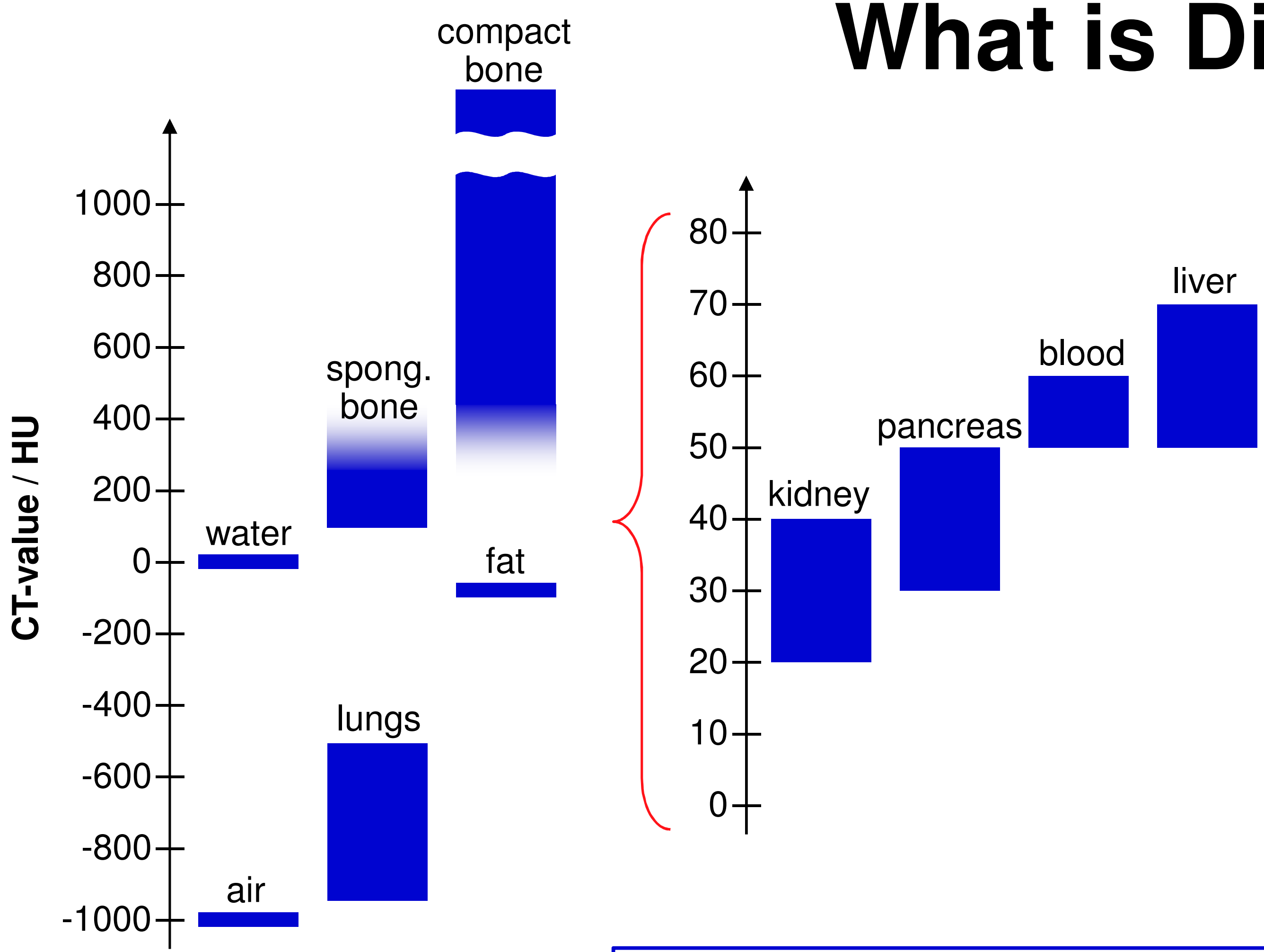
What is Displayed?



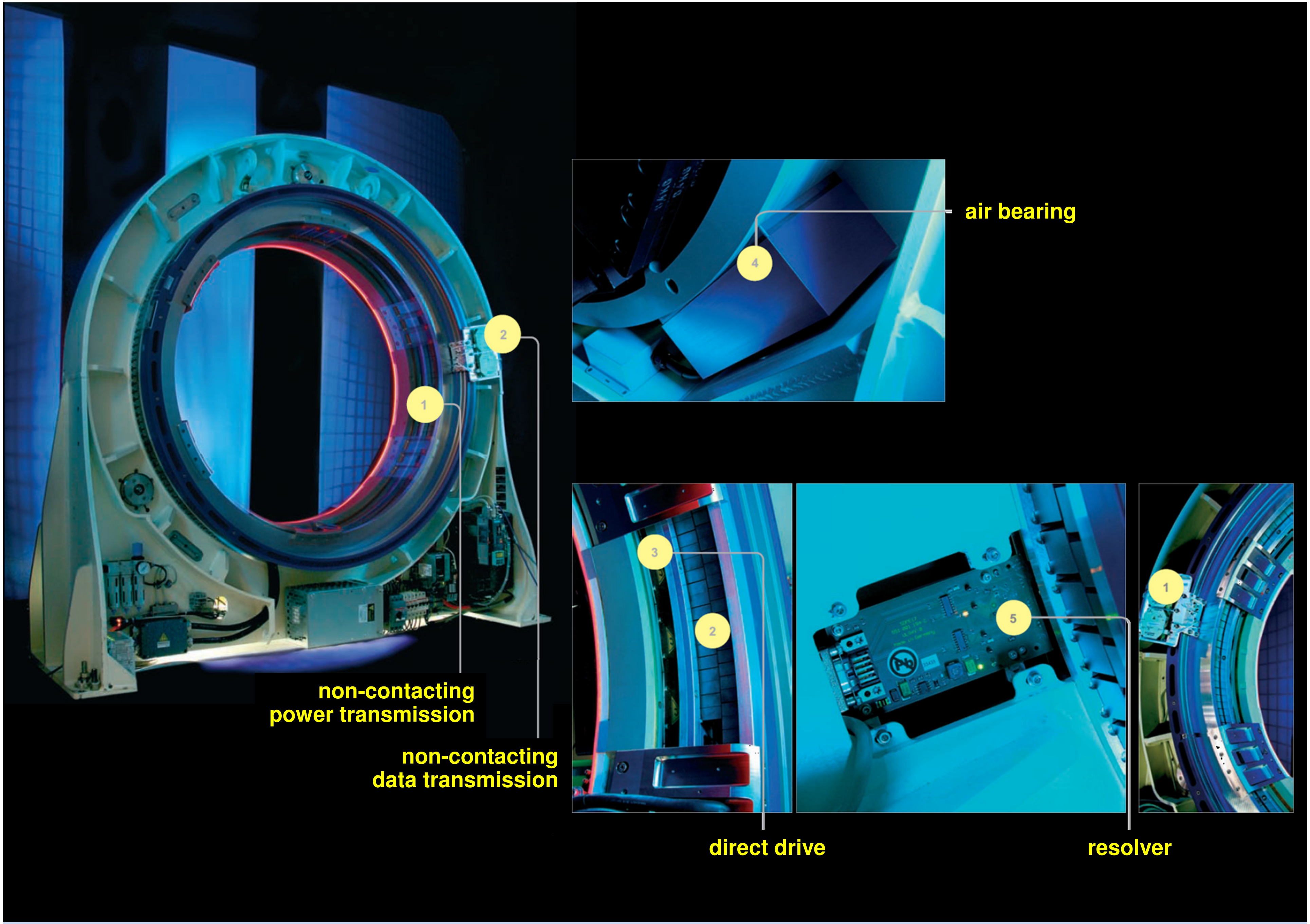
$$CT(\boldsymbol{r}) = \frac{\mu(\boldsymbol{r}) - \mu_{\text{Water}}}{\mu_{\text{Water}}} \cdot 1000 \text{ HU}$$

Basic Parameters
(best-of values typical for modern scanners)

- In-plane resolution: 0.4 … 0.7 mm
- Nominal slice thickness: S = 0.5 … 1.5 mm
- Effective slice thickness: S_{eff} = 0.5 … 10 mm
- Tube (max. values): 120 kW, 150 kV, 1300 mA
- Effective tube current: mAs_{eff} = 10 mAs … 1000 mAs
- Rotation time: T_{rot} = 0.25 … 0.5 s
- Simultaneously acquired slices: M = 16 … 320
- Table increment per rotation: d = 1 … 183 mm
- Pitch value: p = 0.1 … 1.5 (up to 3.2 for DSCT)
- Scan speed: up to 73 cm/s
- Temporal resolution: 50 … 250 ms

Demands on the Mechanical Design

- Continuous data acquisition (spiral, fluoro, dynamic, …)
- Able to withstand very fast rotation
  - Centrifugal force at 550 mm with 0.5 s: $F = 9\,g$
  - with 0.4 s: $F = 14\,g$
  - with 0.3 s: $F = 25\,g$
  - with 0.2 s: $F = 55\,g$
- Mechanical accuracy better than 0.1 mm
- Compact and robust design
- Short installation times
- Long service intervals
- Low cost



Data courtesy of Schleifring GmbH, Fürstenfeldbruck, Germany
and of rsna2011.rsna.org/exbData/1678/docs/Gantry_Subsystem.pdf

Demands on X-Ray Sources

- Tube voltages from 70 to 150 kV
- High instantaneous power levels (typ. 50 to 120 kW)
- High continuous power levels (typ. > 5 kW)
- High cooling rates (typ. > 1 MHU/minute)
- High tube current variation (low inertia)
- Must withstand centrifugal forces
- Compact and robust design

Tube Technology

conventional tube
(rotating anode, helical wire emitter)

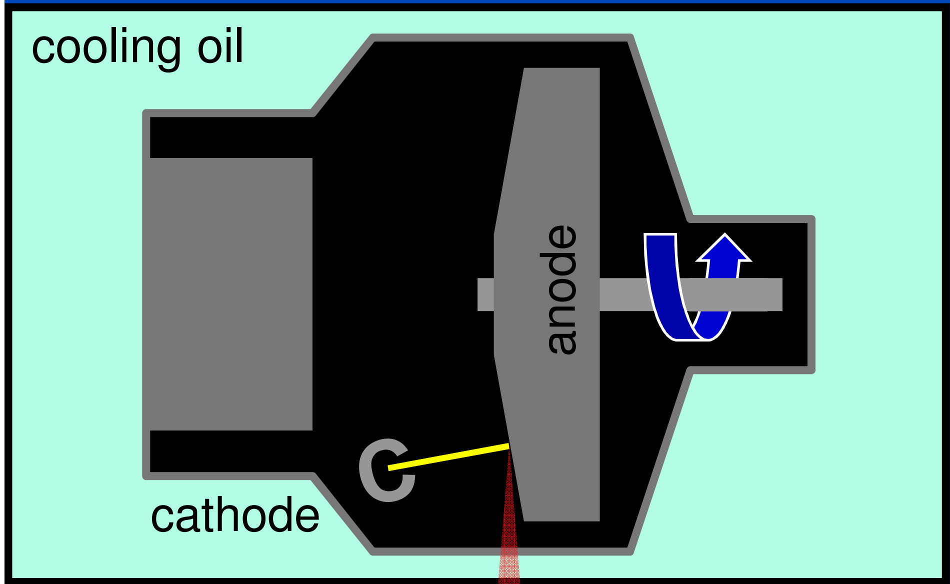


Photo courtesy of GE

high performance tube
(rotating cathode, anode + envelope, flat emitter)

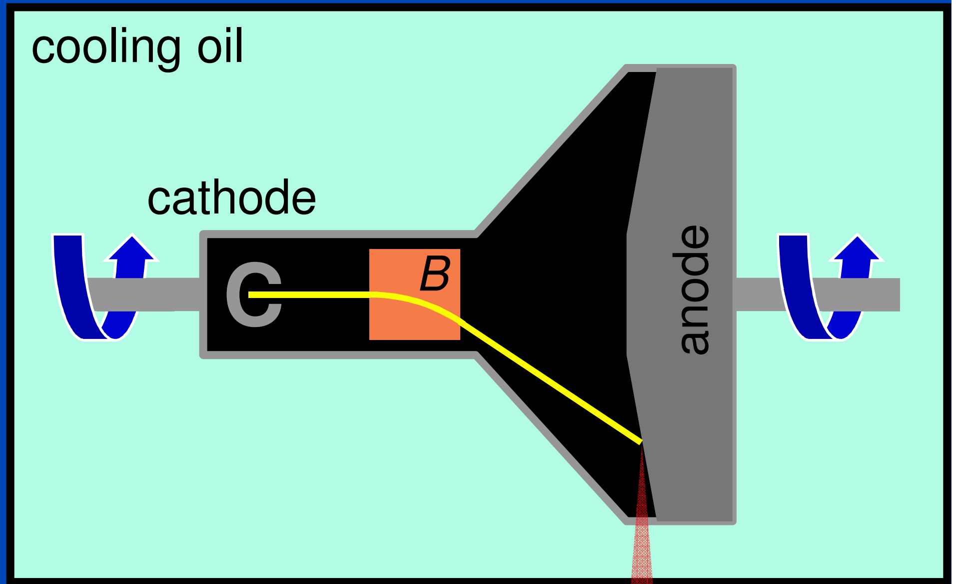


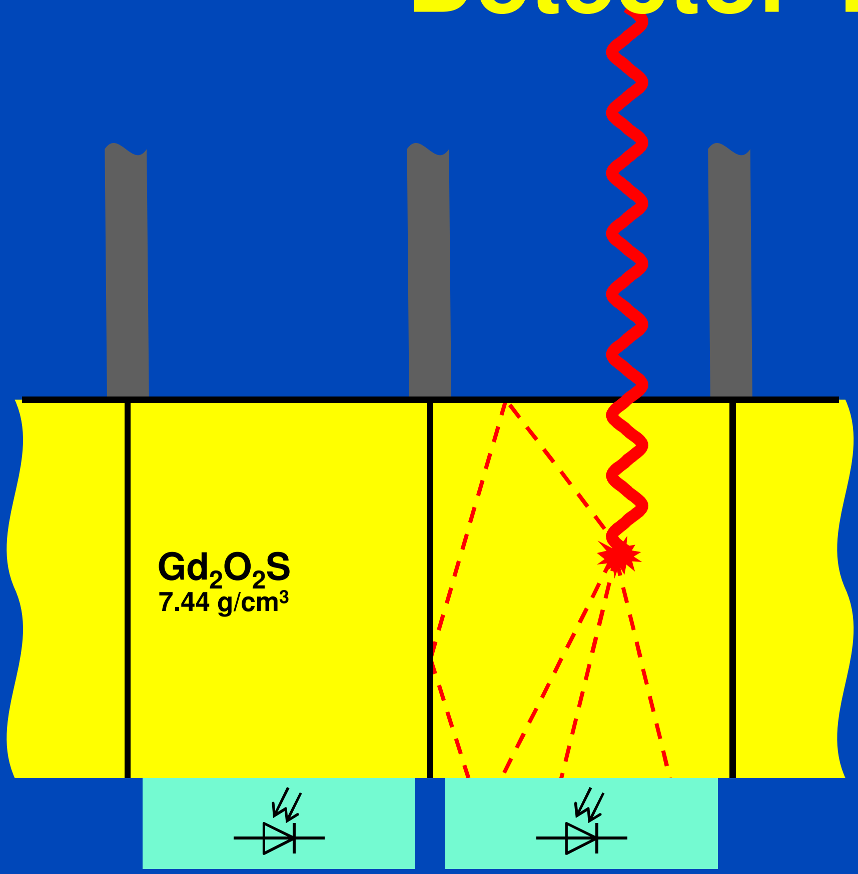
Photo courtesy of Siemens

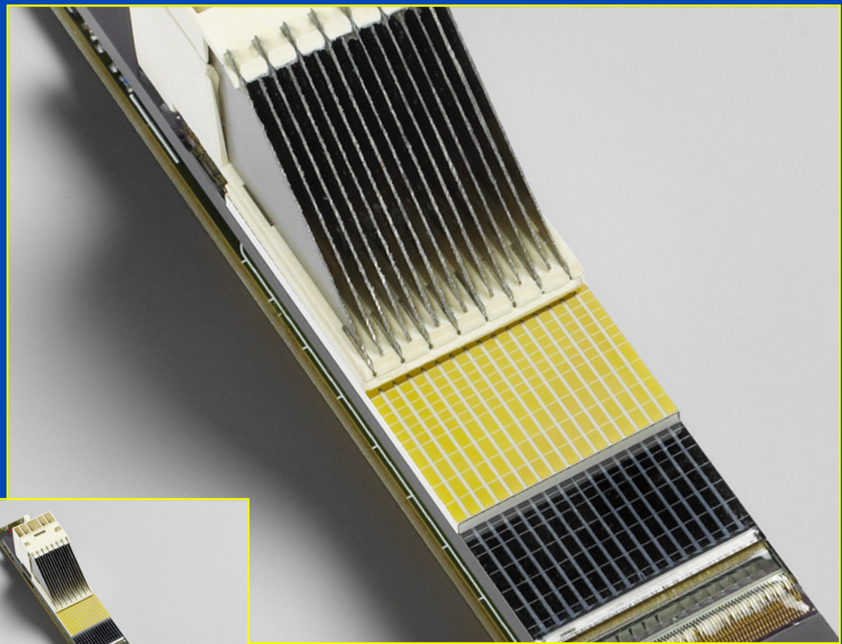
Demands on CT Detector Technology

- **Available as multi-row arrays**
- **Very fast sampling (typ. 300 µs)**
- **Favourable temporal characteristics (decay time < 10 µs)**
- **High absorption efficiency**
- **High geometrical efficiency**
- **High count rate (up to 10^9 cps*)**
- **Adequate dynamic range (at least 20 bit)**

* in the order of 10^5 counts per reading and 10^4 readings per second

Detector Technology





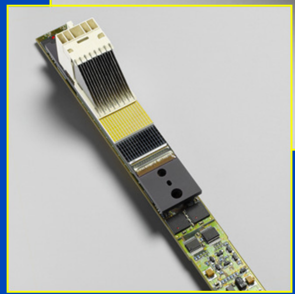
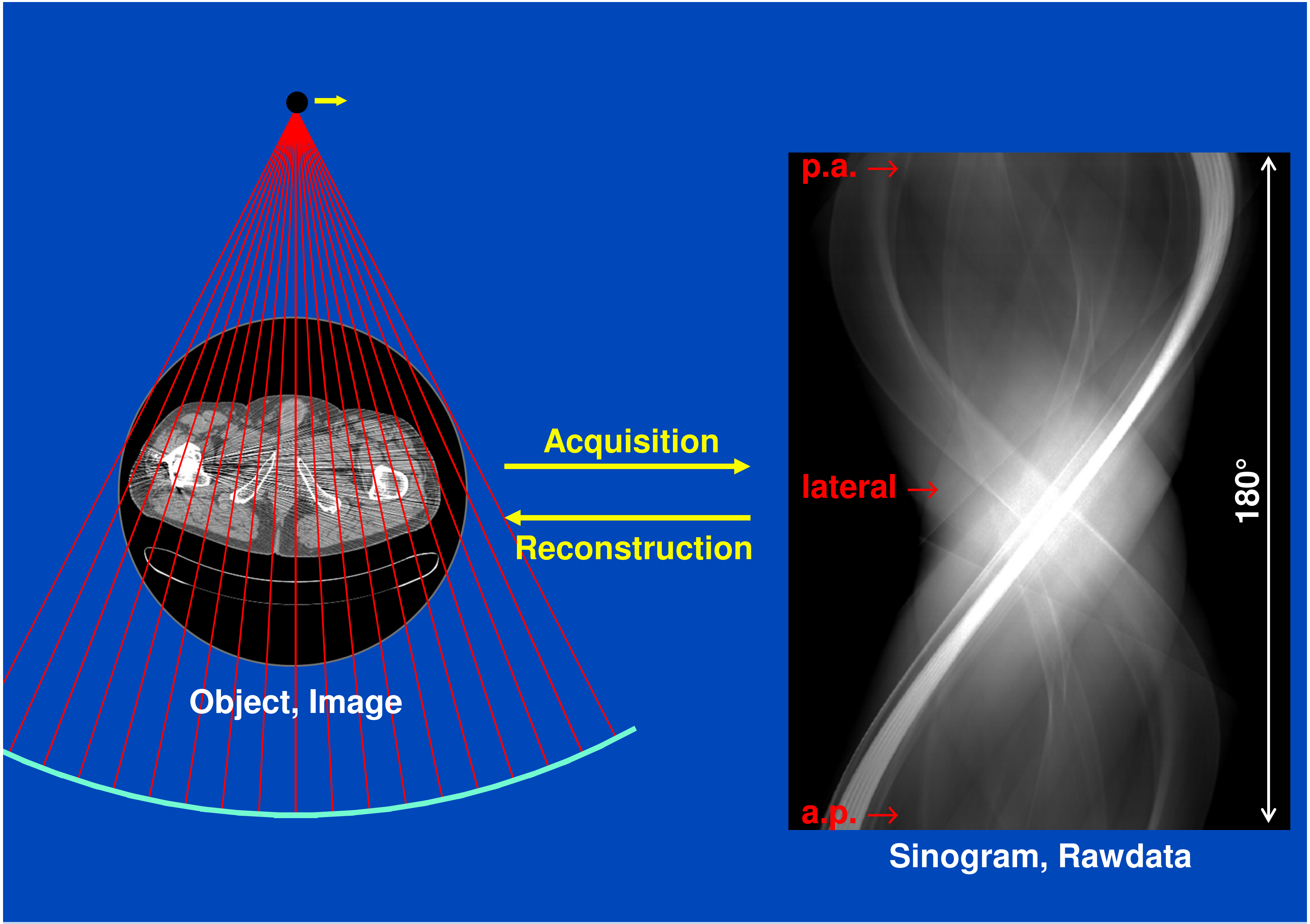


Photo courtesy of Siemens Healthcare, Forchheim, Germany

Demands on Image Reconstruction

- Real-time
- Robust against artifacts
- Accurate and quantitative
- Use all the acquired data (dose!)
- Dose-efficient (use all acquired data appropriately)
- Adjustable image quality (noise vs. spatial resolution)



p.a. →
lateral →
a.p. →
180°
Acquisition
Reconstruction
Object, Image
Sinogram, Rawdata

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Filtered Backprojection (FBP)

Measurement: $p(\vartheta,\xi) = \int dxdy\, f(x,y)\delta(x\cos\vartheta + y\sin\vartheta - \xi)$

Fourier transform:

$$\int d\xi\, p(\vartheta,\xi)e^{-2\pi i\xi u} = \int dxdy\, f(x,y)e^{-2\pi iu(x\cos\vartheta + y\sin\vartheta)}$$

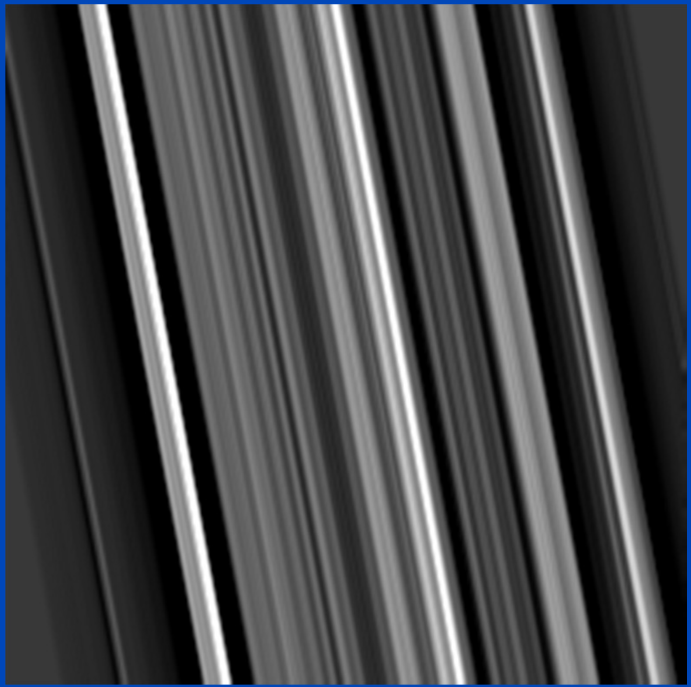
This is the central slice theorem: $P(\vartheta,u) = F(u\cos\vartheta, u\sin\vartheta)$

Inversion: $f(x,y) = \int_0^\pi d\vartheta \int_{-\infty}^{\infty} du\, |u| P(\vartheta,u)e^{2\pi iu(x\cos\vartheta + y\sin\vartheta)}$

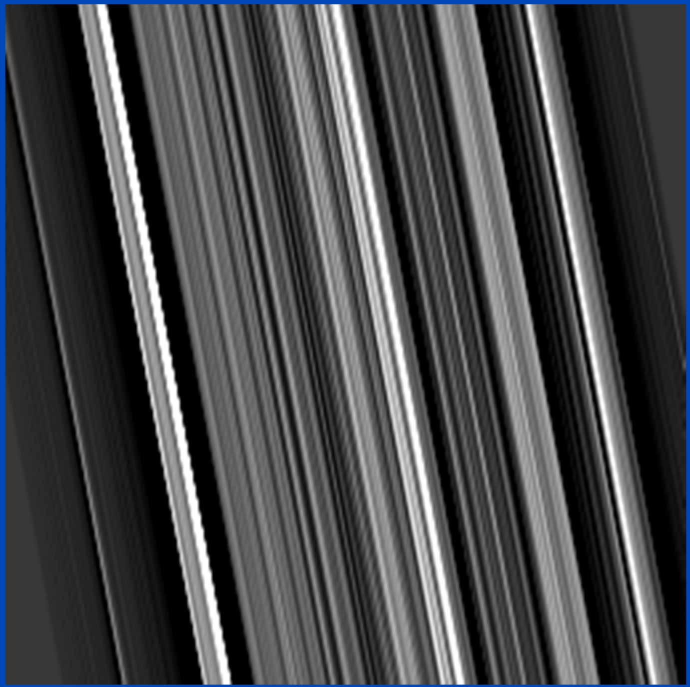
$$= \int_0^\pi d\vartheta\, p(\vartheta,\xi) * k(\xi)\Big|_{\xi = x\cos\vartheta + y\sin\vartheta}$$

Filtered Backprojection (FBP)

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

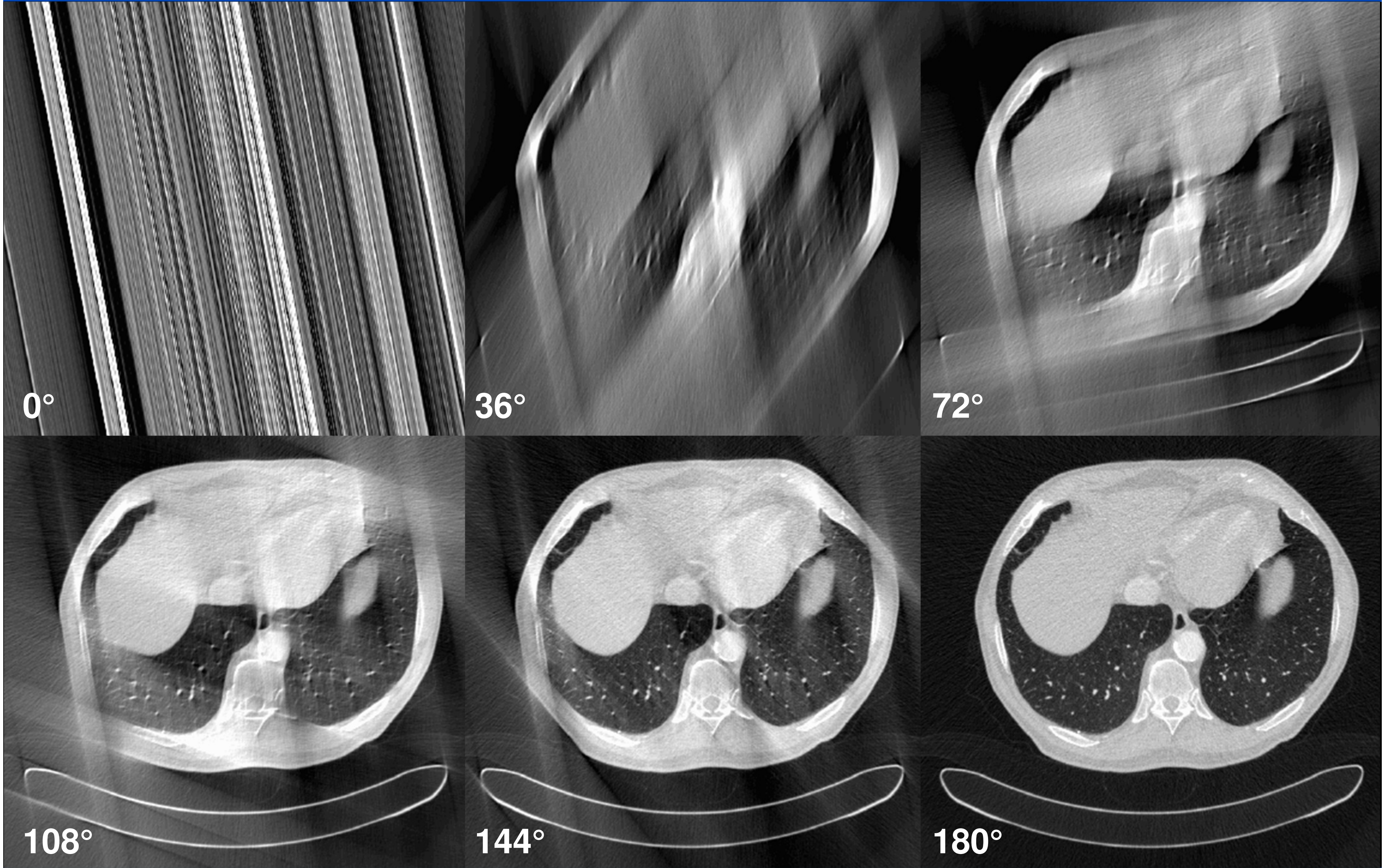


Smooth



Standard

Reconstruction kernels balance between spatial resolution and image noise.



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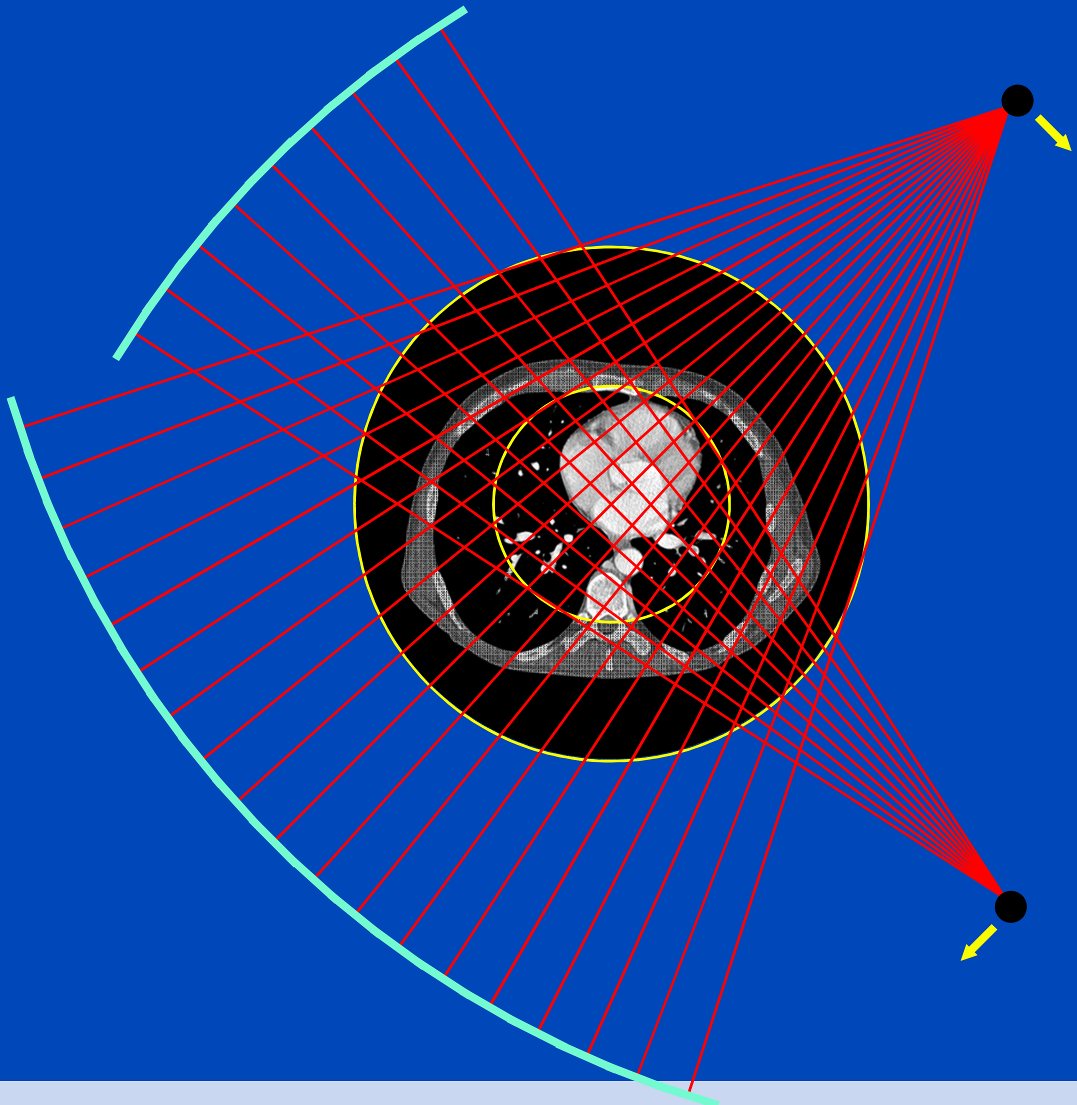
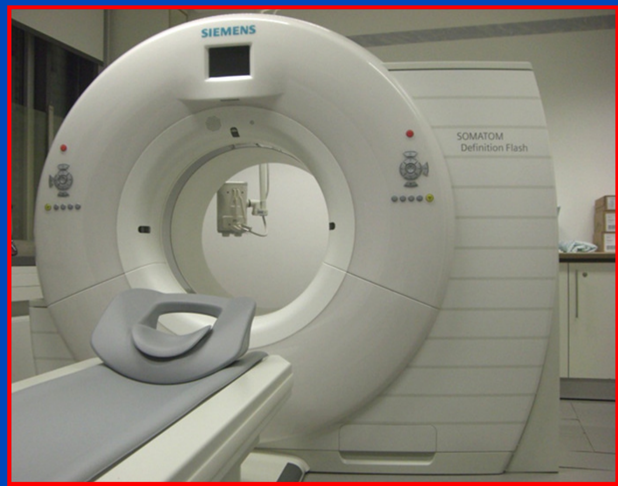
Multi-Threaded CT Scanners and Dual-Source-CT





Siemens SOMATOM Definition Flash dual source cone-beam spiral CT scanner


SIEMENS
300.0
-2000.0
SOMATOM Force

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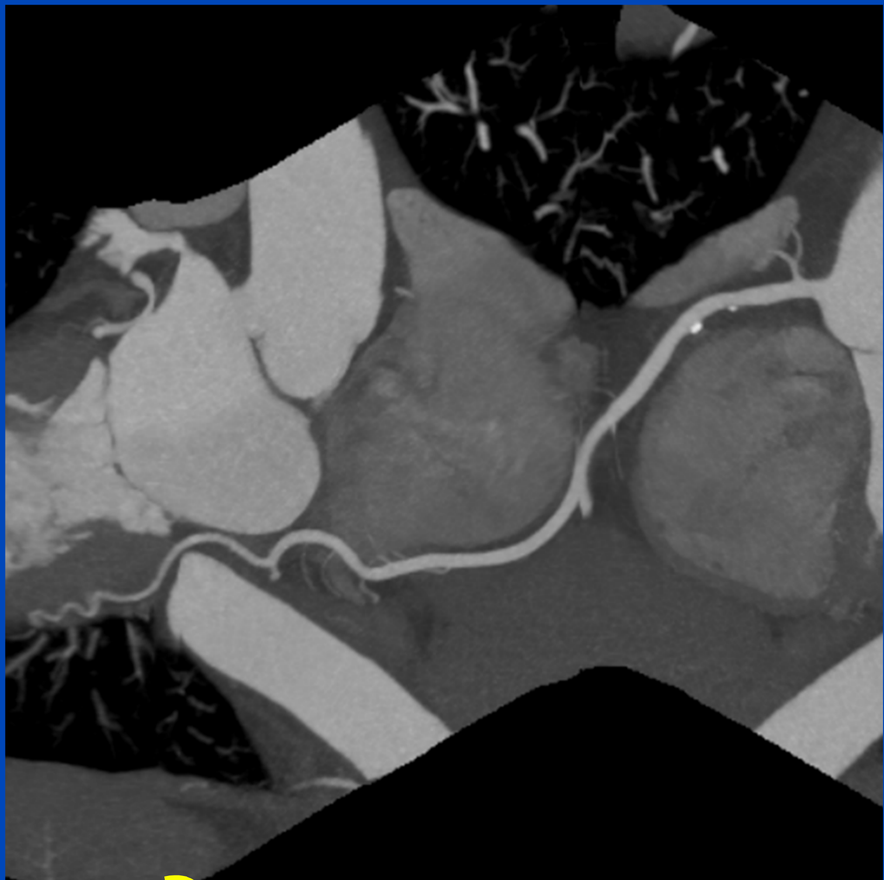
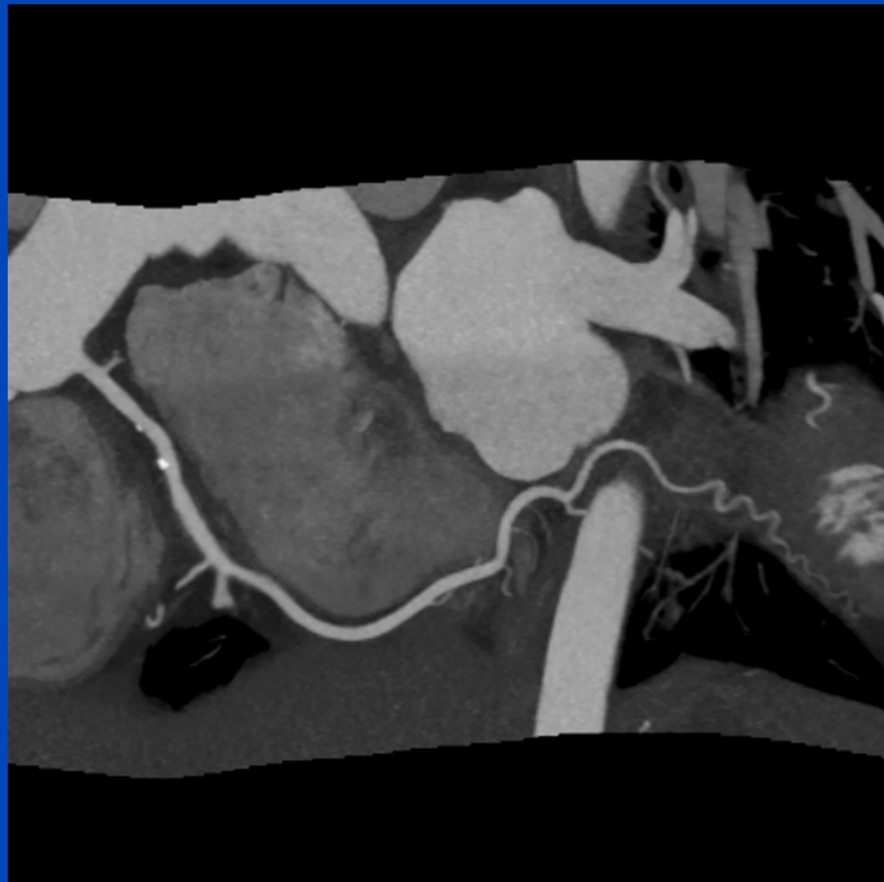
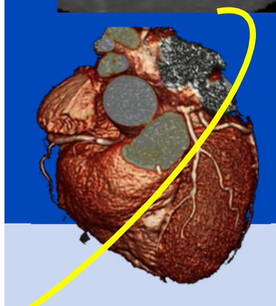
Dual Source CT, Turbo Flash Mode
70 kV, DLP: 39 mGy cm ≈ 0.55 mSv, calcified RCA







Data courtesy of Dr. Stephan Achenbach, Erlangen, Germany

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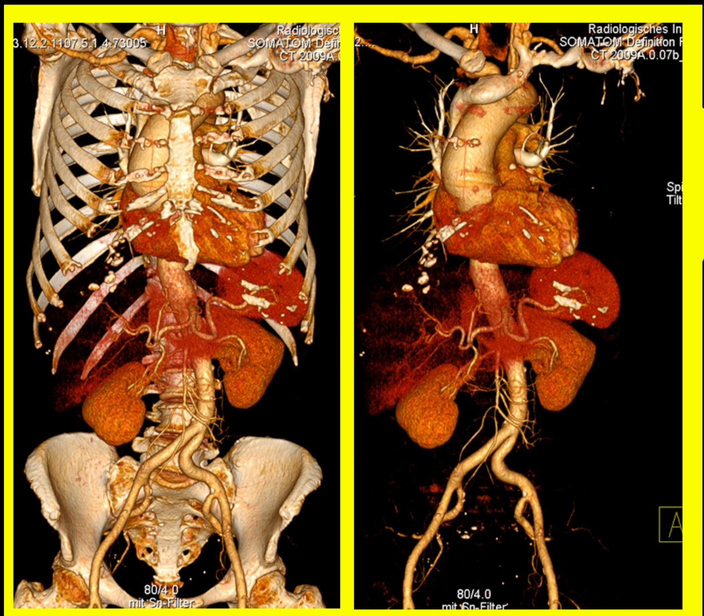
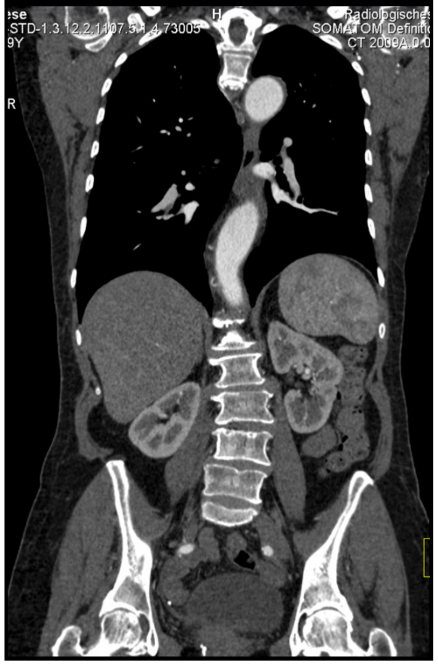
Dual Energy CT: Examples

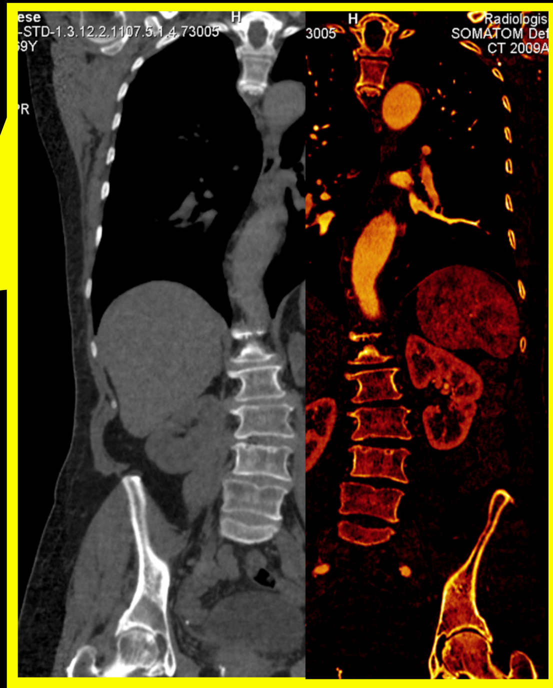
(Slide Courtesy of Siemens Healthcare)

DE bone removal



Single DECT Scan





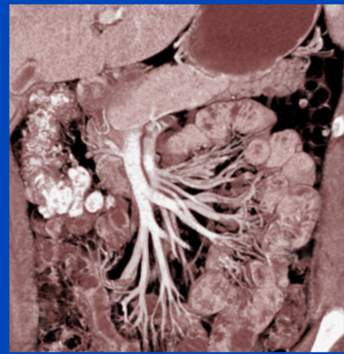
Virtual non-contrast and Iodine image

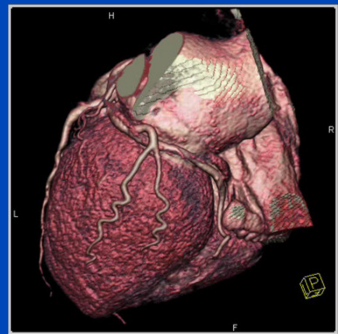
Dual Energy whole body CTA: 100/140 Sn kV @ 0.6mm

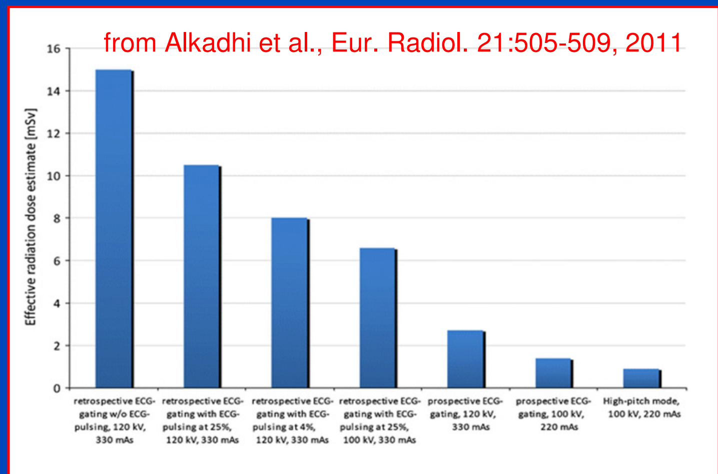
Courtesy of Friedrich-Alexander University Erlangen-Nürnberg

Clinical CT (also used Preclinically)

- Many specialized applications
  - Dedicated injection protocols
  - CT angiography (CTA)
  - Cardiac CT and cardiac CT angiography (CCTA)
  - Dual energy CT
  - Perfusion CT
  - CT colonoscopy
  - ...
- Sophisticated dose management
  - Tube current modulation
  - Automatic exposure control
  - Protection of organs at risk
  - Dose decreased by an order of magnitude
  - Iterative image reconstruction
  - ...
- Image quality
  - Low contrast (5 HU), low noise (5 … 50 HU)
  - submillimeter isotropic spatial resolution
  - ...

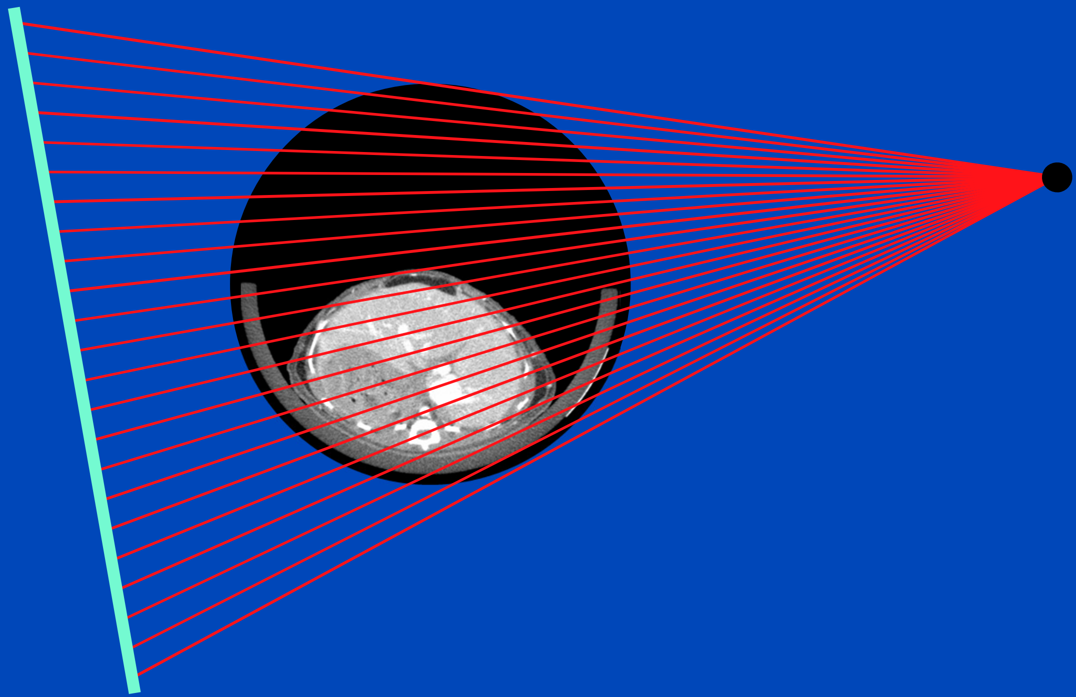






from Alkadhi et al., Eur. Radiol. 21:505-509, 2011

Preclinical In-Vivo Micro-CT



Kromek MARS CT

NanoFocus XRay NFR Polaris-G90

CT Imaging TomoScope

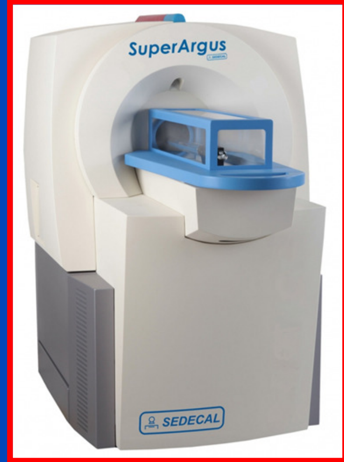
Siemens Inveon PET/SPECT/CT

PerkinElmer Quantum FX

GE eXplore Locus Ultra

Bruker microCT SkyScan 1176

Sedecal Super Argus PET/CT



Scanco Medical VivaCT 40/75/80

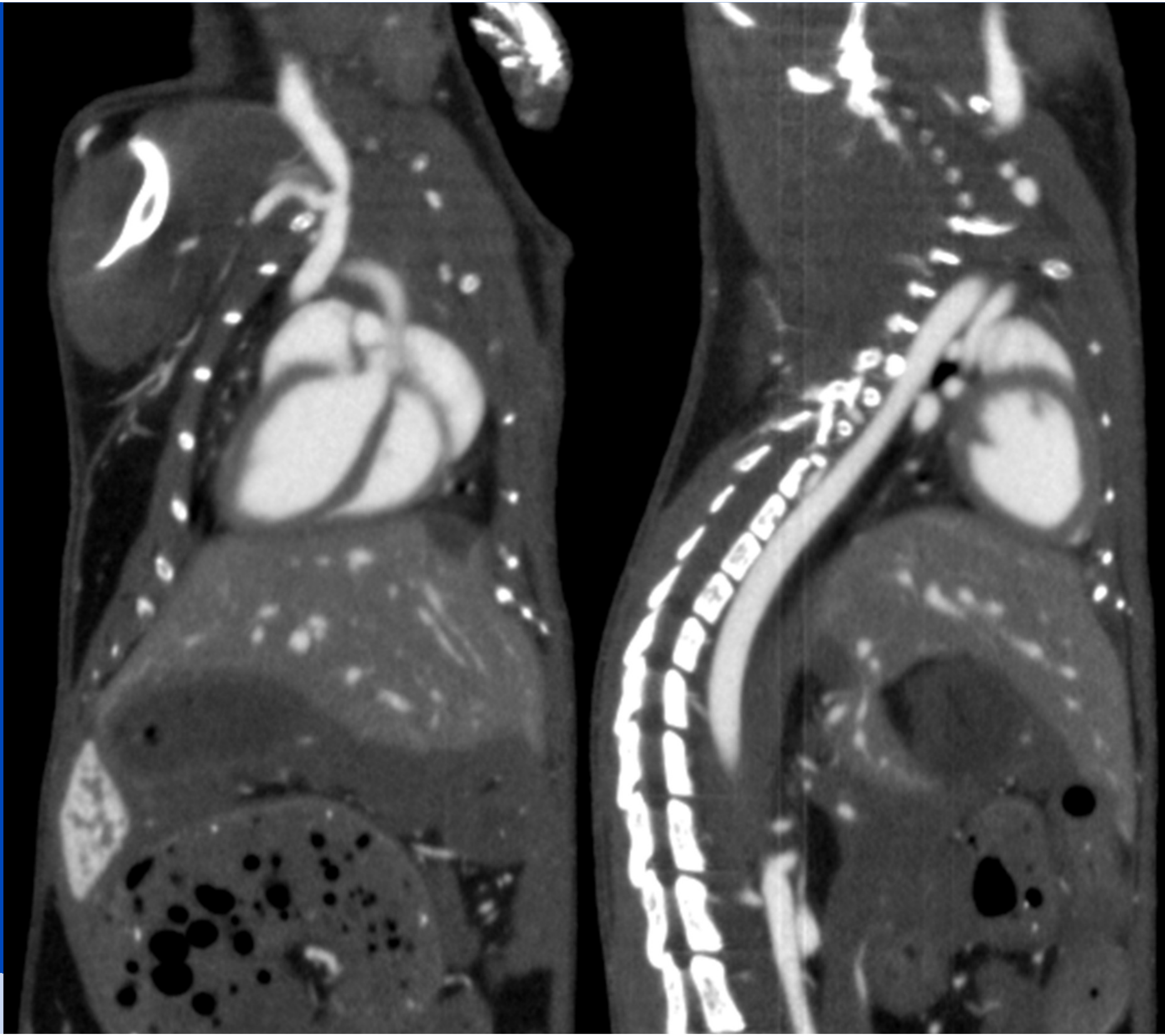
TriFoil Imaging eXplore CT

MiLabs U-SPECT+/CT

Hitachi Aloka Medical LaTheta LCT-200

inviscan imaging IRIS PET/CT

For these systems almost no technical information (on the CT modality) is publicly available.



In-Vivo Micro-CT

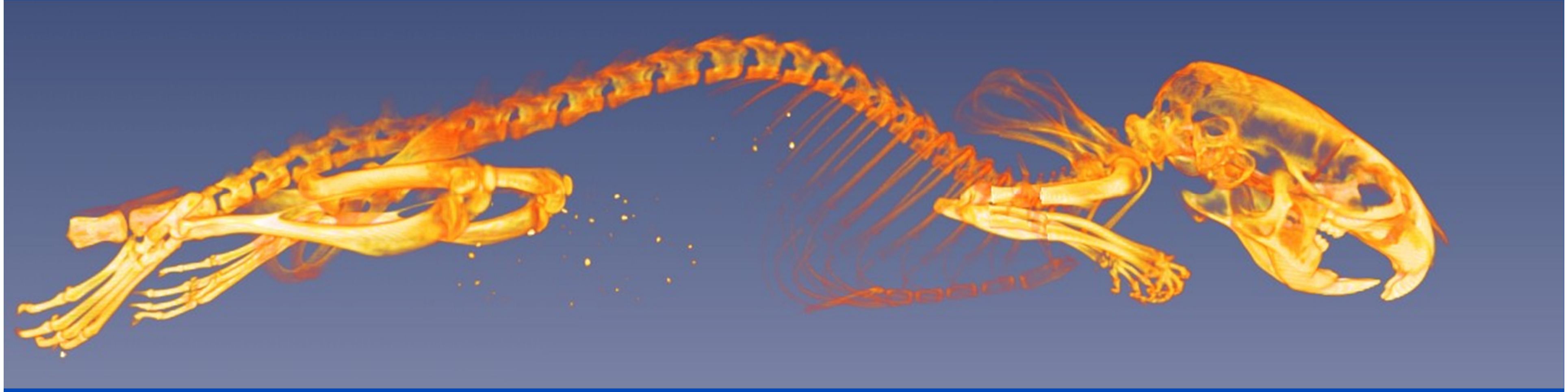
- Many more vendors (13) compared to diagnostic CT
- Tiny market (<< 1% of sales) compared to diagnostic CT
- Vendors not experienced in diagnostic CT
- Vendors typically not specialists in CT imaging
- CT is often only the add-on, e.g. to PET or SPECT
- No quality assurance for preclinical imaging
- Customers only look at spatial resolution
- No image quality vs. dose competition among vendors
- Almost no innovations, no basic research
- The image quality and the types of available applications are insufficient from a diagnostic CT point-of-view!
- In-vivo micro-CT is still very useful, as we will see.

dkfz.

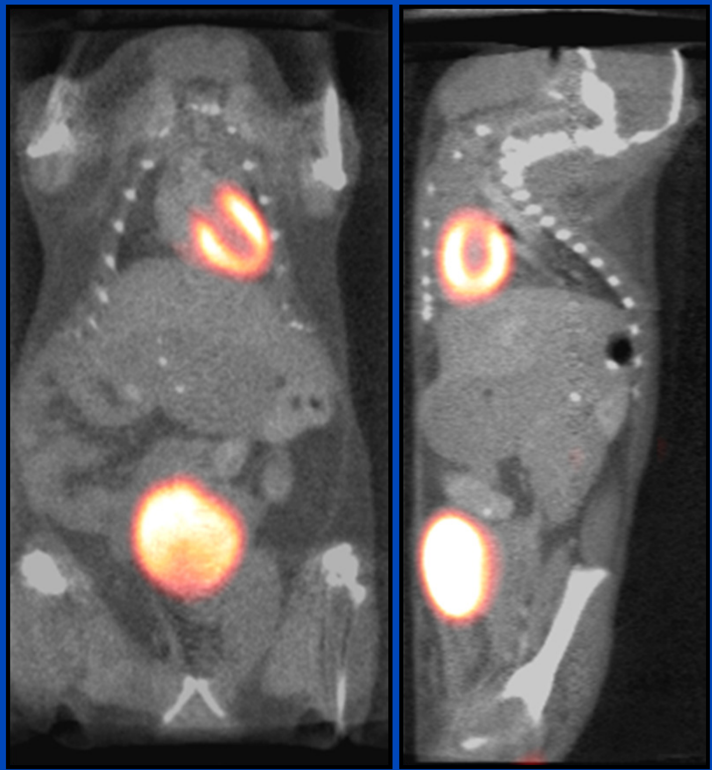
Basic Parameters
(best-of values typical for in-vivo micro-CT scanners)

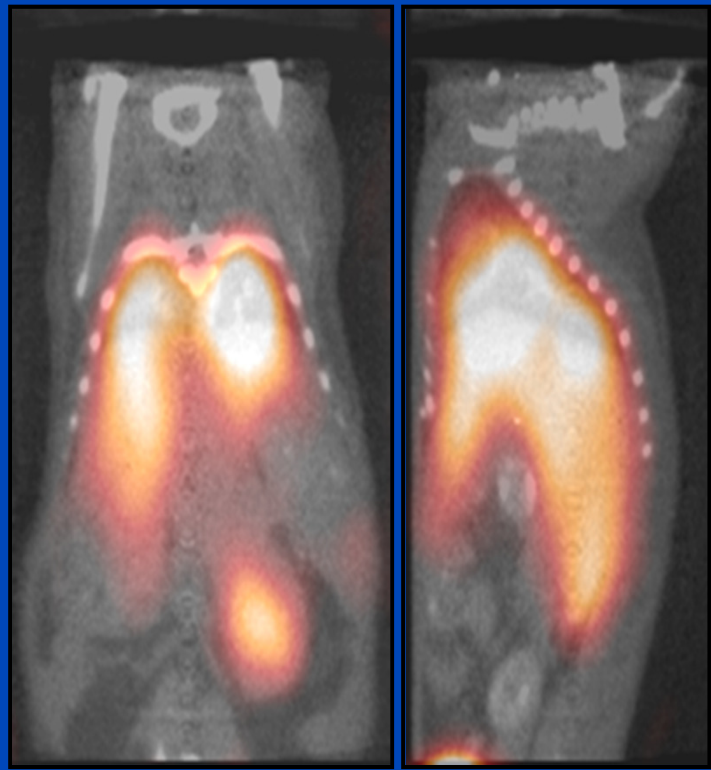
- Spatial resolution: 9 … 80 µm
- Detector size: 1000×1000 … 4000×4000
- Detector frame rate: 1 … 100 fps
- X-ray tube
  - Stationary anode
  - Transmission or reflection
  - 5 … 25 W, 20 … 140 kV, 0.1 … 0.5 mA
- Rotation time: T_{rot} = 1 s … 1 h
- Temporal resolution: 0.5 s … 1 h

dkfz.



Micro-PET/CT



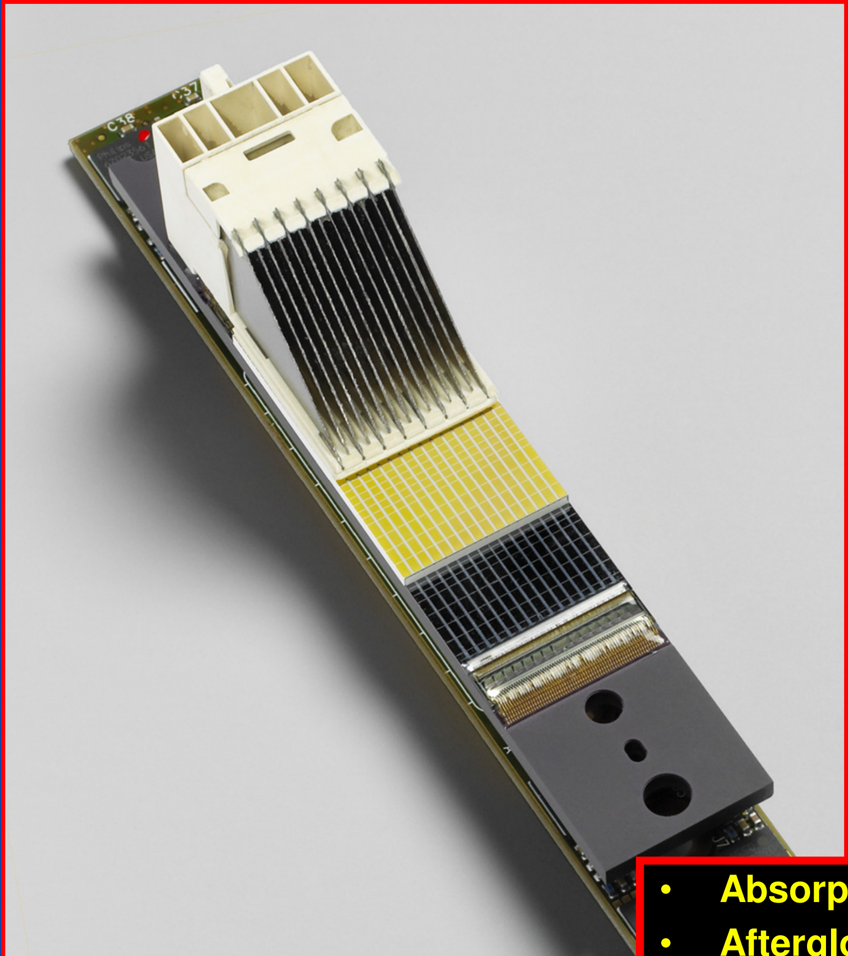


^{18}F labelled melanom cells

University of California, Davis

Detector Technology

Clinical CT Detector

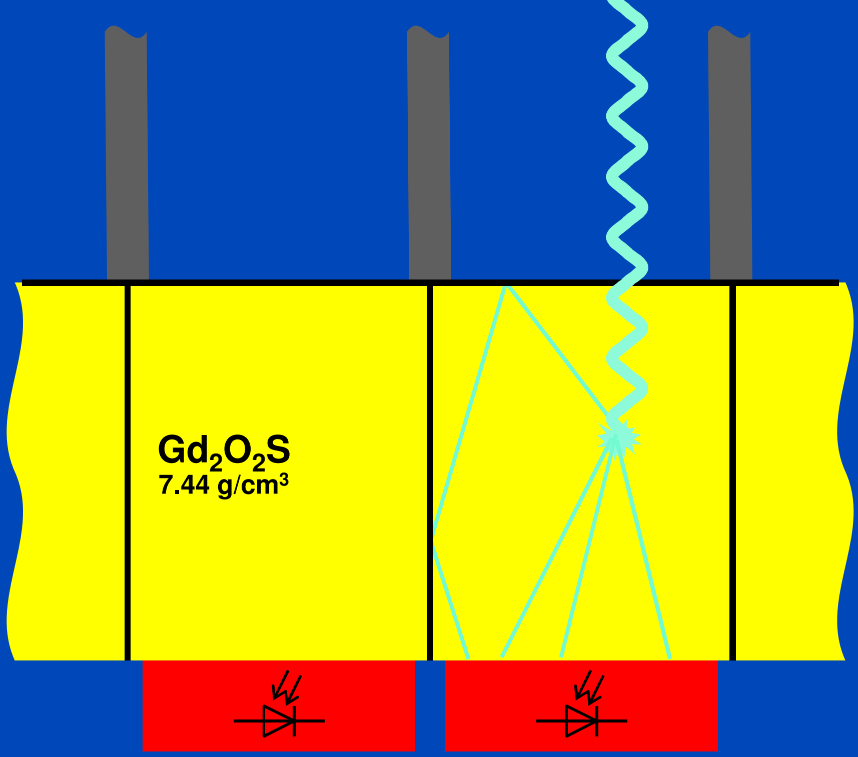


Flat Detector

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

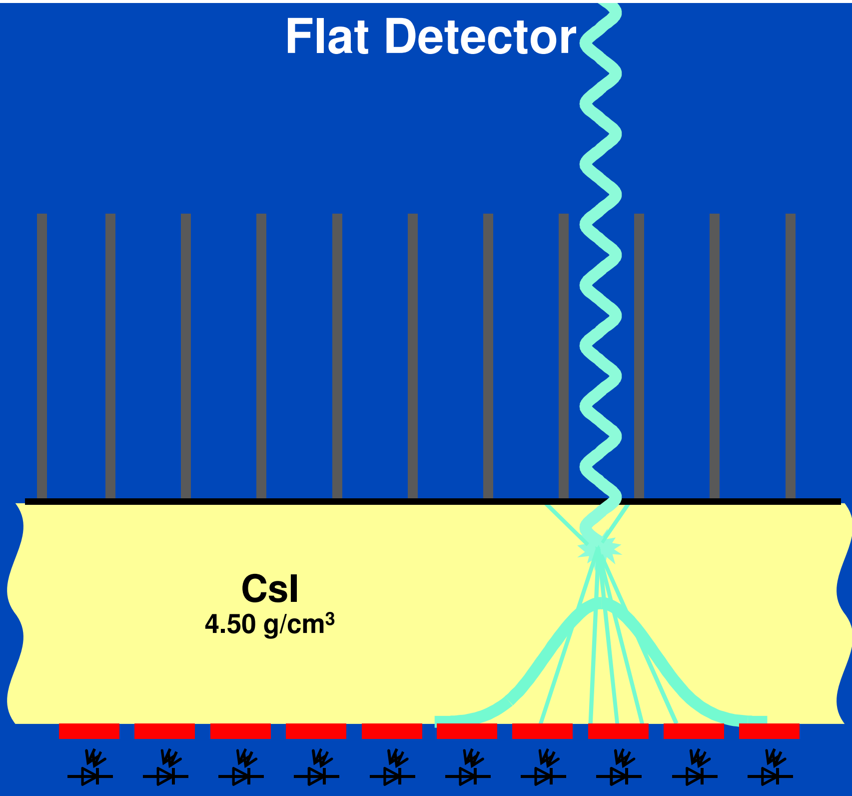
dkfz.

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

	Clinical CT (120 kV)			Flat Detector CT (120 kV)			Micro CT (60 kV)		
Material	Gd_2O_2S			CsI			CsI		
Density	7.44 g/cm³			4.5 g/cm³			4.5 g/cm³		
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.

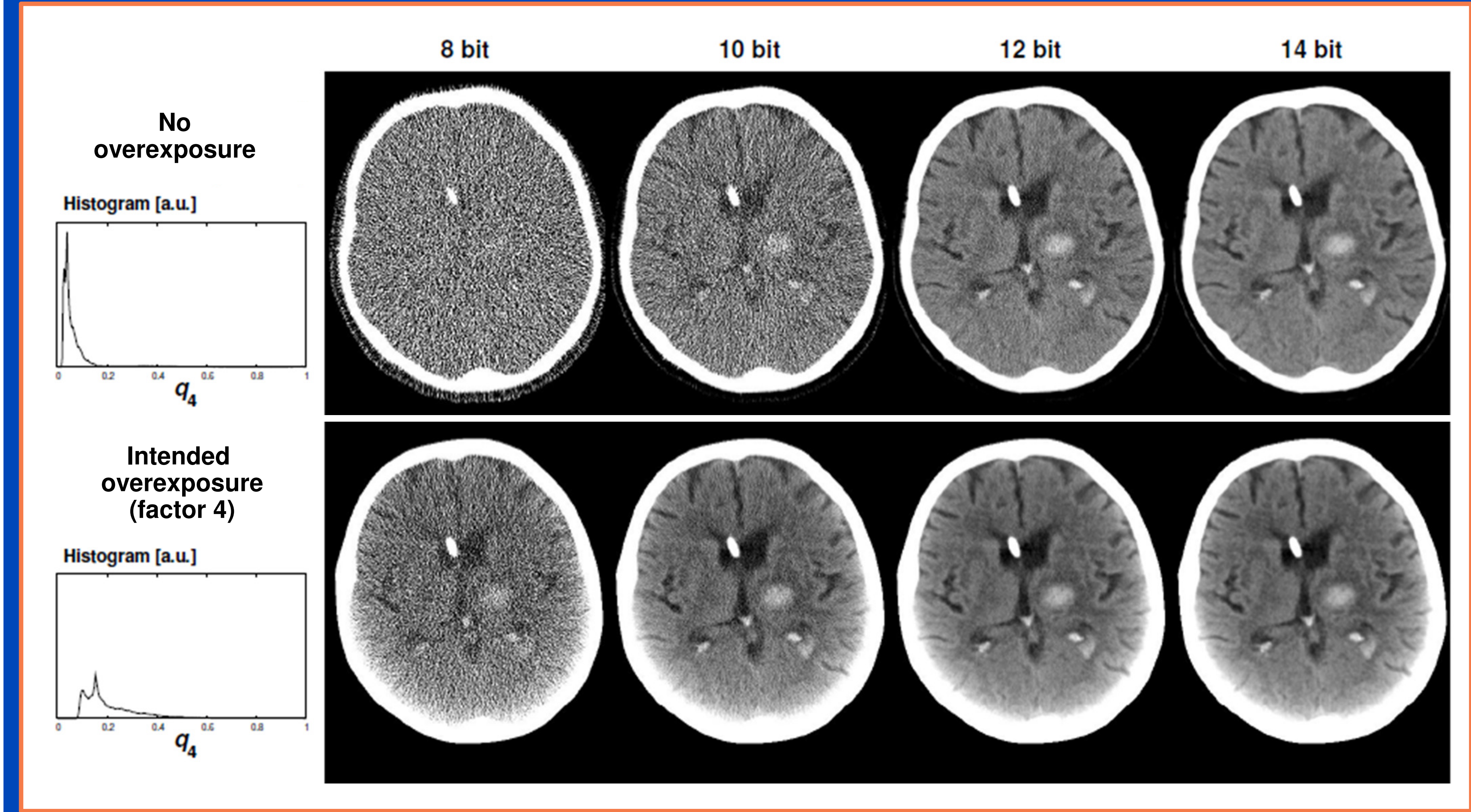
Dynamic Range in Flat Detectors

	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

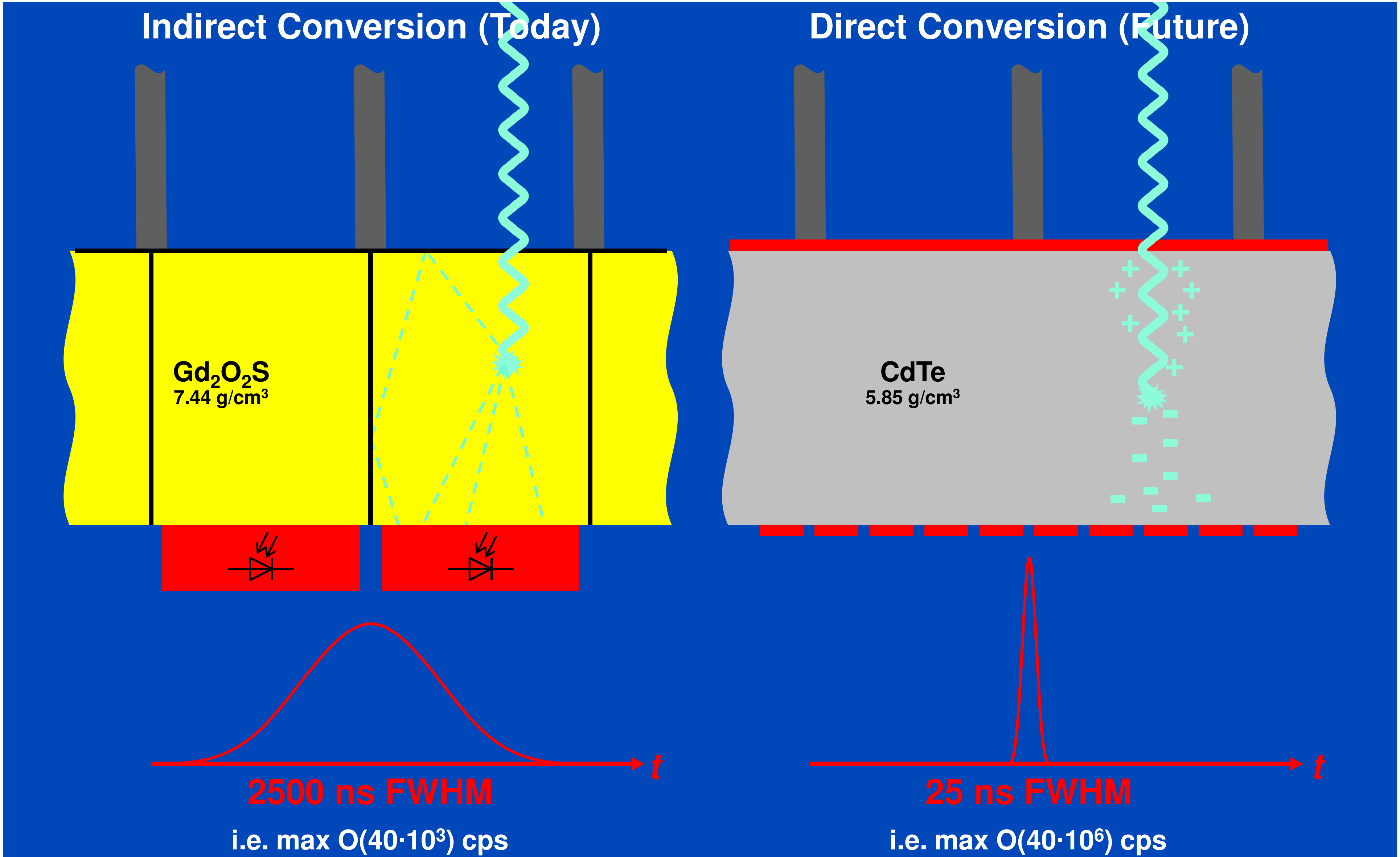
Table 2 4030CB dynamic range in available imaging modes

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

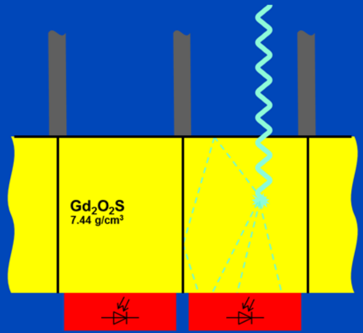
Indirect Conversion (Today) / Direct Conversion (Future)



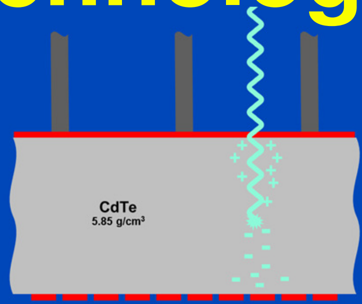
Requirements for CT: up to 10^9 x-ray photon counts per second per mm^2.
Hence, photon counting only achievable for direct converters.

dkfz.

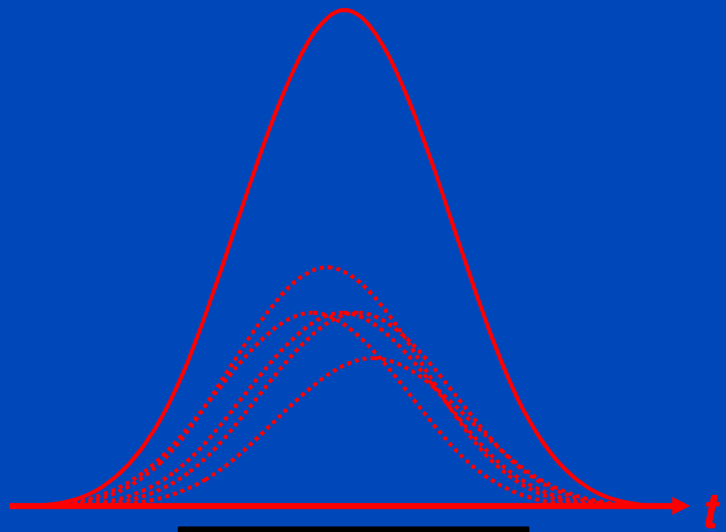
Integrating vs. Photon Counting Detector Technology

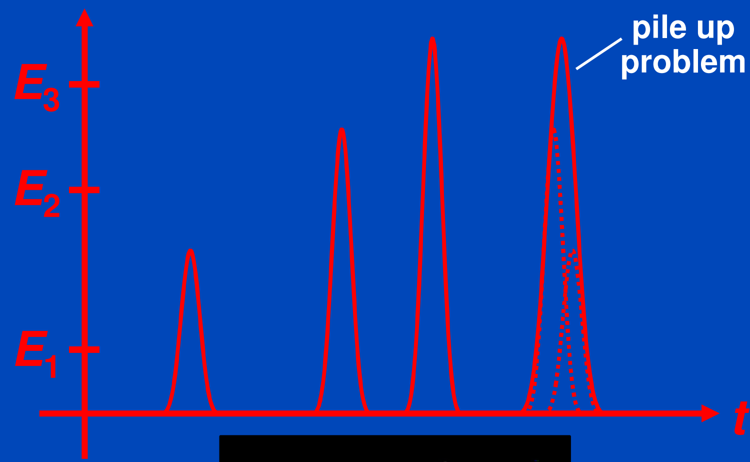


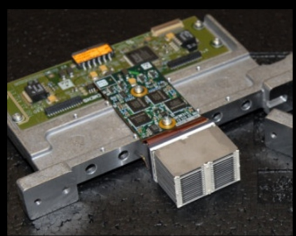
indirect conversion
= pile up only
= energy integrating



direct conversion
= photon counting
= energy selective







CT detector

Medipix detector

Summary

- Technology that is mature in diagnostic CT does not arrive in micro-CT systems.
- Micro-CT is often just used as an anatomical reference.
- Still, micro-CT is a very useful tool.


Thank You!
This presentation will soon be available at www.dkfz.de/ct.
Parts of the reconstruction software were provided by
RayConStruct® GmbH, Nürnberg, Germany.