Basics of Tomography 1: X-Ray Computed Tomography

Prof. Dr. Marc Kachelrieß

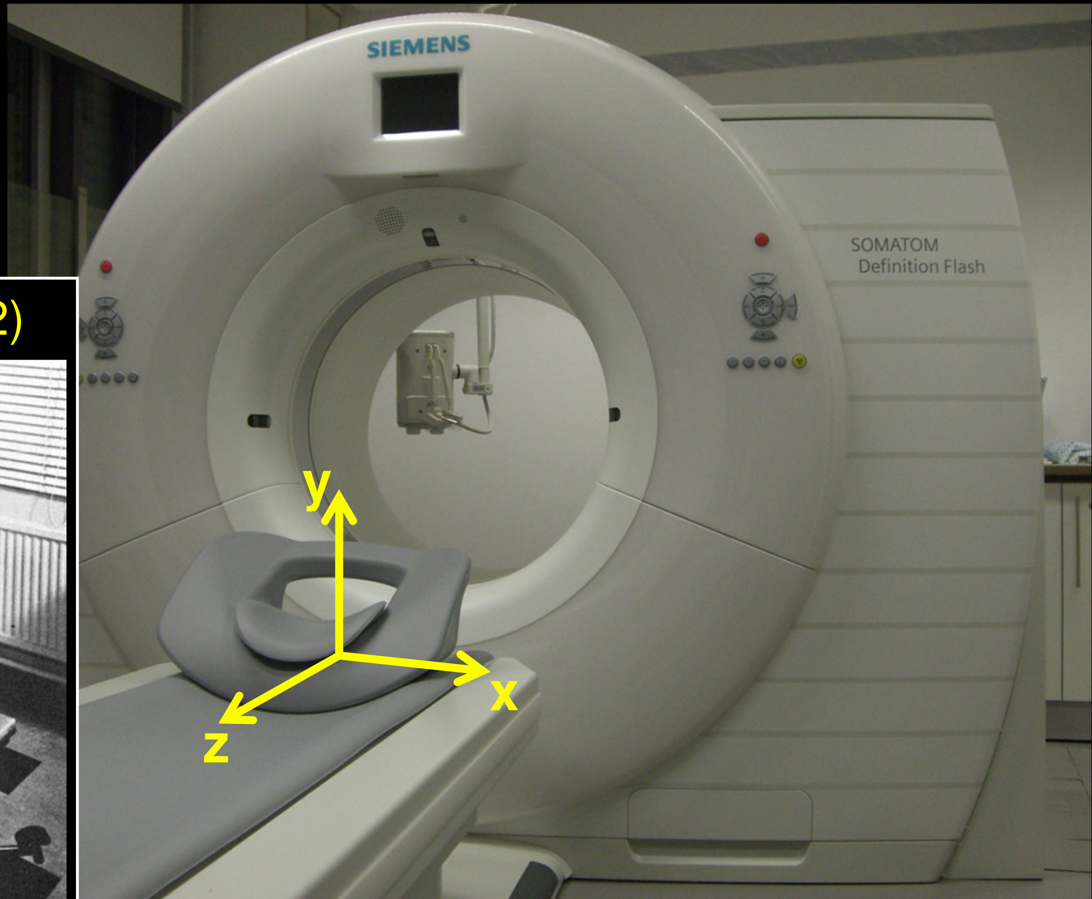
German Cancer Research Center (DKFZ)
Heidelberg, Germany
www.dkfz.de/ct

DEUTSCHES
KREBSFORSCHUNGSZENTRUM
IN DER HELMHOLTZ-GEMEINSCHAFT

Contents

- Basics of Tomography 1 (90 min): CT
- Basics of Tomography 2 (60 min): Image reconstruction
- Basics of Tomography 3 (45 min):
  - Either SPECT, PET
  - or spectral CT, incl. dual energy CT
  - or data sparsity, incl. motion compensation and interventional CT

Siemens 2·2·64=256-slice dual source cone-beam spiral **CT**(2008)



1152 views per rotation in 0.28 s

2·64×(736+480) 2-byte channels per view

600 MB/s data transfer rate

5 GB data size typical

EMI parallel beam scanner (1972)

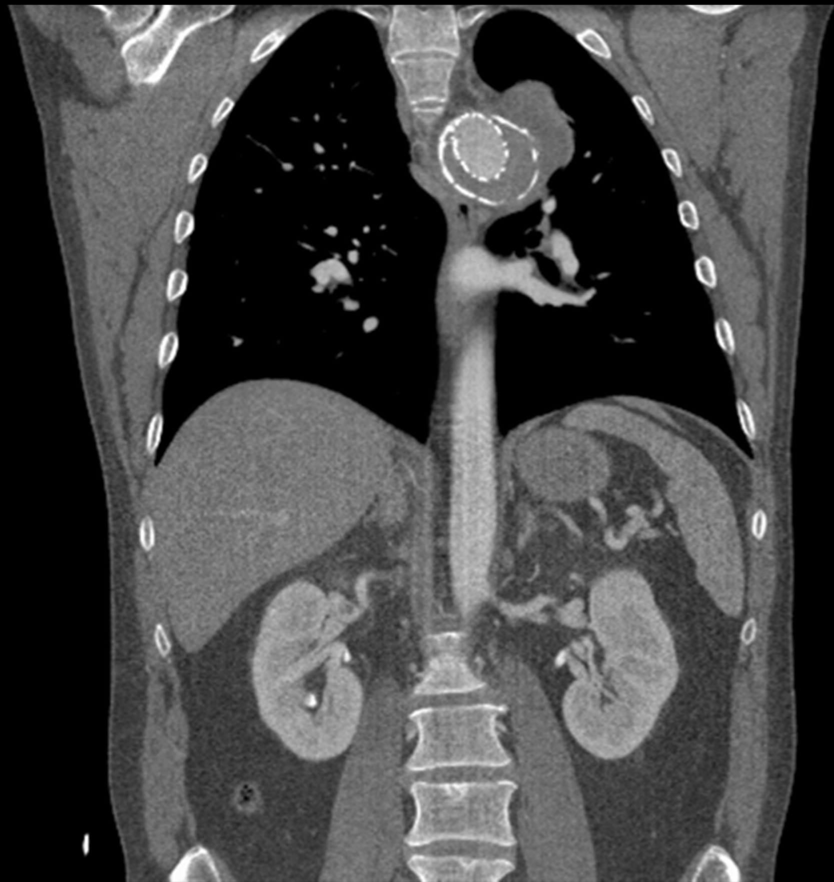
180 views per rotation in 300 s

2×160 positions per view

384 B/s data transfer rate

113 kB data size

Siemens 2·2·64=256-slice dual source cone-beam spiral **CT**(2008)



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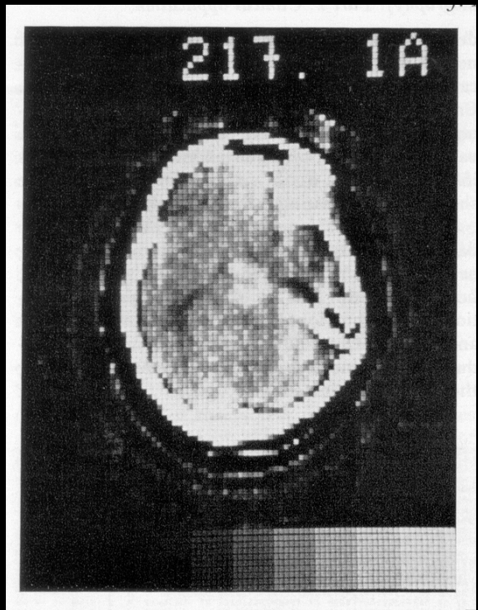


180 views per rotation in 300 s

2×160 positions per view

384 B/s data transfer rate

113 kB data size

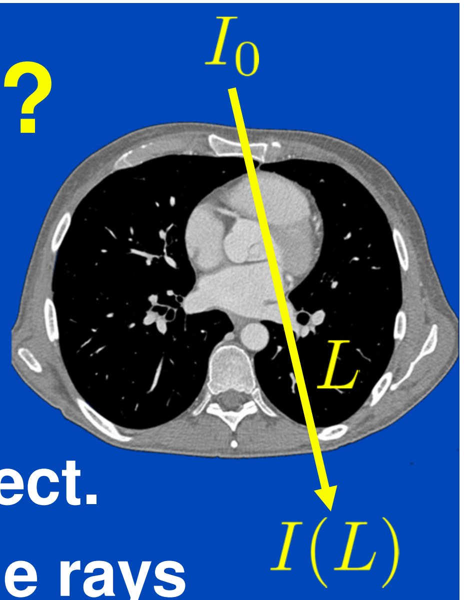
GE Discovery GSI

Philips Brilliance iCT

Siemens Somatom Force

Toshiba Aquilion ONE Vision

What does CT Measure?



- **X-rays are generated in an x-ray tube.**
- **The polychromatic radiation is attenuated in the patient. X-ray photon attenuation is dominated by the photo and the Compton effect.**
- **Detectors measure the x-ray intensity after the rays have passed through the patient along several lines *L*.**
- **The log intensity is the so-called x-ray transform:**

$$p(L) = -\ln \frac{I(L)}{I_0} = -\ln \int dE\, w(L,E) e^{-\int dL \mu(\boldsymbol{r}, E)}$$

- **Often, the follwing monochromatic approximation is used:**

$$p(L) \approx \int dL \mu(\boldsymbol{r}, E_{\text{eff}})$$

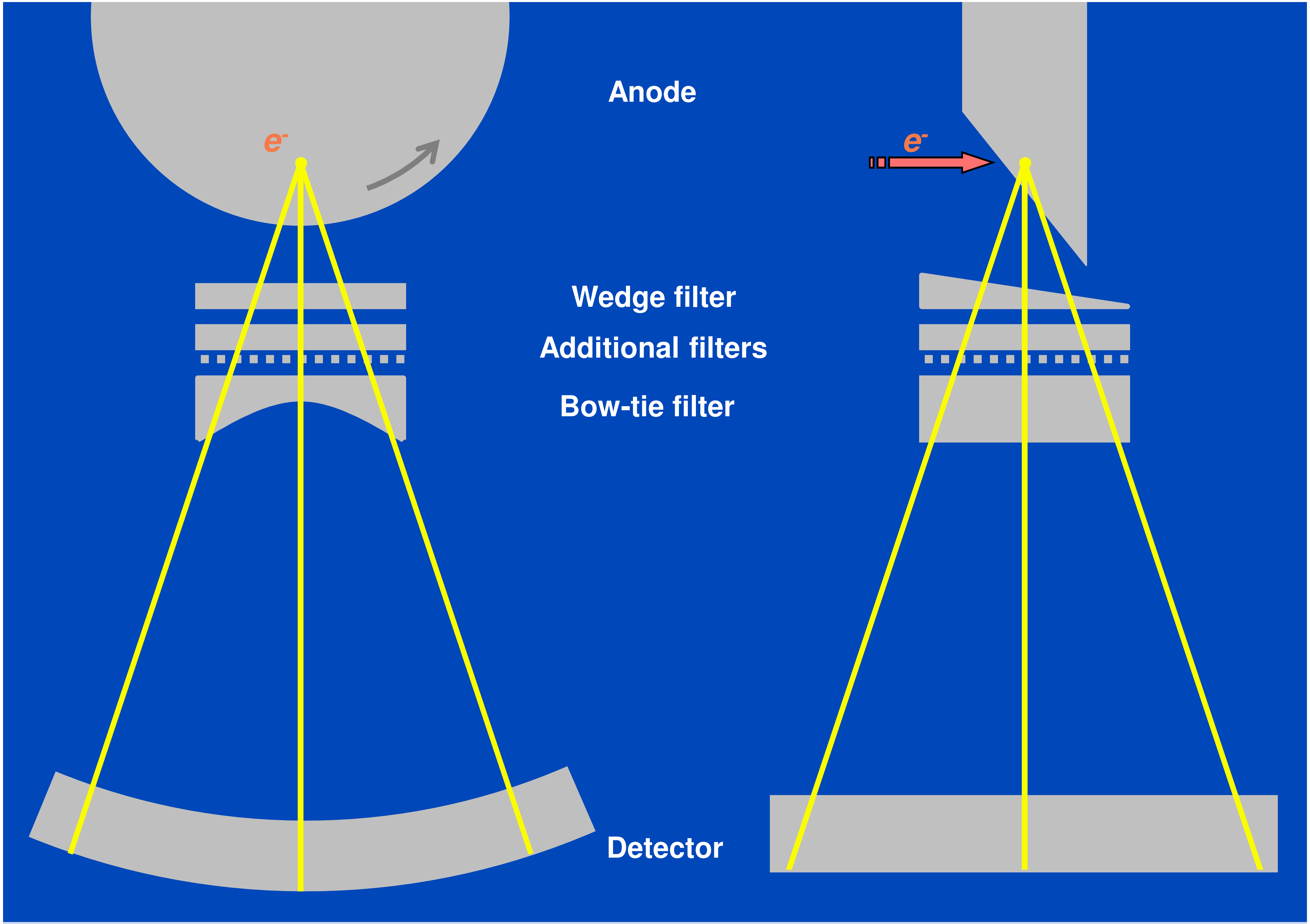


Figure not drawn to scale. Order of prefiltration may differ from scanner to scanner.

The detected spectrum is a function of the line of integration *L*:

$$p(L) = -\ln \int dE\, w(L,E)\, e^{-\int dL \mu(\boldsymbol{r},E)}$$

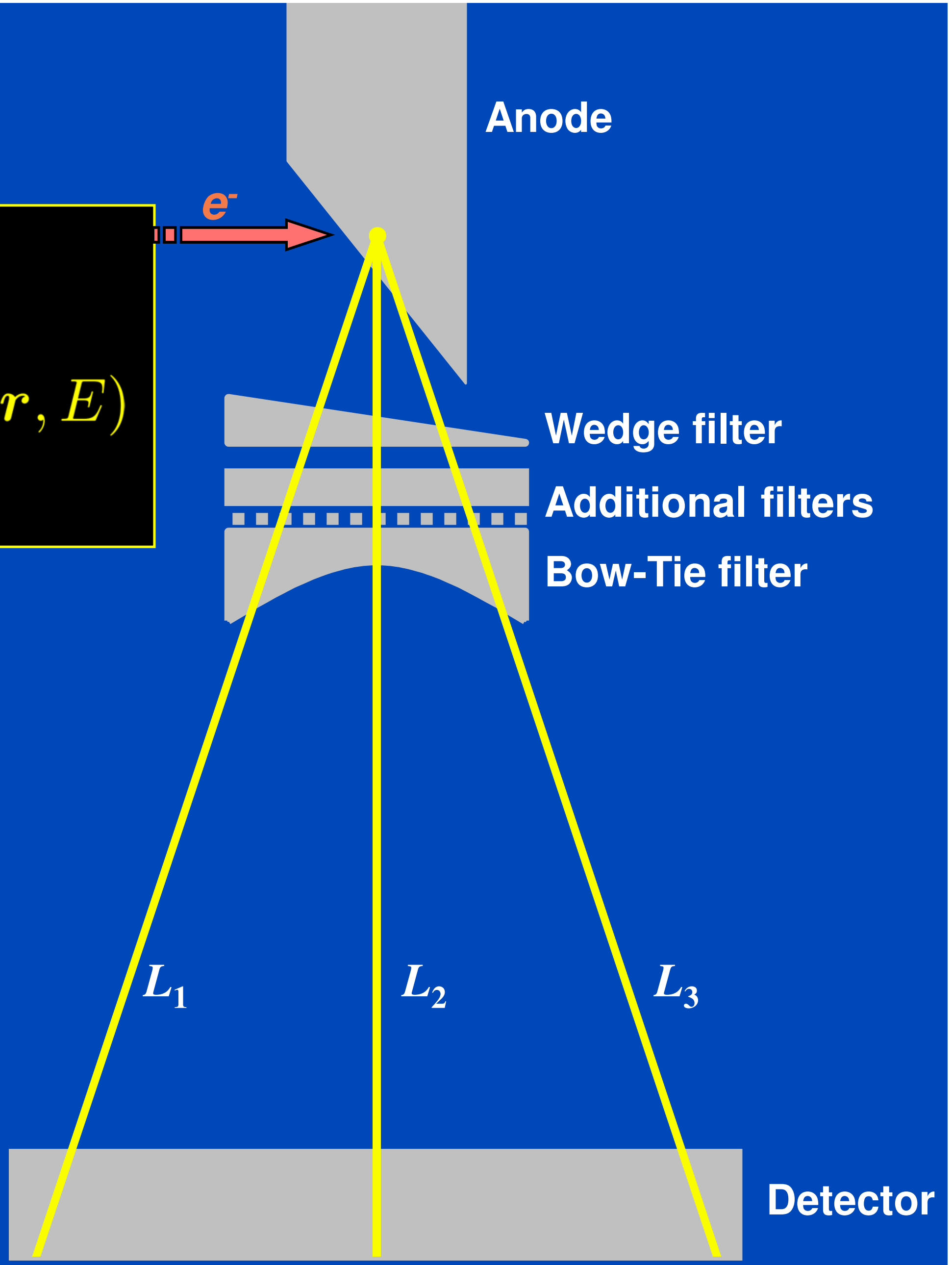
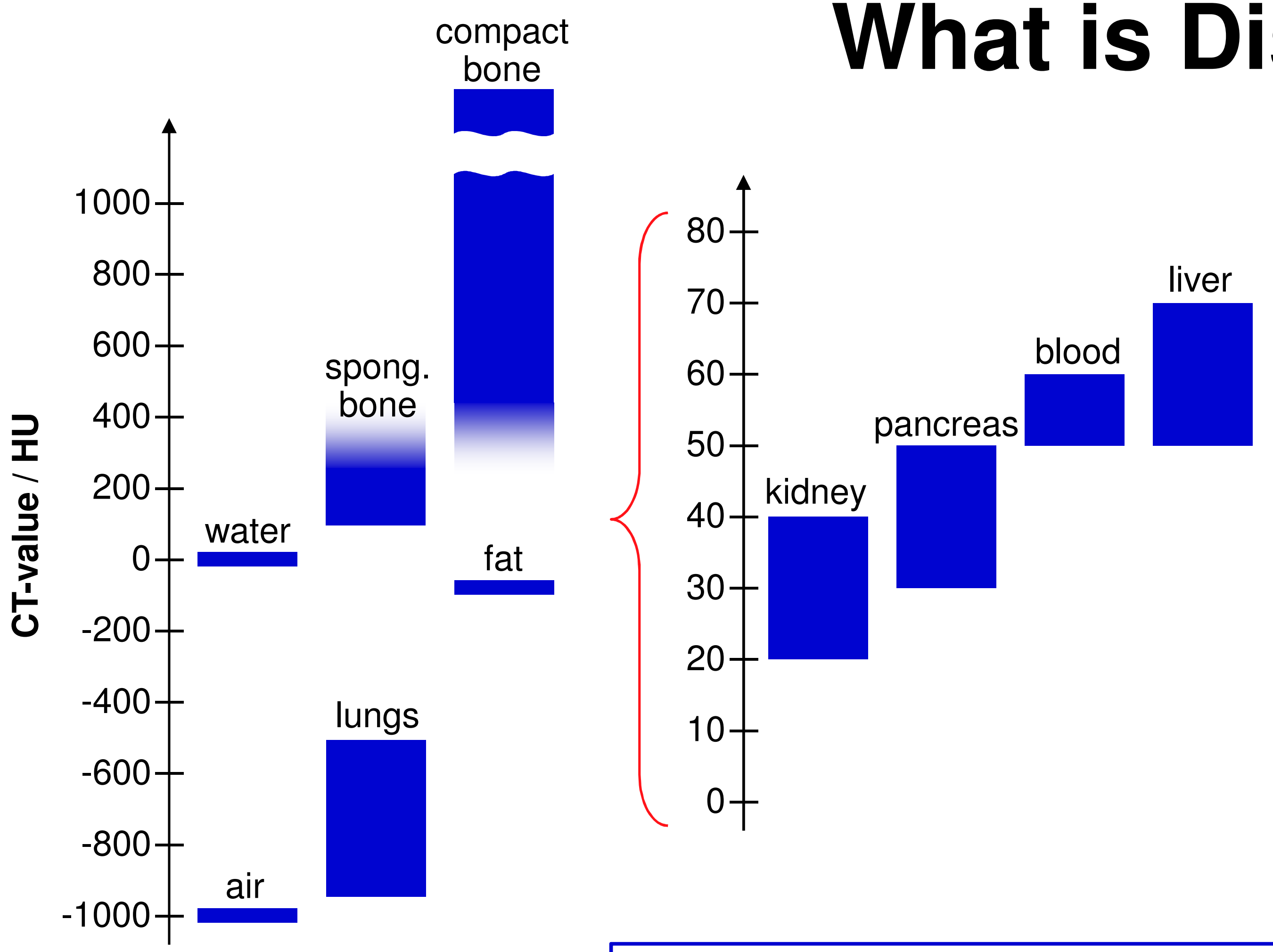
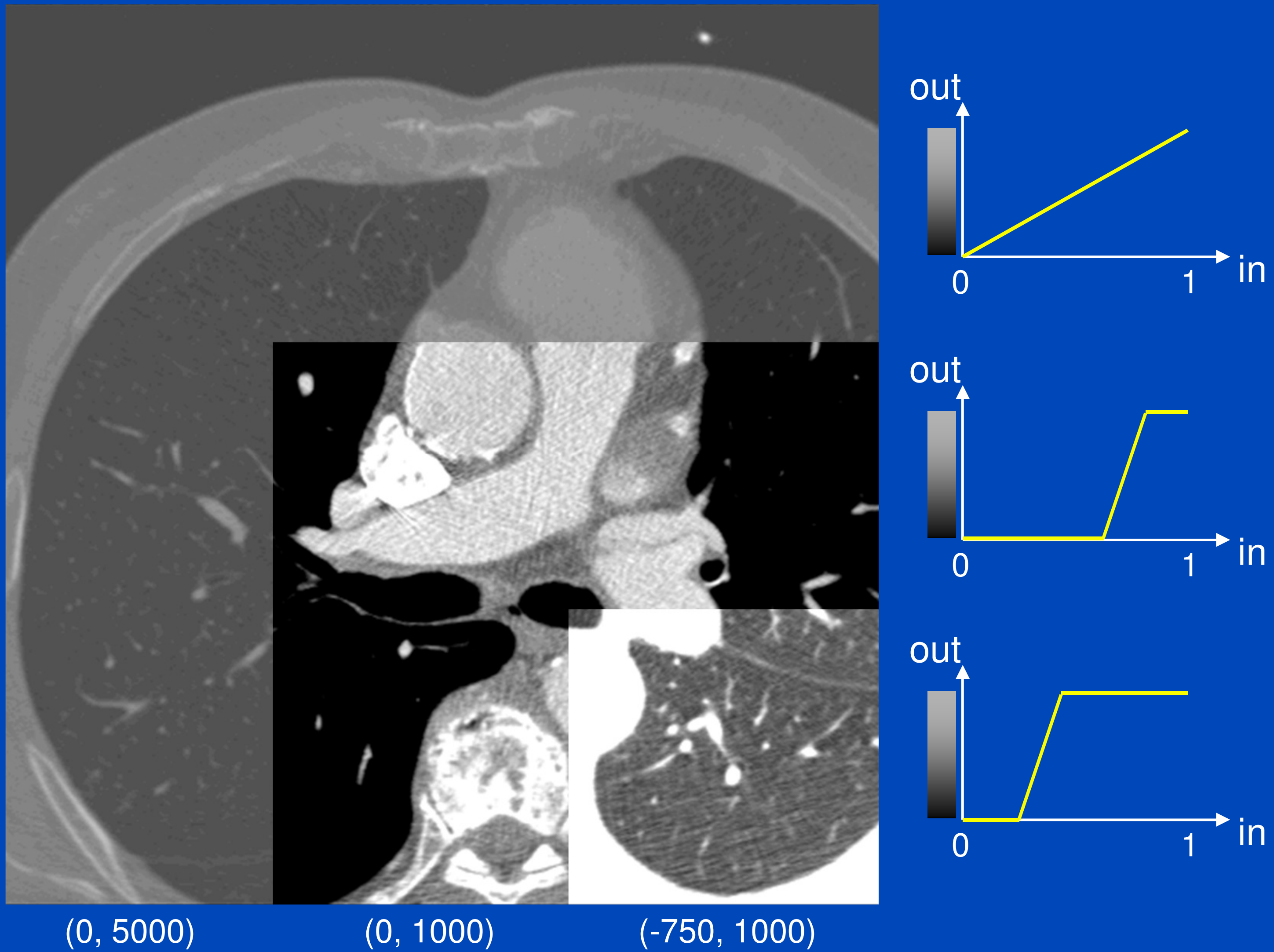


Figure not drawn to scale. Order of prefiltration may differ from scanner to scanner.

What is Displayed?

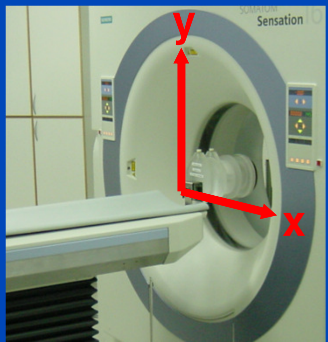


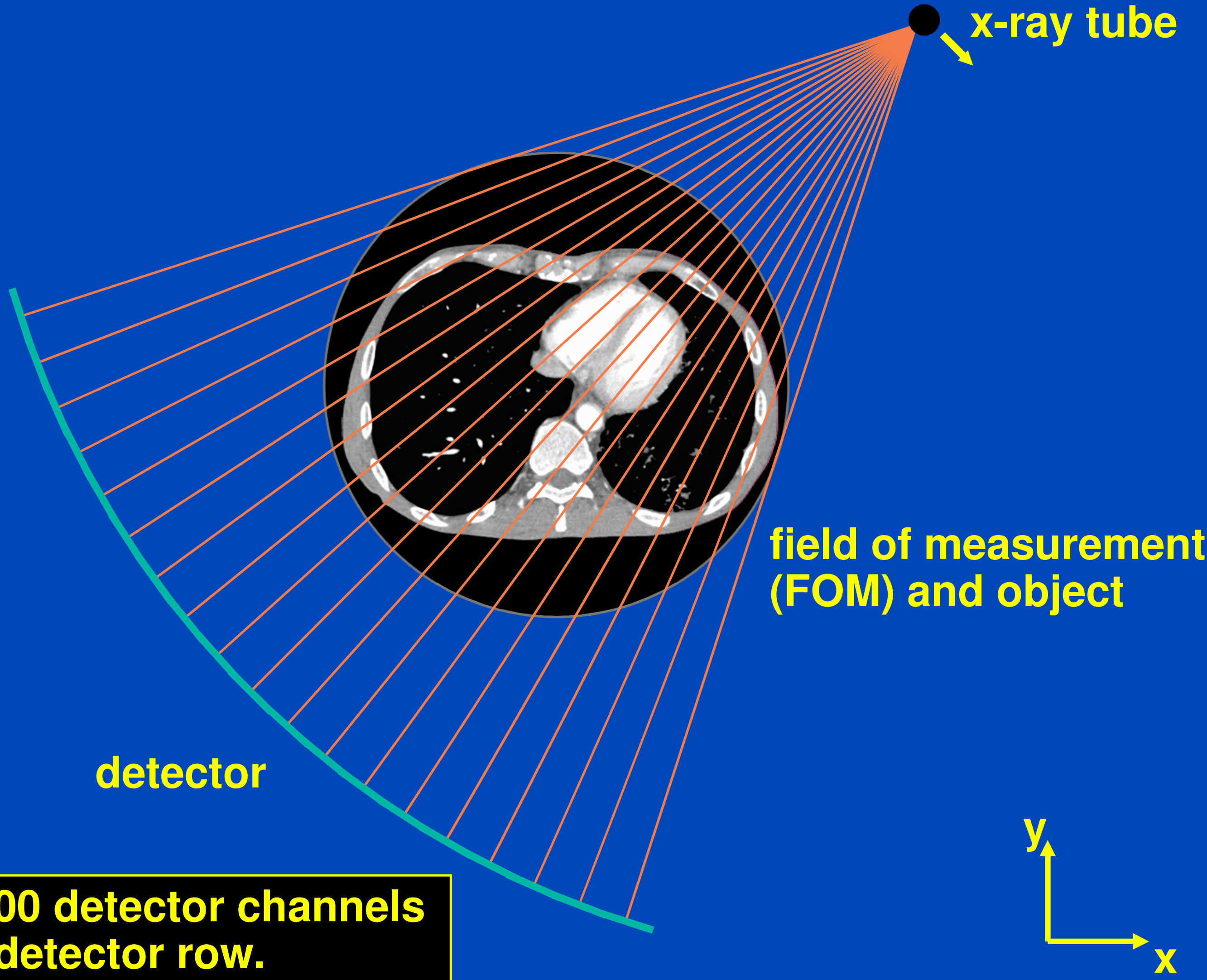
$$CT(\boldsymbol{r}) = \frac{\mu(\boldsymbol{r}) - \mu_{\text{Water}}}{\mu_{\text{Water}}} \cdot 1000\ \text{HU}$$



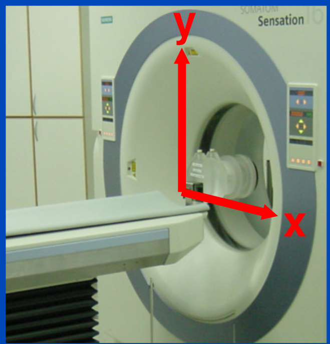
out
in
0
1
(0, 5000)
(0, 1000)
(-750, 1000)

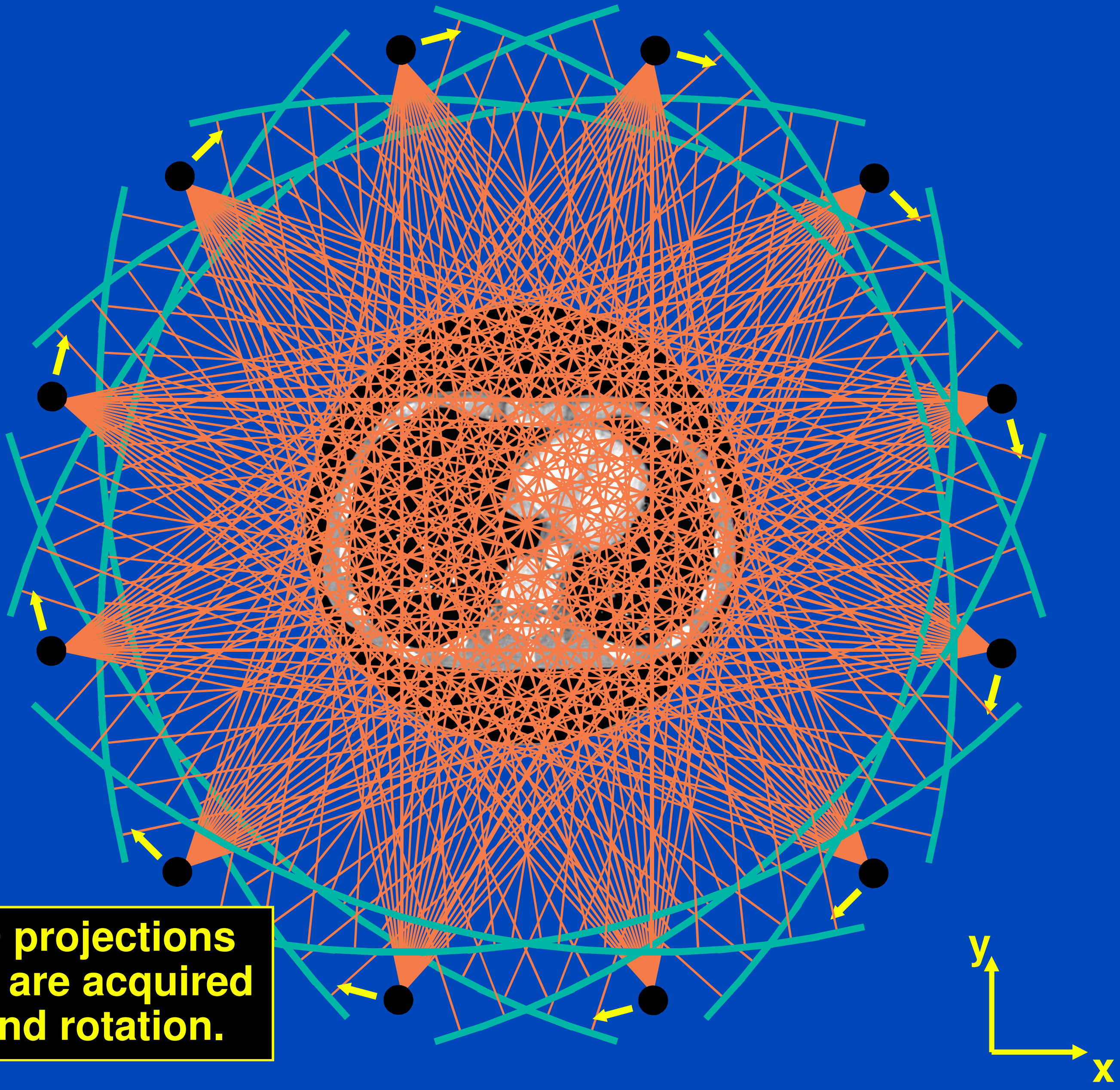
Fan-Beam Geometry (transaxial / in-plane / x-y-plane)





In the order of 1000 detector channels are available per detector row.





In the order of 1000 projections with 1000 channels are acquired per detector slice and rotation.

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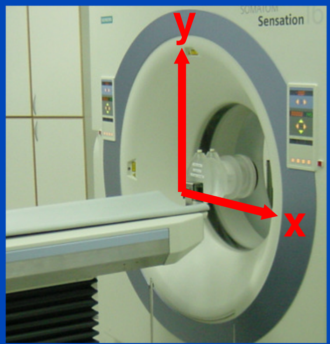
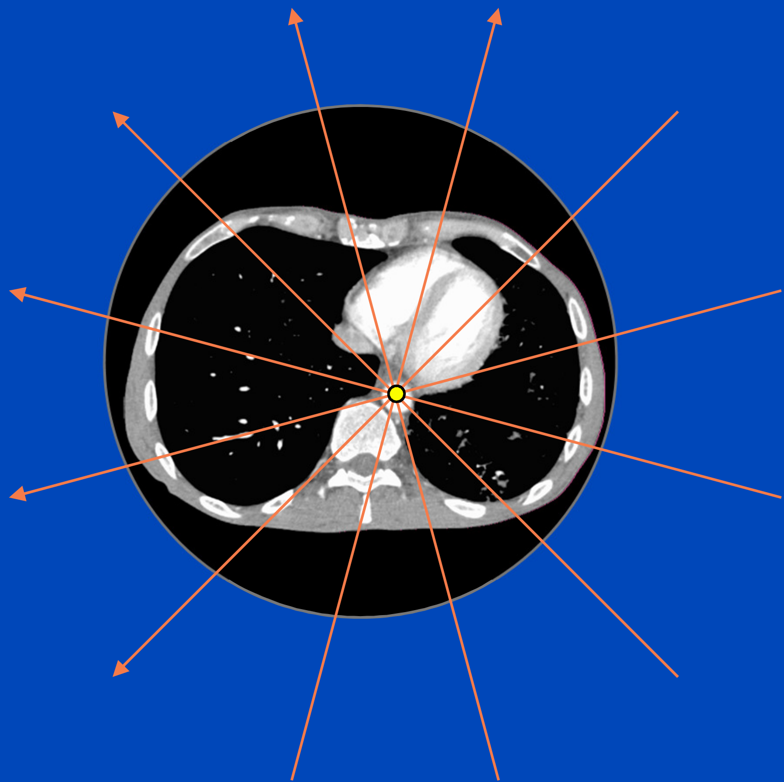
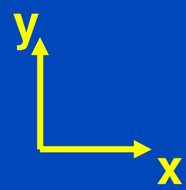
Data Completeness

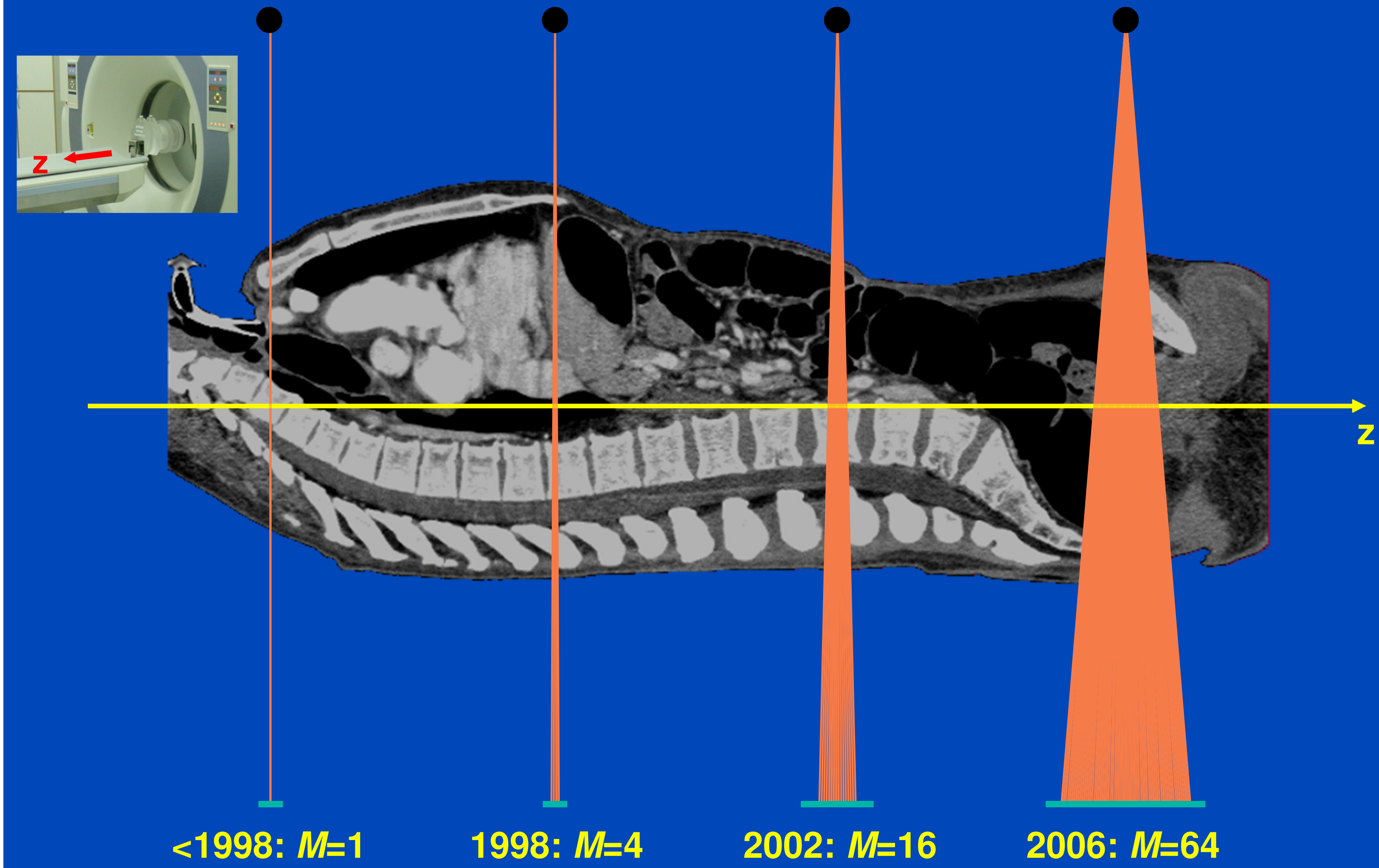




Each object point must be viewed by an angular interval of 180° or more. Otherwise image reconstruction is not possible.



Axial Geometry (z-Direction)



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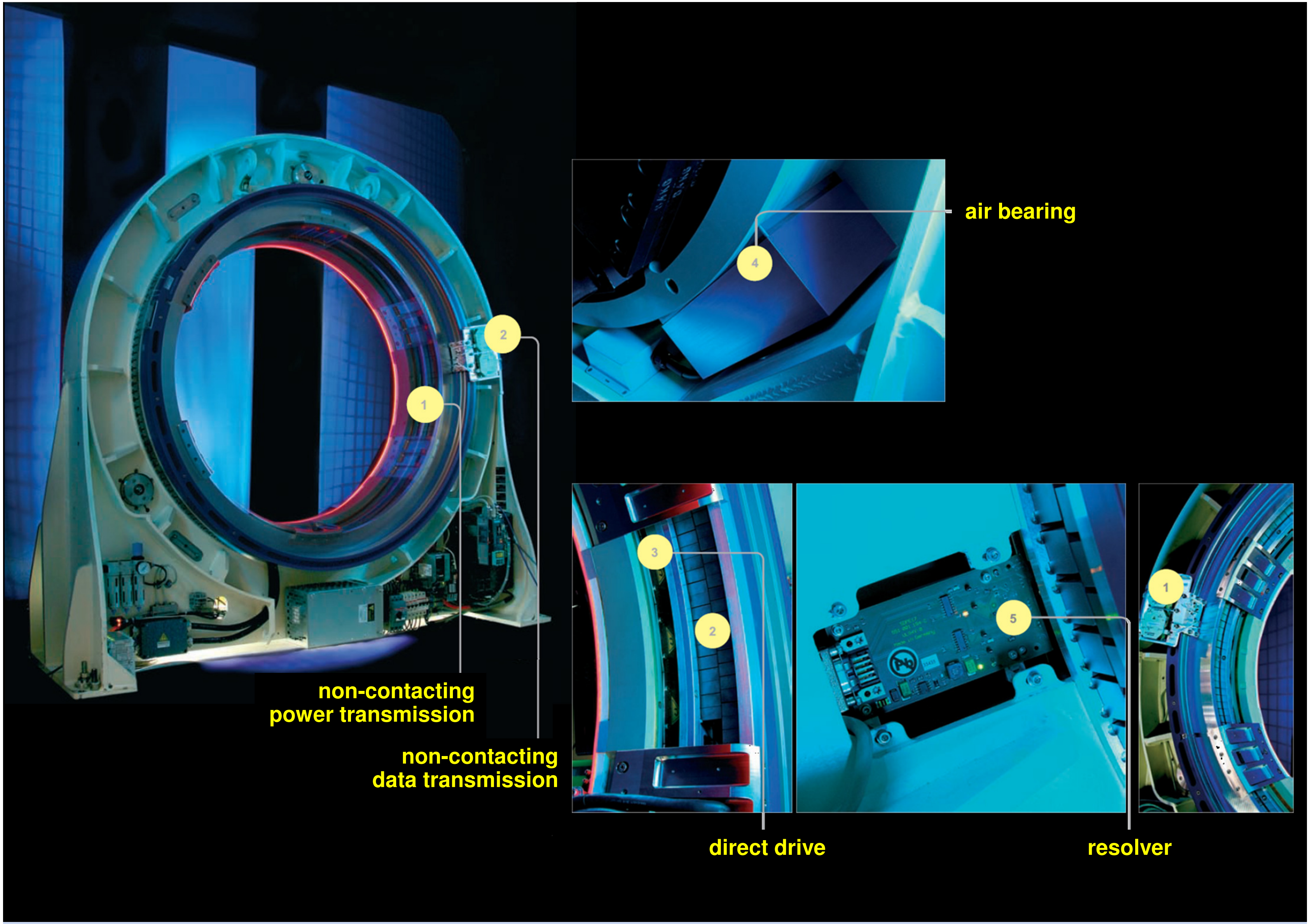
Equipment Technology

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



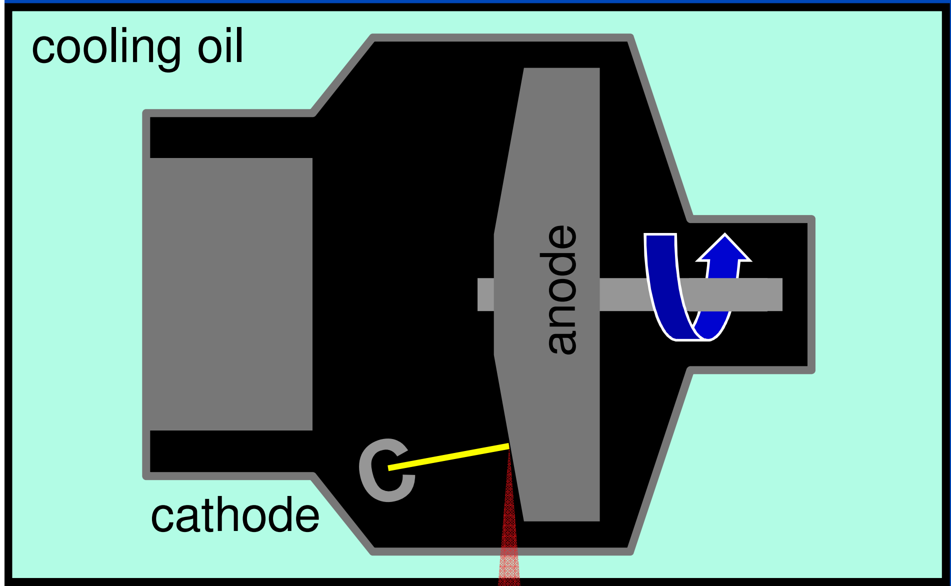
Data courtesy of Schleifring GmbH, Fürstenfeldbruck, Germany
and of rsna2011.rsna.org/exbData/1678/docs/Gantry_Subsystem.pdf

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)



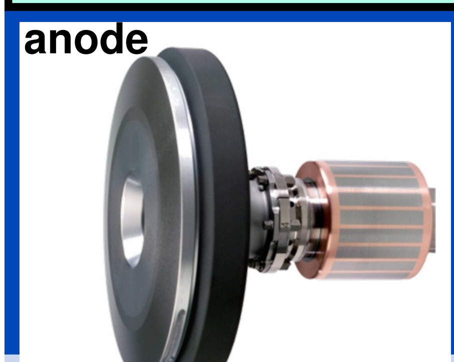


Photo courtesy of GE

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

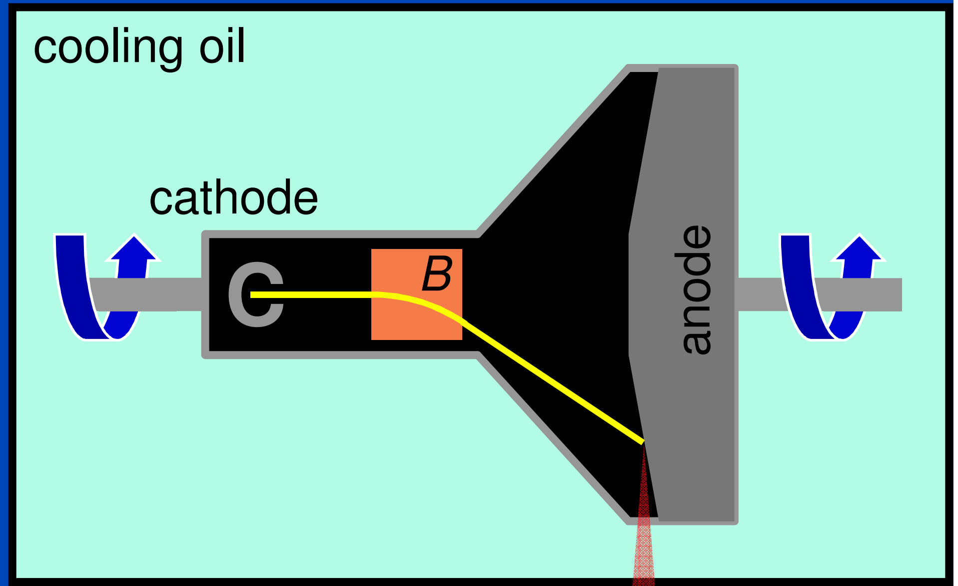
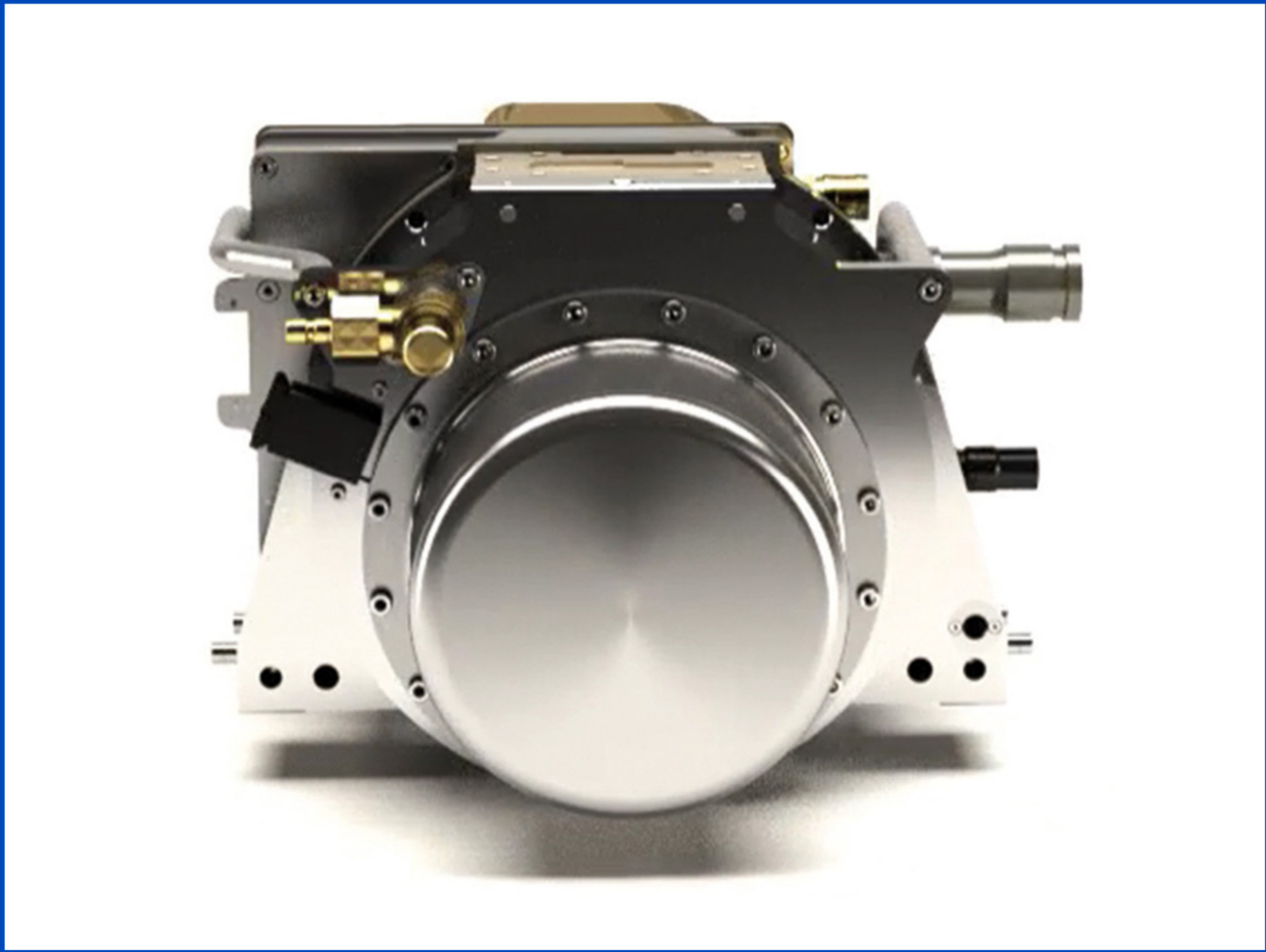


Photo courtesy of Siemens

Alternative design of a directly cooled tube
(Photo courtesy by Philips)



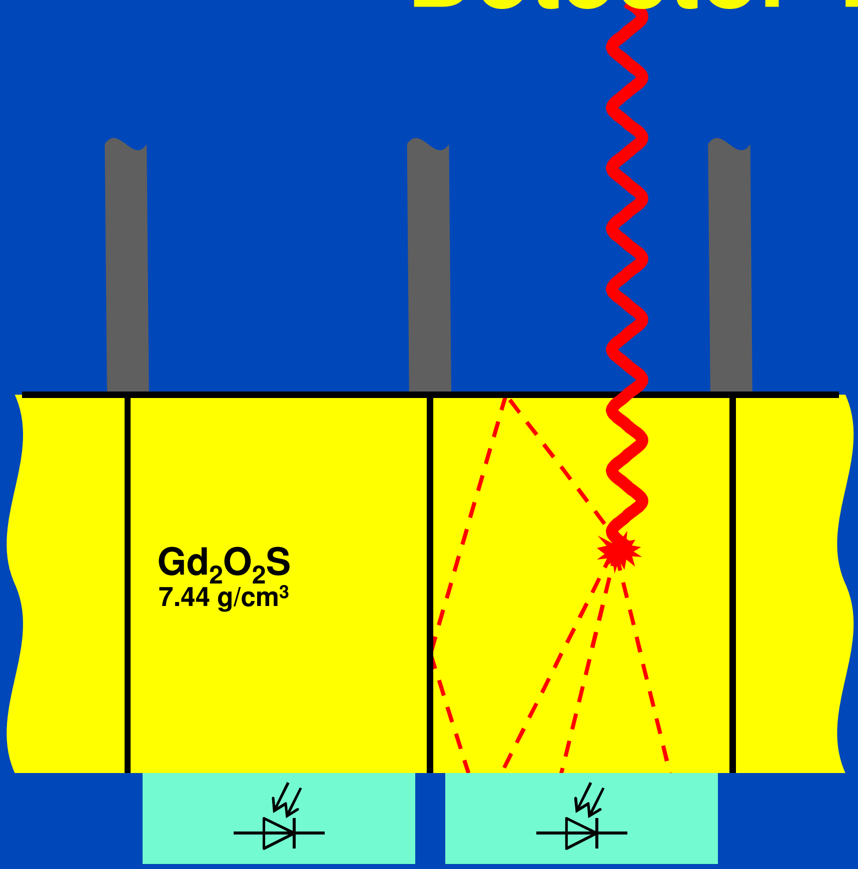
Alternative design of a directly cooled tube: The Siemens Vectron tube
(Photo courtesy by Siemens)

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



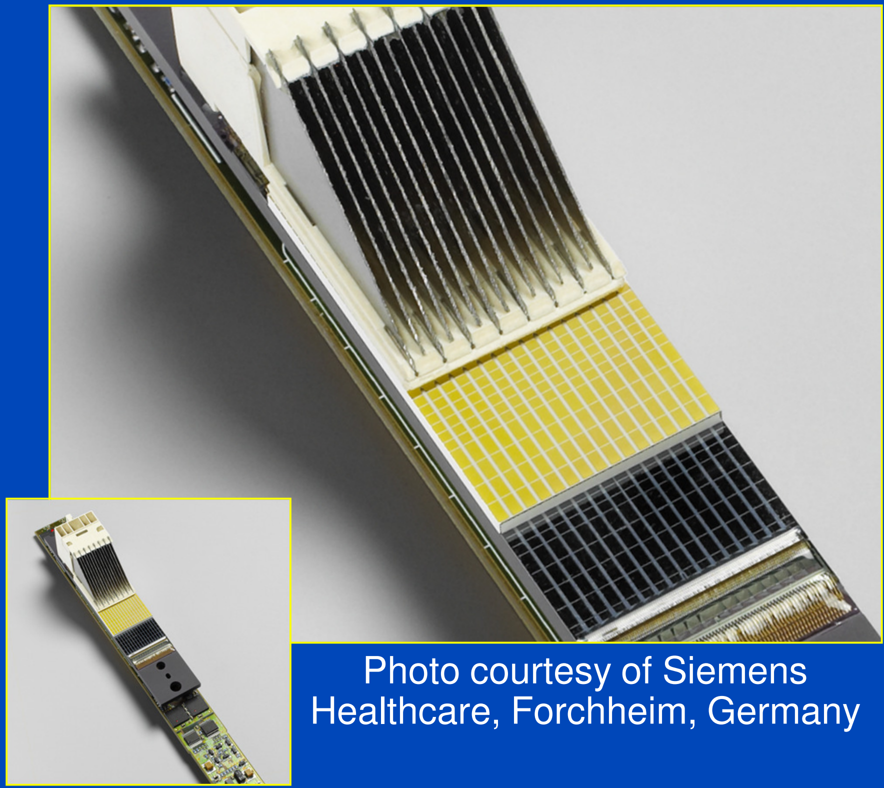
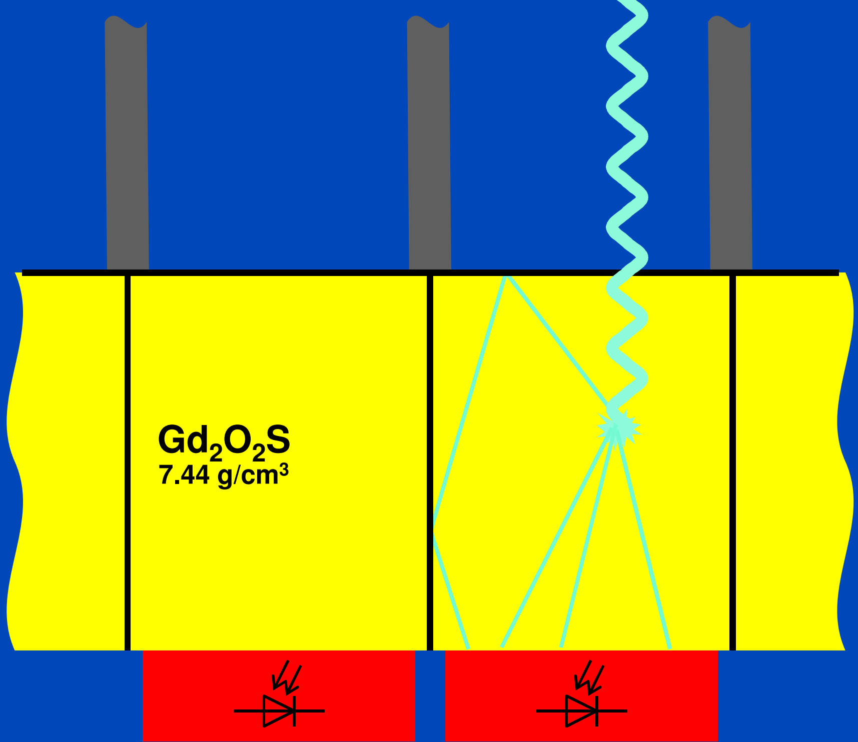
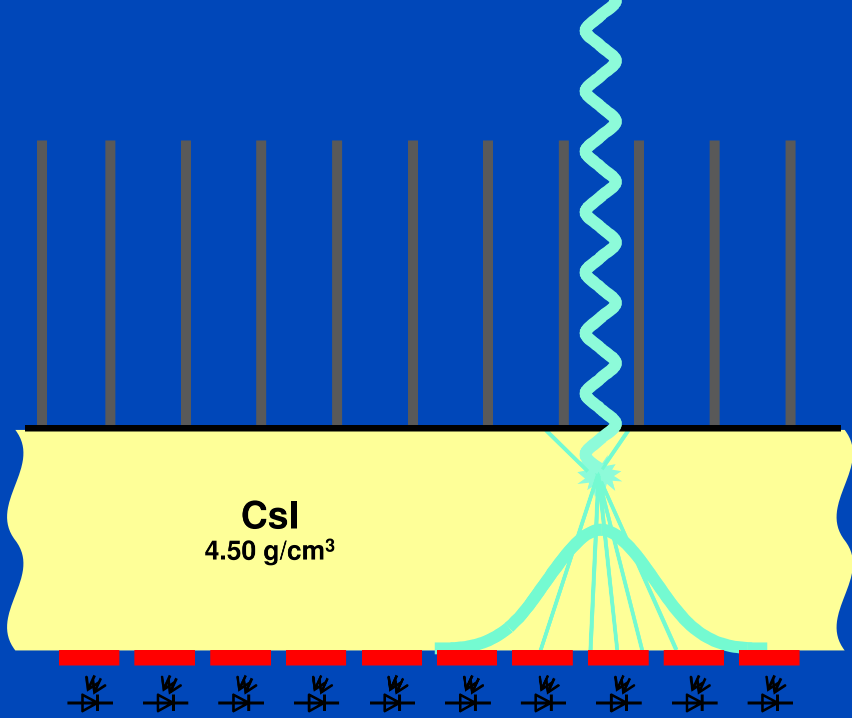


Photo courtesy of Siemens Healthcare, Forchheim, Germany

Clinical CT Detector



Flat Detector



Clinical CT Detector

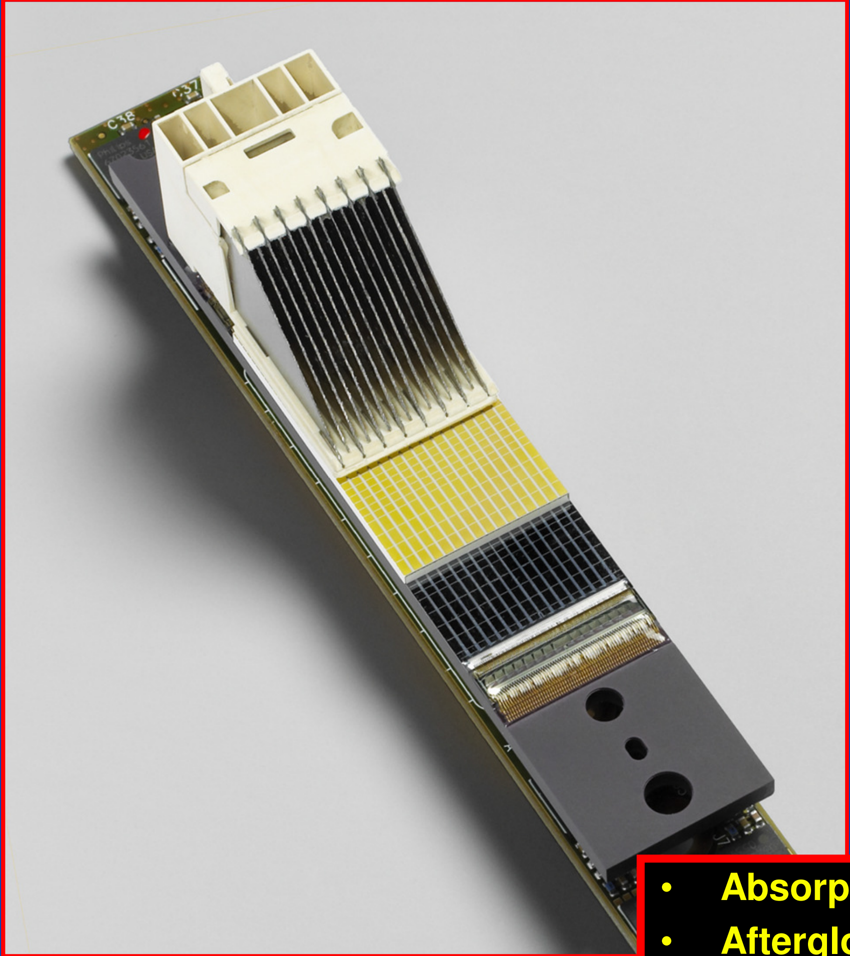
- Anti-scatter grids are aligned to the detector pixels
- Anti-scatter grids reject scattered radiation
- Detector pixels are of about 1.2 mm size
- Detector pixels are structured, reflective coating maximizes light usage and minimizes cross-talk
- Thick scintillators improve dose usage
- Gd_2O_2S is 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

Detector Technology

Clinical CT Detector



Flat Detector

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

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/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.

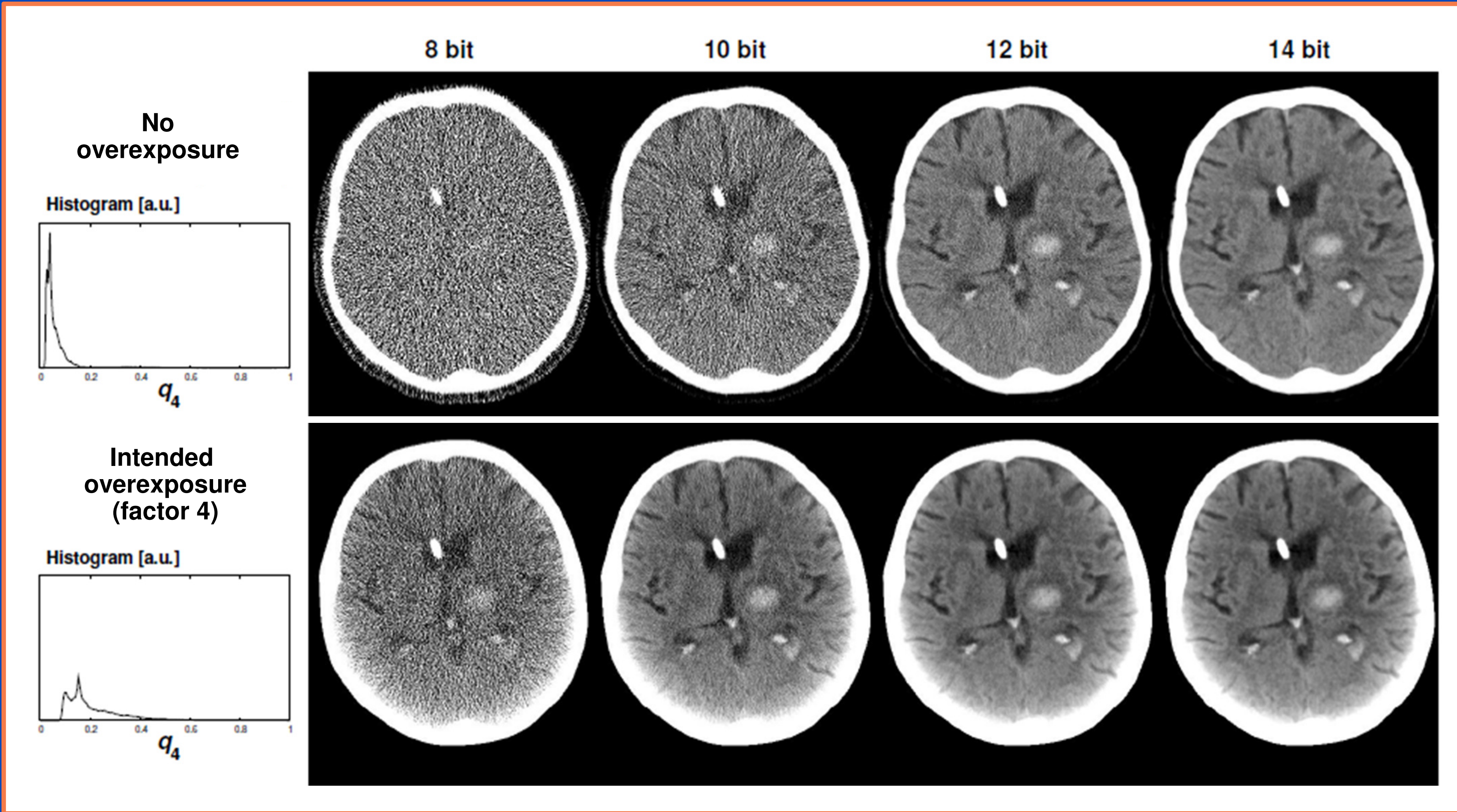
Dynamic Range in Flat Detectors

	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

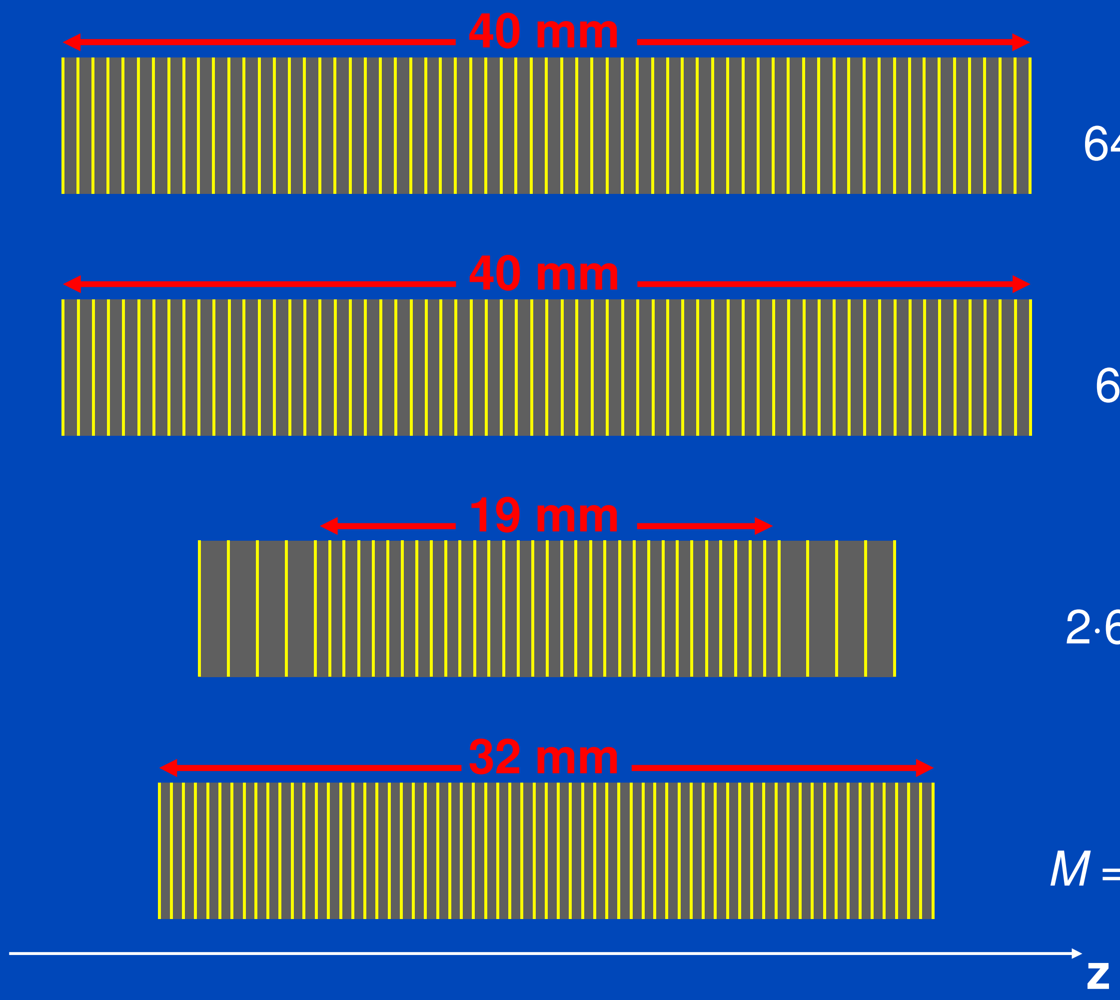
A2 is defined as the exposure where QuantumNoise=ElectronicNoise.

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.



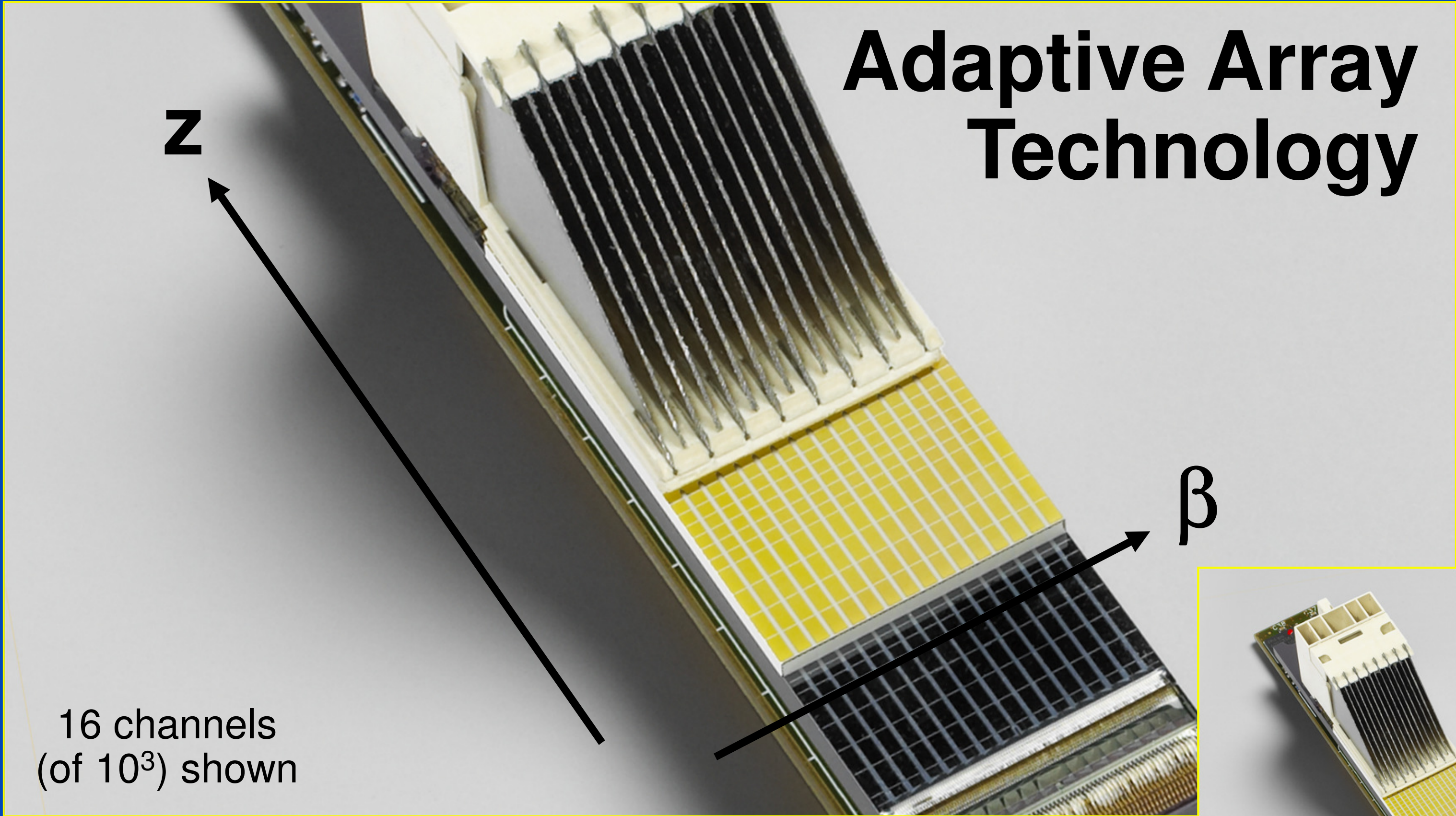
8 bit
10 bit
12 bit
14 bit
No overexposure
Histogram [a.u.]
0
0.2
0.4
0.6
0.8
1
q_4
Intended overexposure (factor 4)
Histogram [a.u.]
0
0.2
0.4
0.6
0.8
1
q_4

Multirow Detectors for Multi-Slice CT 2006



Detector rows	Vendor	M / t_{rot} / Γ
64 × 0.625 mm	GE	64 / 0.37 s / 3.8°
64 × 0.625 mm	Philips	64 / 0.4 s / 3.8°
2·2·32 × 0.6 mm 24 × 1.2 mm	Siemens	2·64 / 0.33 s / 1.9°
64 × 0.5 mm	Toshiba	M = 64 / 0.4 s / 3.2°

Number of simultaneously acquired slices M / Rotation time t_{rot} / Cone-angle Γ



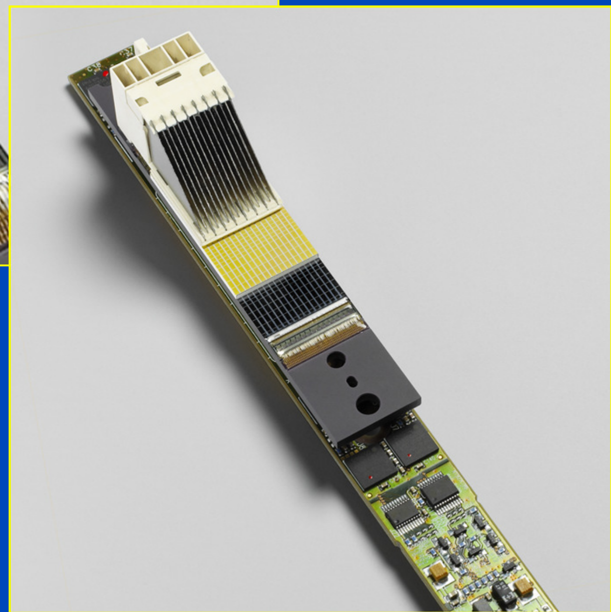


Photo courtesy of Siemens Healthcare, Forchheim, Germany

Multirow Detectors for Multi-Slice CT 2009 – 2013

• GE	64 × 0.625 mm	=	40 mm	0.35 s
• Philips	2·128 × 0.625 mm	=	80 mm	0.27 s
• Siemens	2·2·64 × 0.6 mm	=	38 mm	0.28 s
• Toshiba	320 × 0.5 mm	=	160 mm	0.275 s

Multirow Detectors for Multi-Slice CT 2009 – 2013

• GE	64 × 0.625 mm	=	40 mm	0.35 s
• Philips	2·128 × 0.625 mm	=	80 mm	0.27 s
• Siemens	2·2·64 × 0.6 mm	=	38 mm	0.28 s
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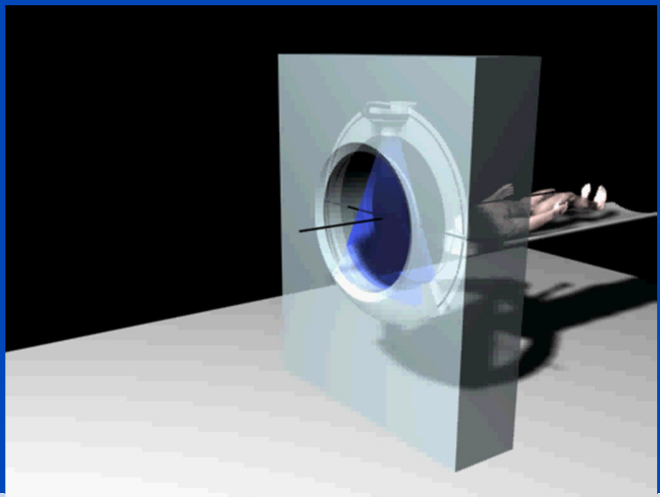


Courtesy of Siemens

2012/2013	Configuration	Collimation	Rotation	Sampling
GE **Discovery 750**	64 × 0.625 mm	40 mm	0.35 s	6.4 kHz
Philips **Brilliance iCT**	2·128 × 0.625 mm	80 mm	0.27 s	8.9 kHz
Siemens **Flash**	2·2·64 × 0.6 mm	38.4 mm	0.28 s	4.6 kHz
Toshiba **Acquil. ONE Vision**	320 × 0.5 mm	160 mm	0.275 s	2.9 kHz


Photo courtesy by GE


Photo courtesy by Philips

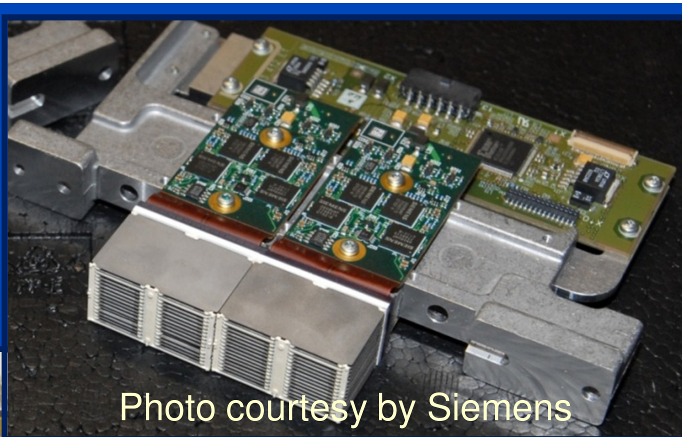


Photo courtesy by Siemens

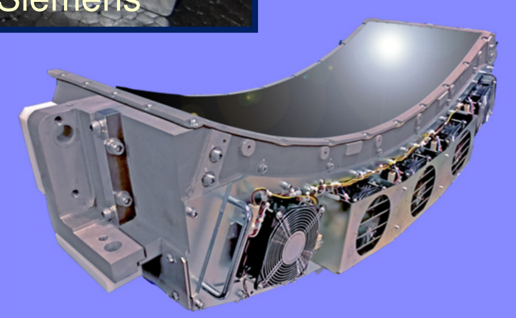


Image courtesy by Toshiba

Folie 74

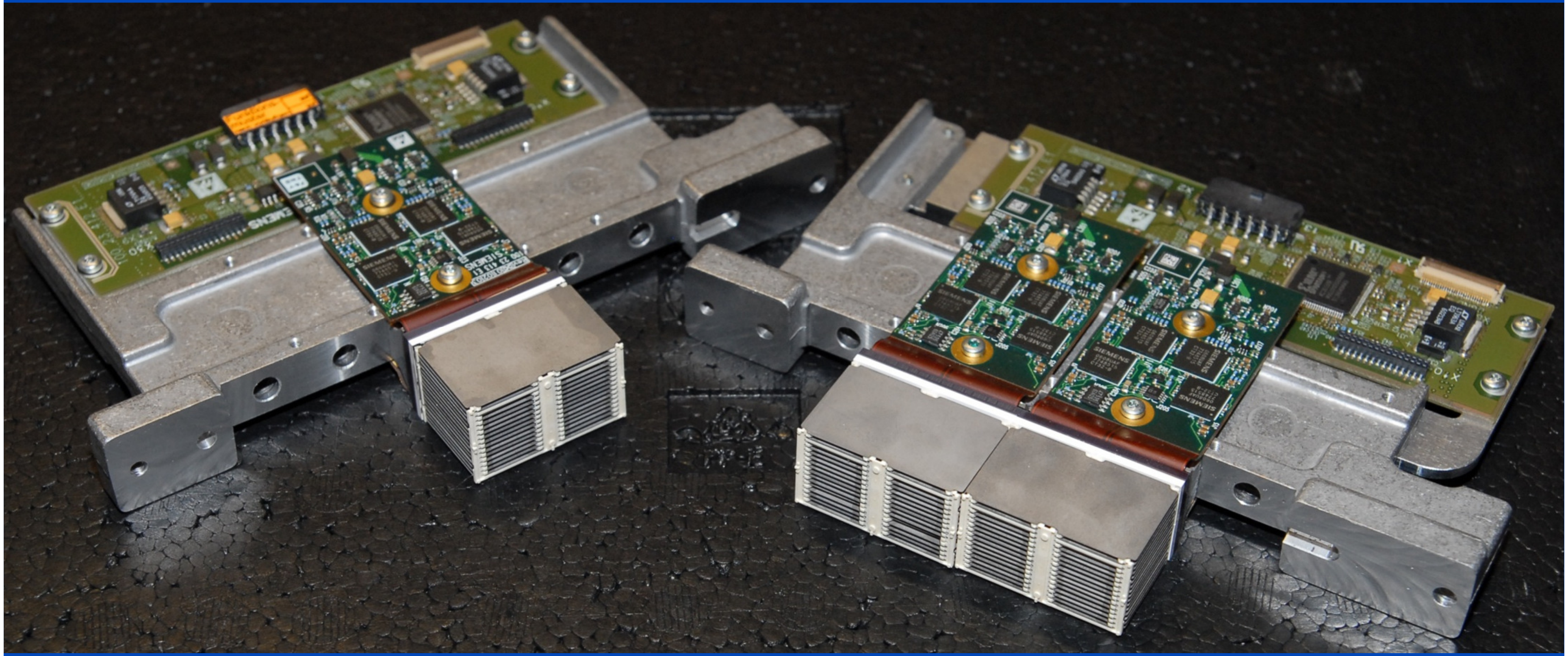
MK1

Siemens: 2*1160 in 0.5 s
Philips iCT: (2400 readings / rotation) / (0.27 seconds / rotation) = 8.889 kHz
Thoshiba: "Sampling rate is 2.6 KHz. ", Mike Silver, Mail of 20.5.2012
Prof. Dr. Marc Kachelrieß; 21.05.2012

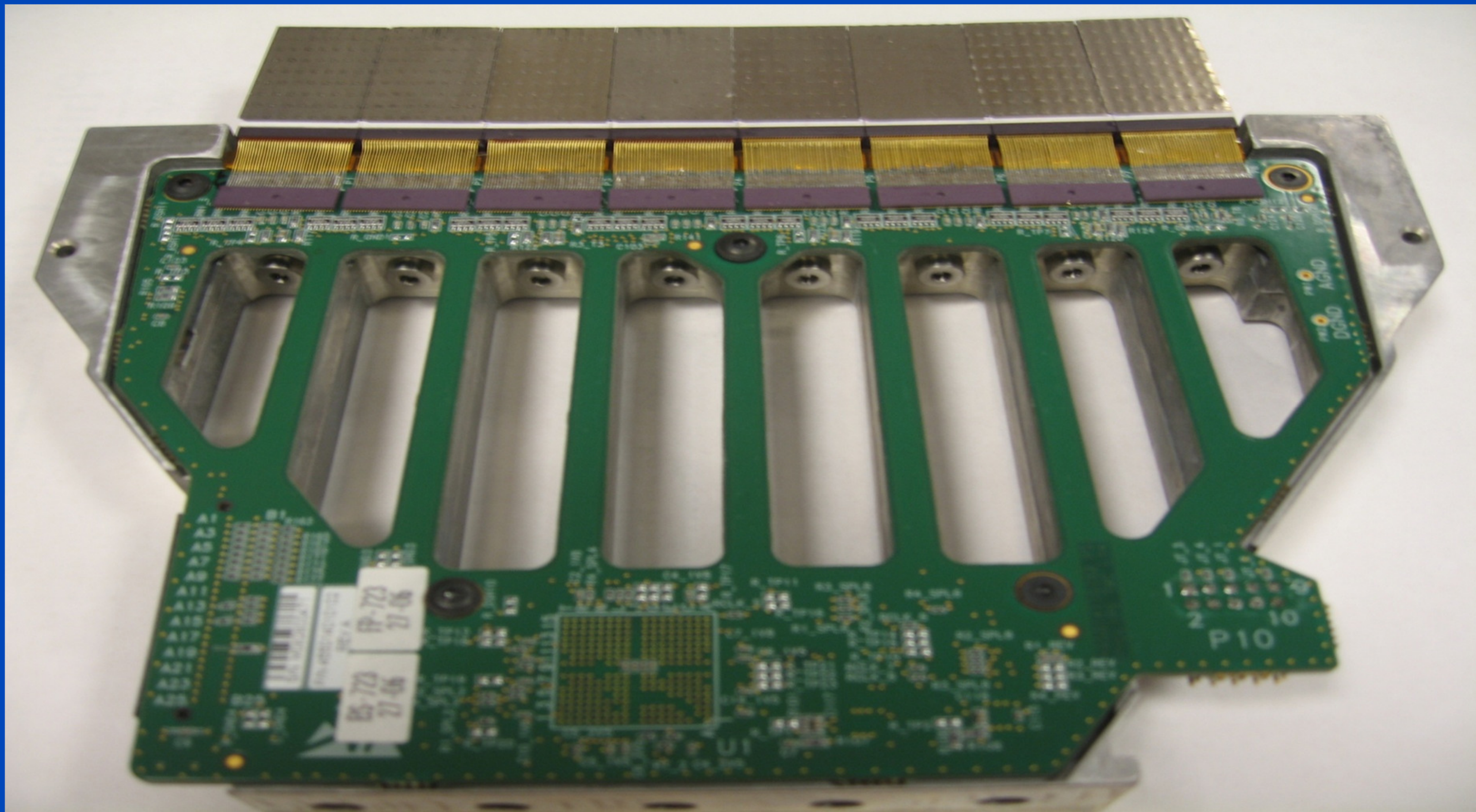
2014/2015	Configuration	Collimation	Rotation	Sampling
GE Revolution	256 × 0.625 mm	160 mm	0.28 s	?
Philips Brilliance iCT	2·128 × 0.625 mm	80 mm	0.27 s	8.9 kHz
Philips IQon	2·64 × 0.625 mm	40 mm	0.27 s	?
Siemens Flash	2·2·64 × 0.6 mm	38.4 mm	0.28 s	4.6 kHz
Siemens Force	2·2·96 × 0.6 mm	57.6 mm	0.25 s	?
Toshiba Acquil. ONE Vision	320 × 0.5 mm	160 mm	0.275 s	?

Folie 75

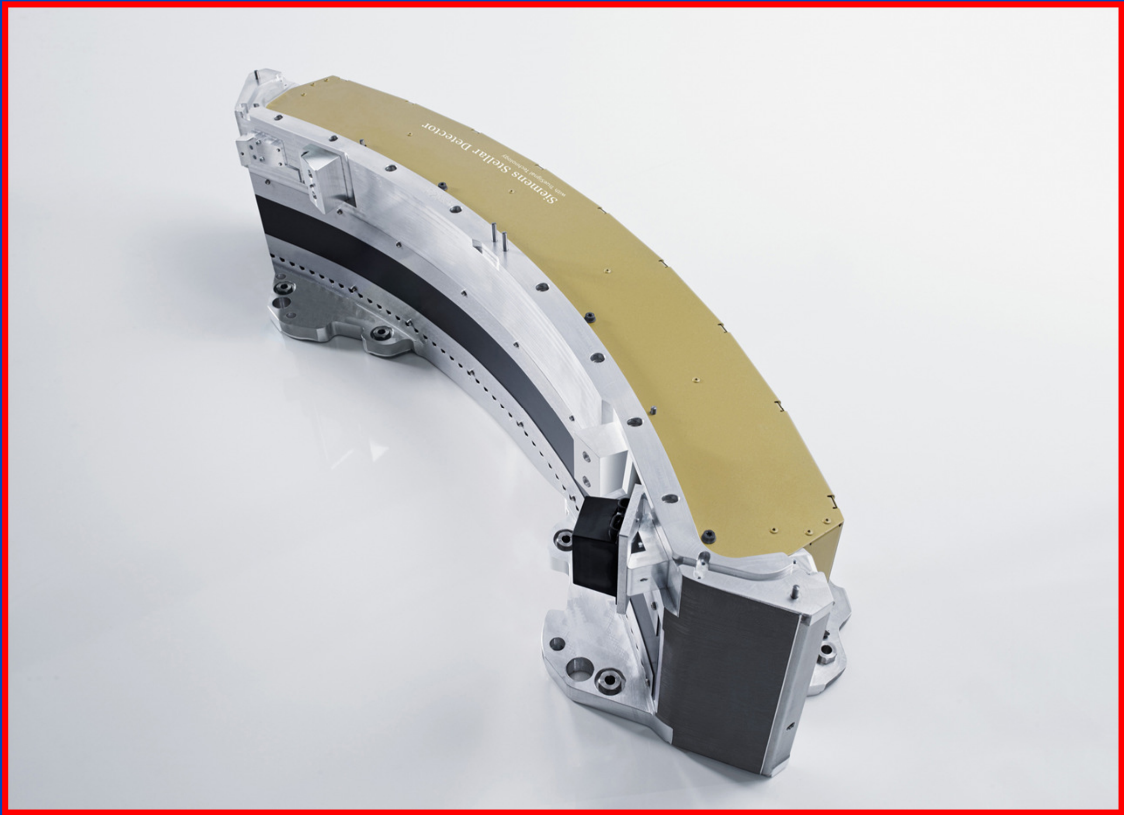
MK2 Siemens: 2*1160 in 0.5 s
Philips iCT: (2400 readings / rotation) / (0.27 seconds / rotation) = 8.889 kHz
Thoshiba: "Sampling rate is 2.6 KHz. ", Mike Silver, Mail of 20.5.2012
Prof. Dr. Marc Kachelrieß; 21.05.2012

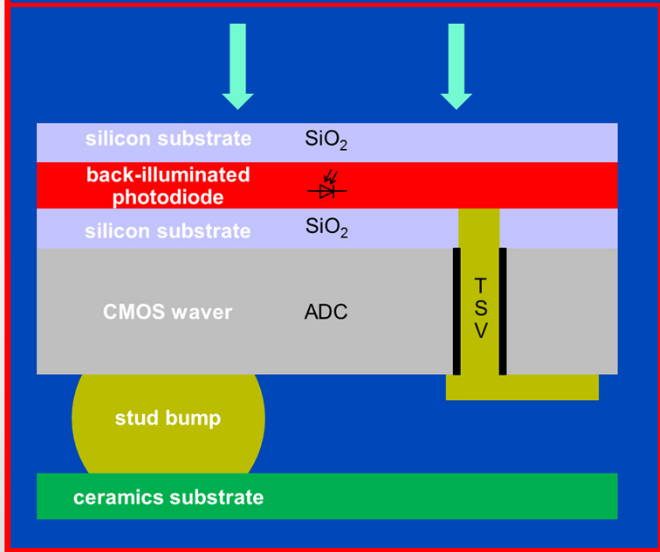


modular and 2D tileable, 1D anti-scatter grid,
modules arranged on the surface of a cylinder segment
(Photo courtesy by Siemens)



“Nano-panel detectors”, modular and 2D tilable, focussed 2D anti scatter grid
(Photo courtesy by Philips)





“Stellar detector”, modular and 2D tilable, focussed 1D anti scatter grid (Photo courtesy by Siemens)

Scan Trajectories

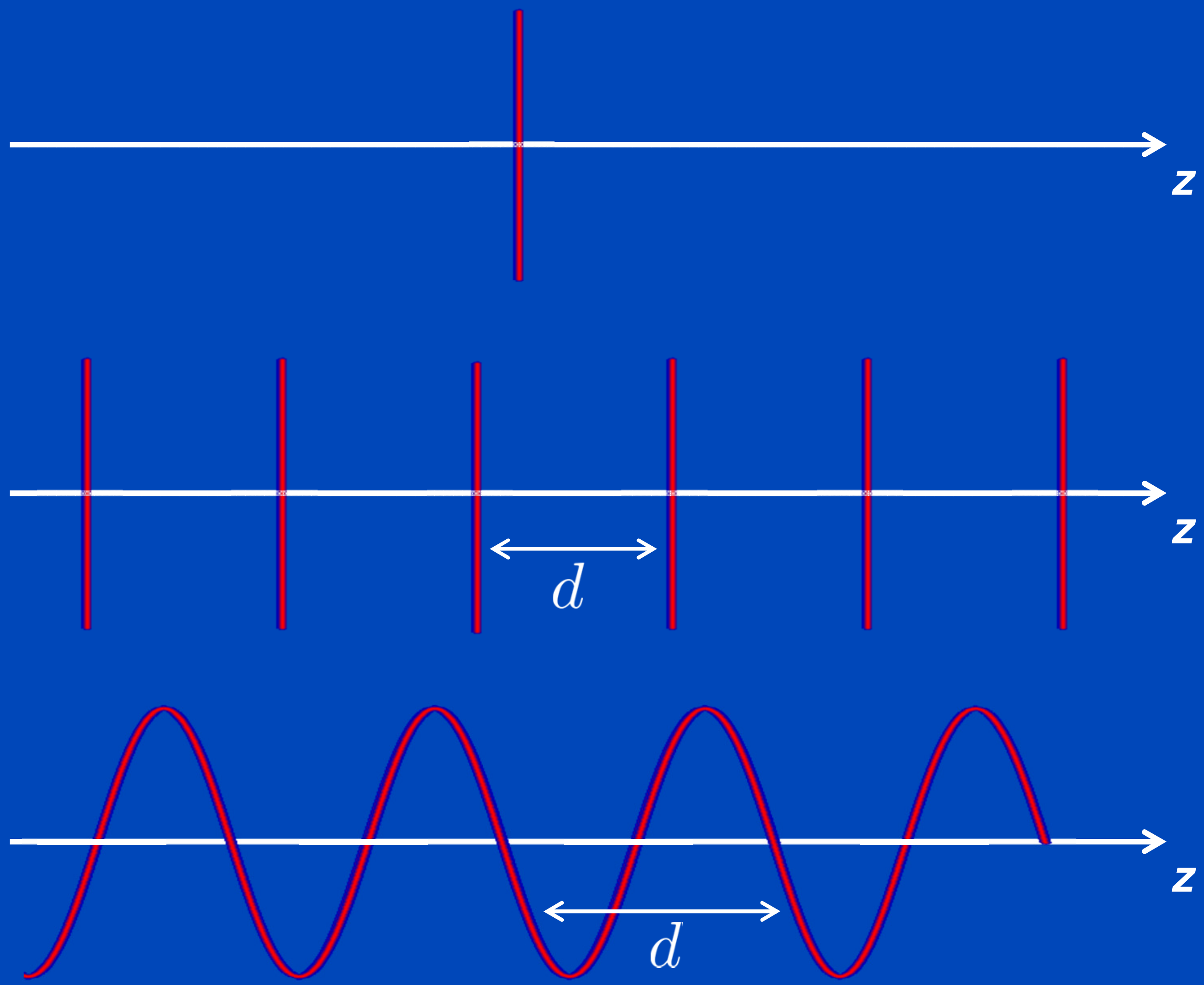
Circle

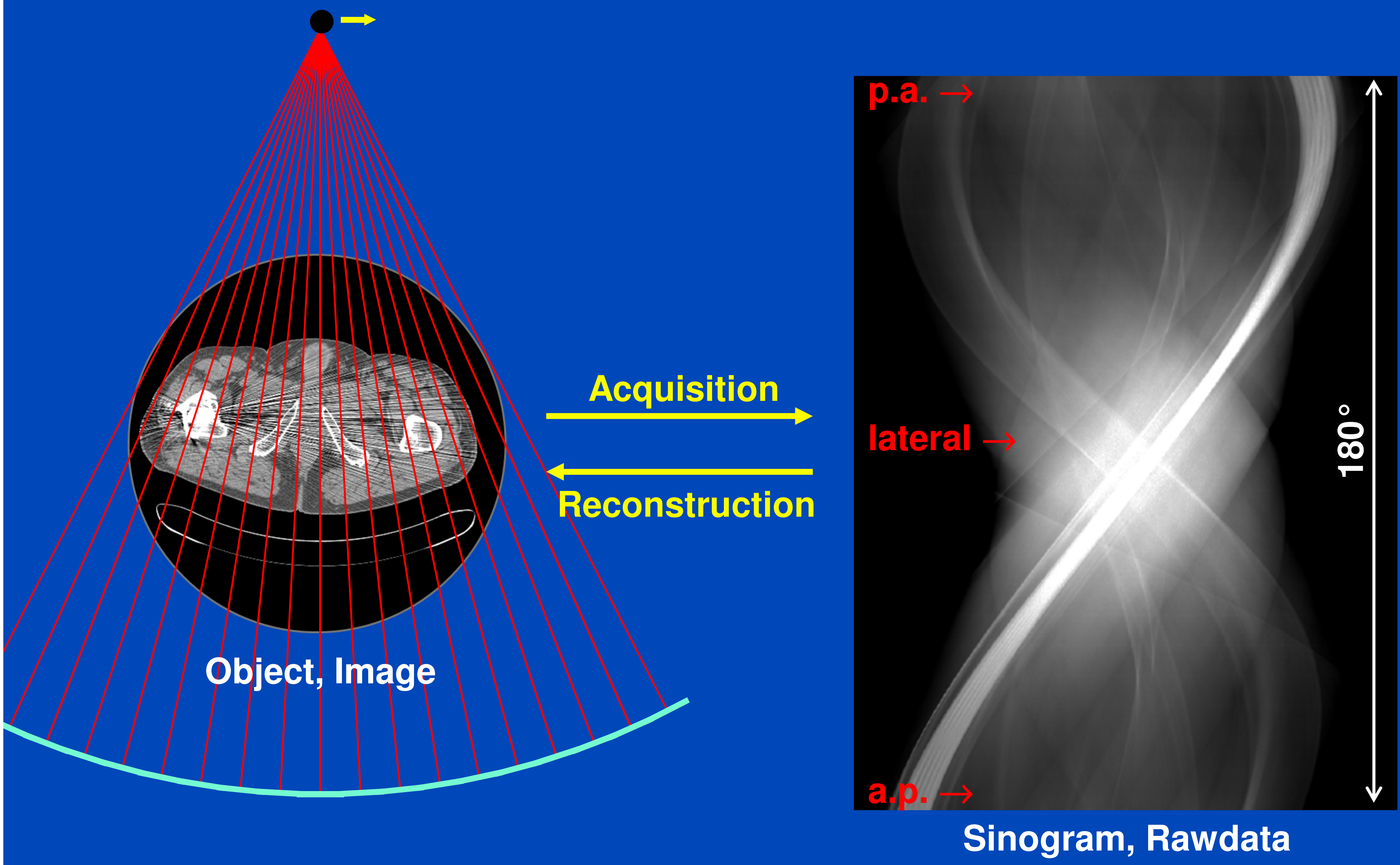
Sequence

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

Spiral

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

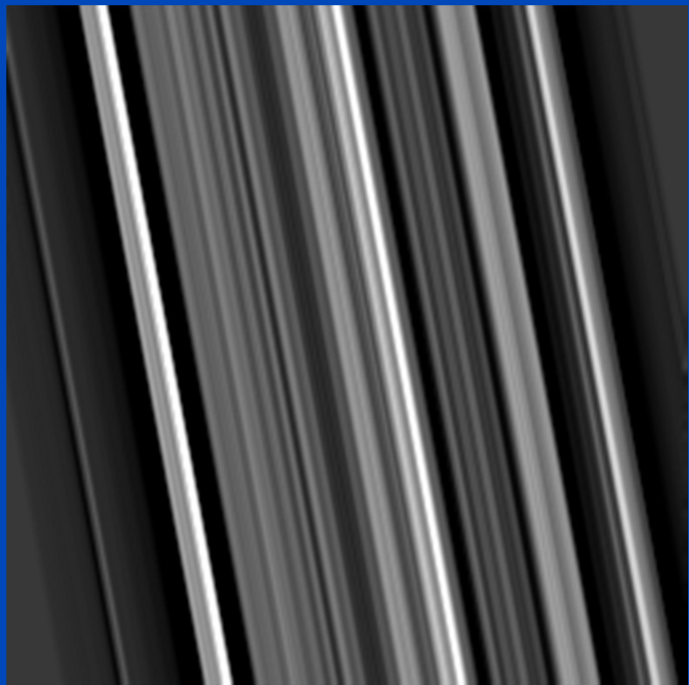




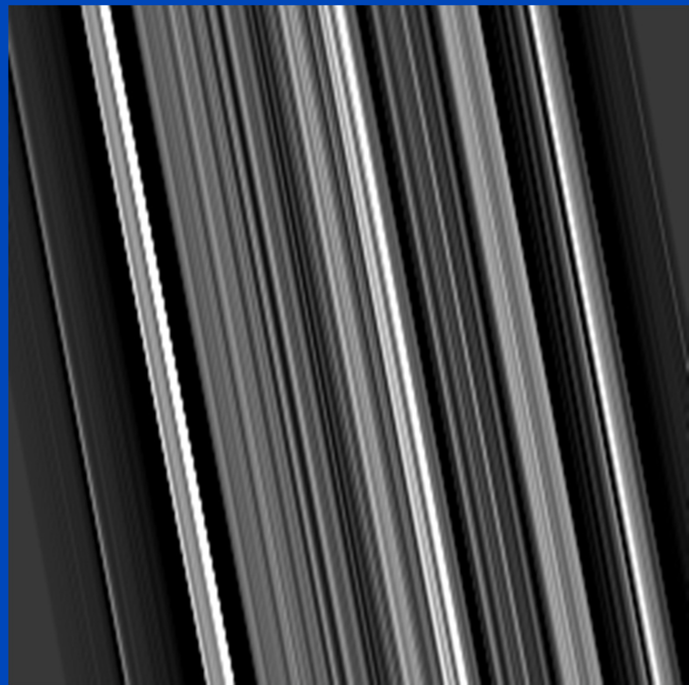
Acquisition
Reconstruction
Object, Image
p.a.
lateral
a.p.
180°
Sinogram, Rawdata

Filtered Backprojection (FBP)

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

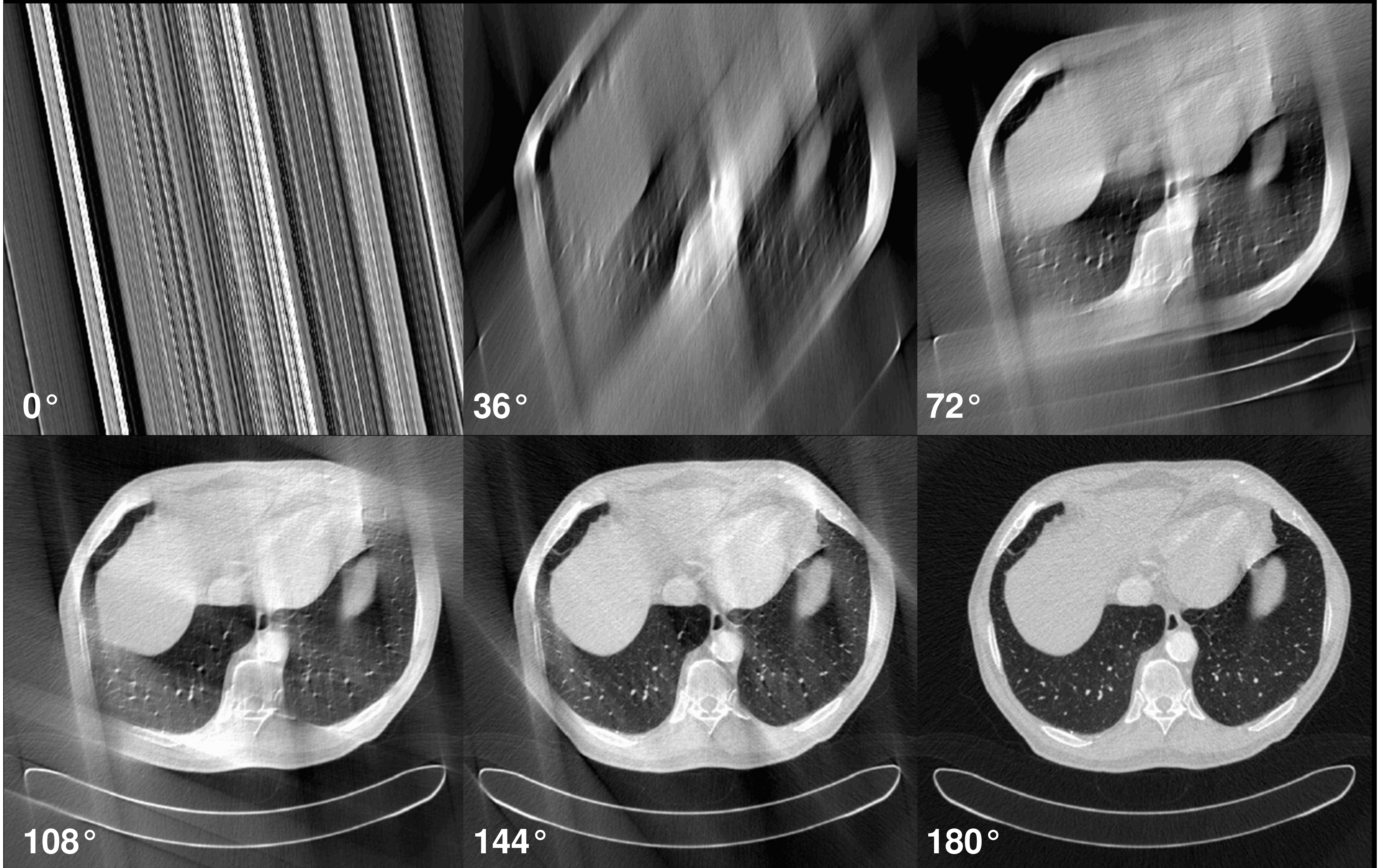


Smooth



Standard

Reconstruction kernels balance between spatial resolution and image noise.



0°
36°
72°
108°
144°
180°

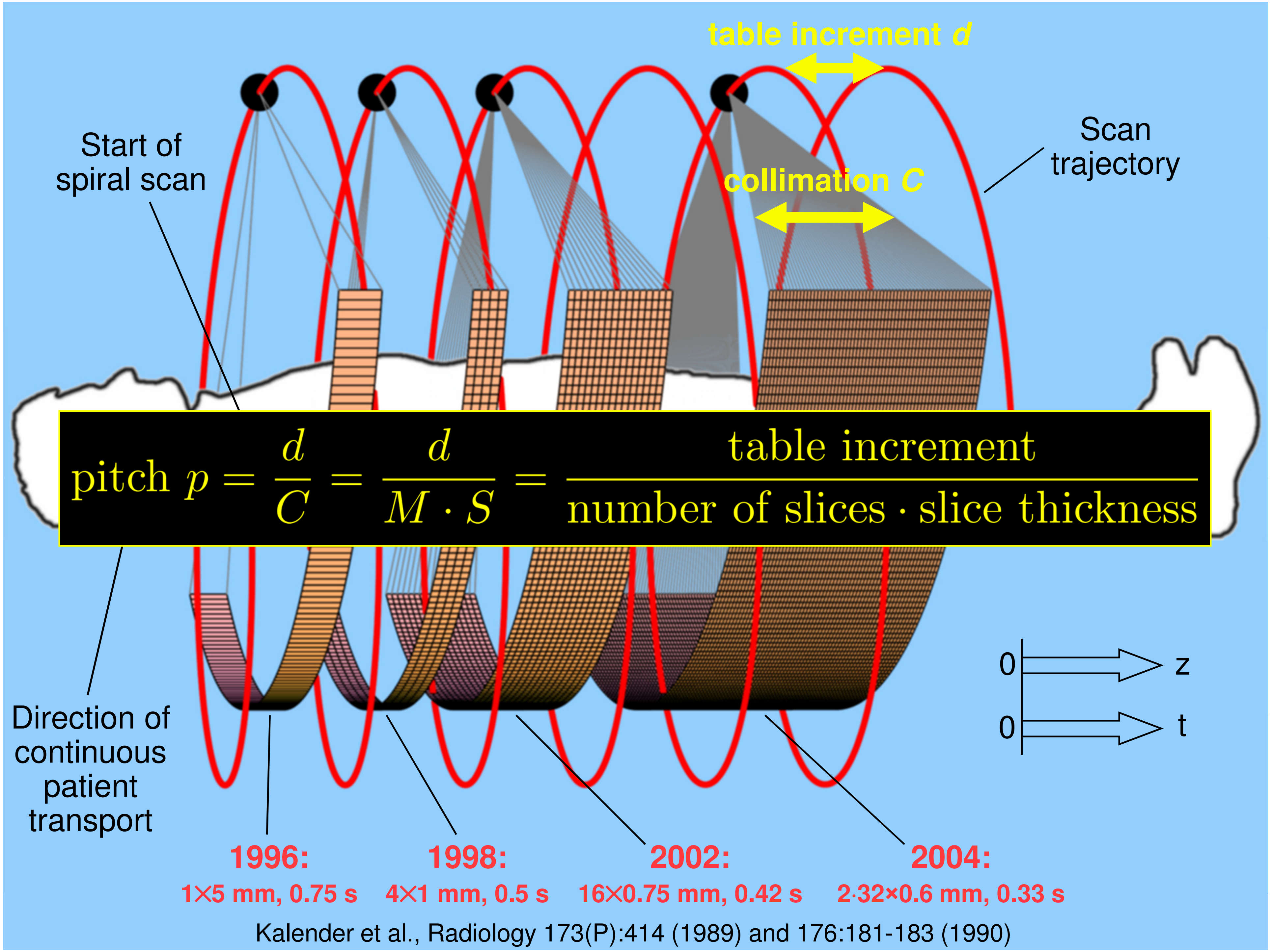
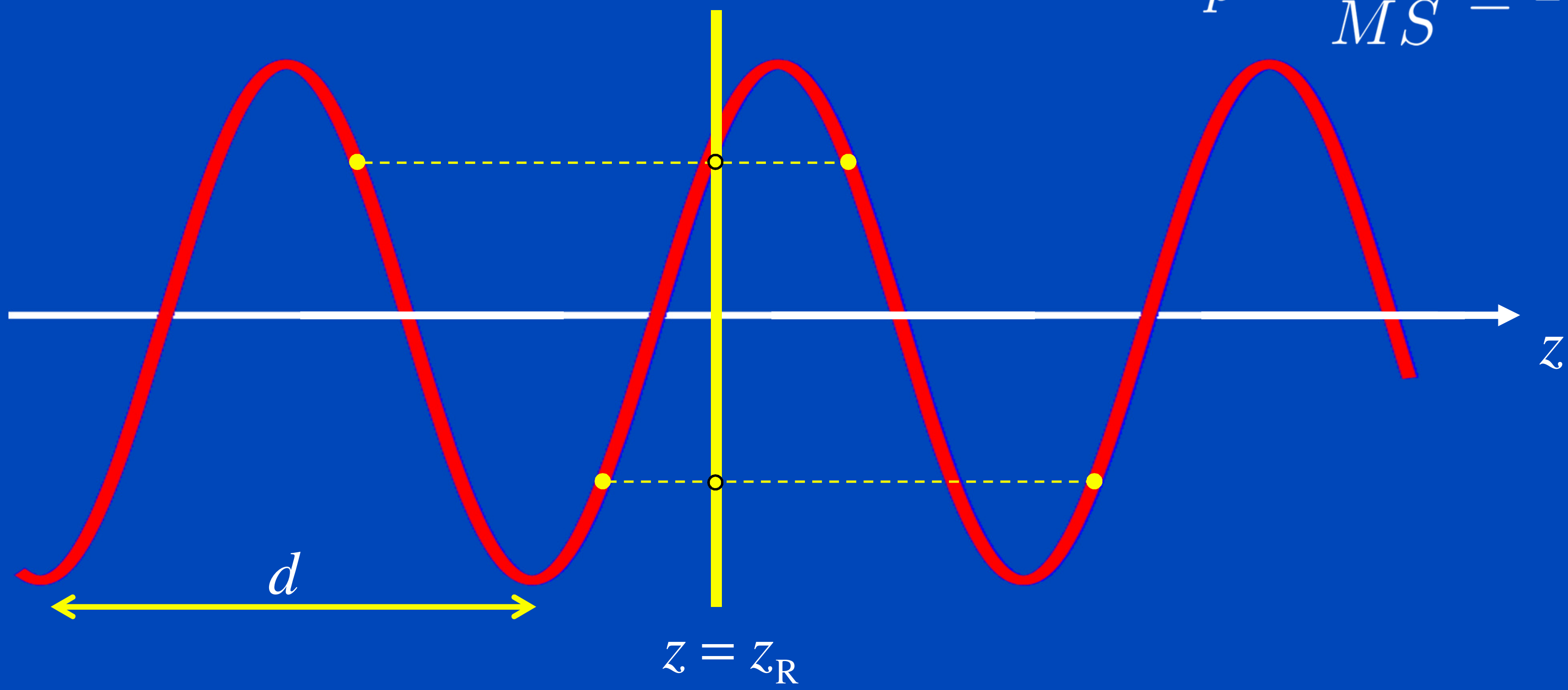


table increment d
collimation C
Start of spiral scan
Scan trajectory
pitch $p = \frac{d}{C} = \frac{d}{M \cdot S} = \frac{\text{table increment}}{\text{number of slices} \cdot \text{slice thickness}}$
Direction of continuous patient transport
0 z
0 t
1996:
1×5 mm, 0.75 s
1998:
4×1 mm, 0.5 s
2002:
16×0.75 mm, 0.42 s
2004:
2·32×0.6 mm, 0.33 s
Kalender et al., Radiology 173(P):414 (1989) and 176:181-183 (1990)

360° LI Spiral z-Interpolation for Single-Slice CT (*M*=1)

$$p = \frac{d}{MS} \le 2$$

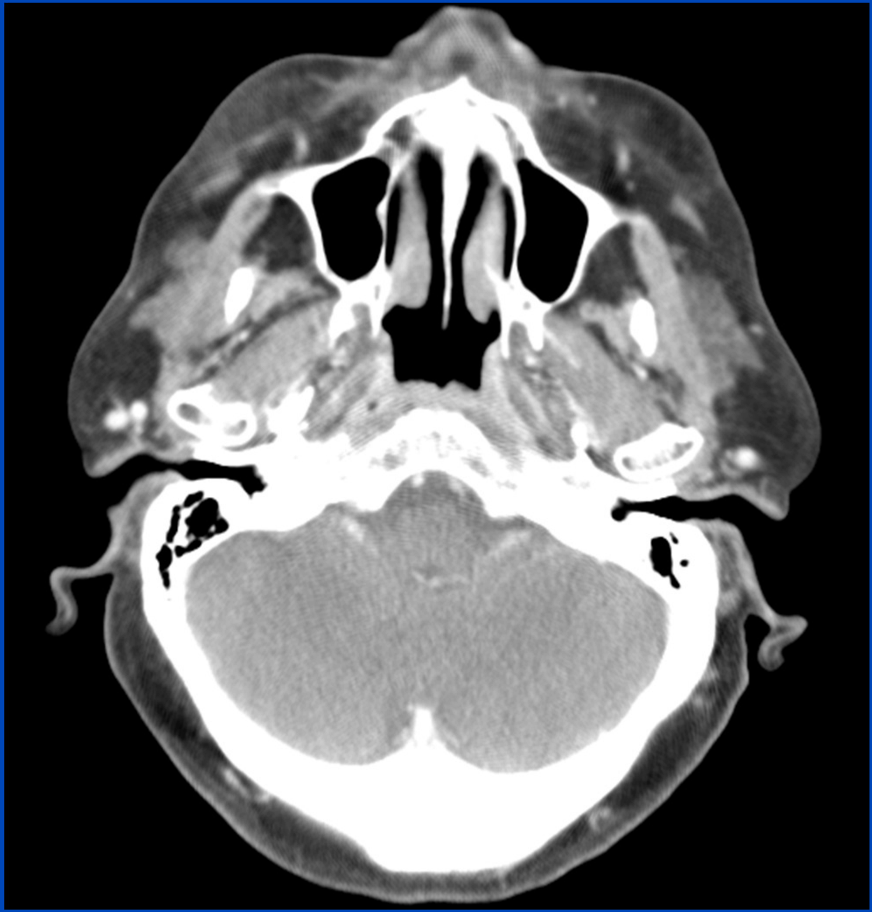


Spiral z-interpolation is typically a linear interpolation between points adjacent to the reconstruction position to obtain circular scan data.

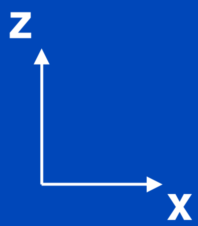
dkfz.

without *z*-interpolation

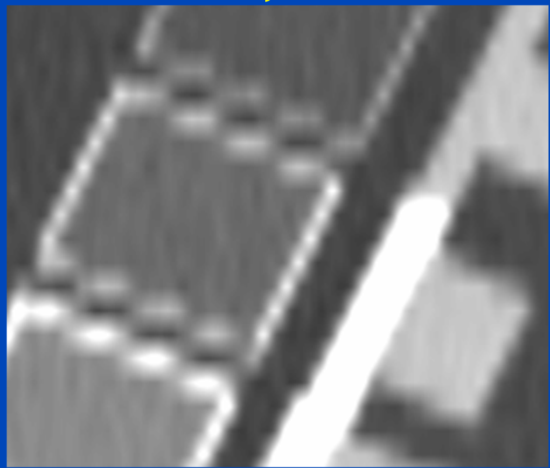
with *z*-interpolation



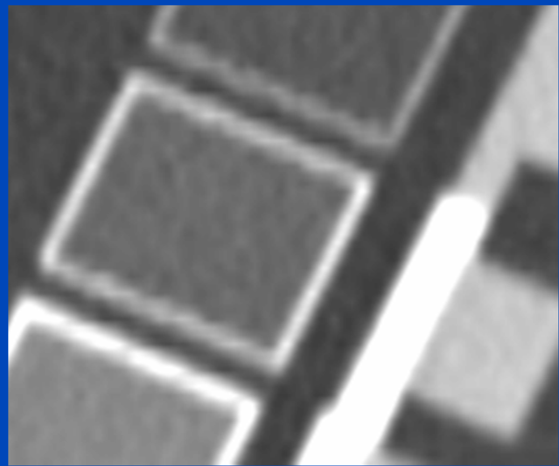
What's so Nice about Spiral CT?



S = 3 mm, *RI* = 3 mm



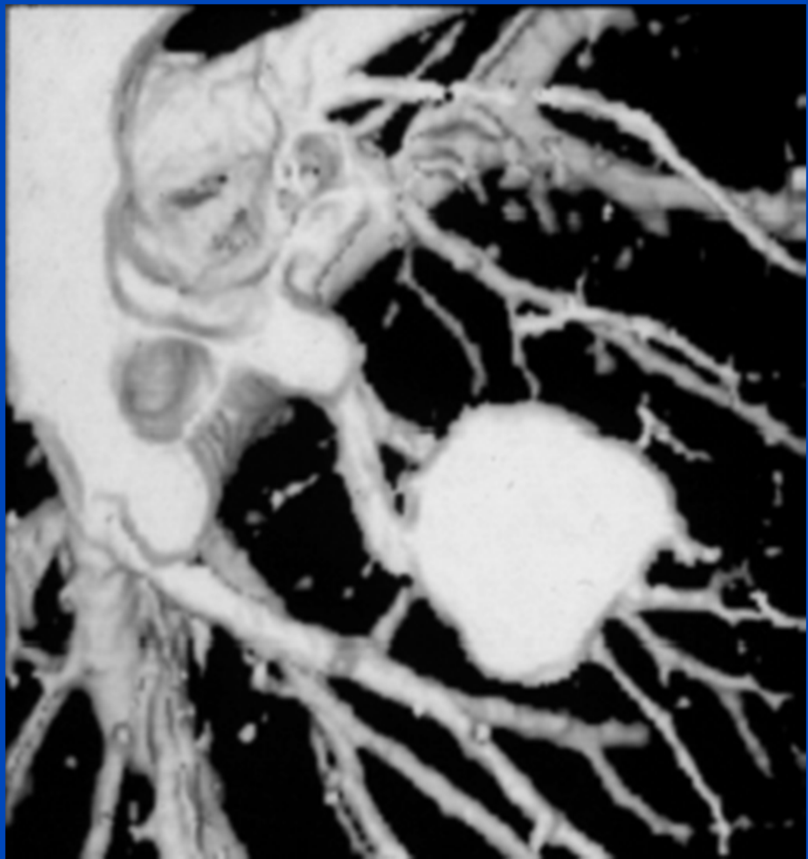
S = 3 mm, *RI* = 1 mm

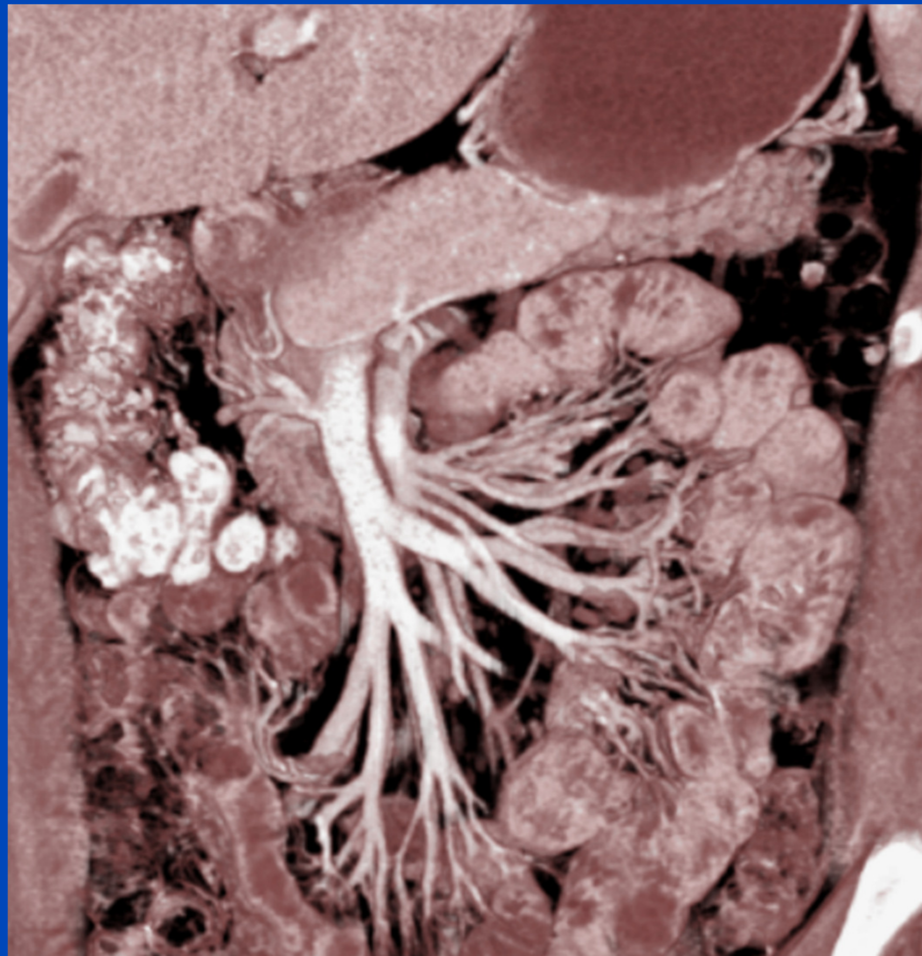


MPR images of the European Spine Phantom (inclined at 25°).

Kalender WA, Polacin A, Süß C. Radiology 1994; 193:170-171

RSNA 1989
SSCT (*M* = 1)





RSNA 2001
MSCT (*M* = 16)

The Pitch Value is the Measure for Scan Overlap

The pitch is defined as the ratio of the table increment per full rotation to the *total* collimation width in the center of rotation:

$$p = \frac{d}{M \cdot S}$$

Recommended by and in:

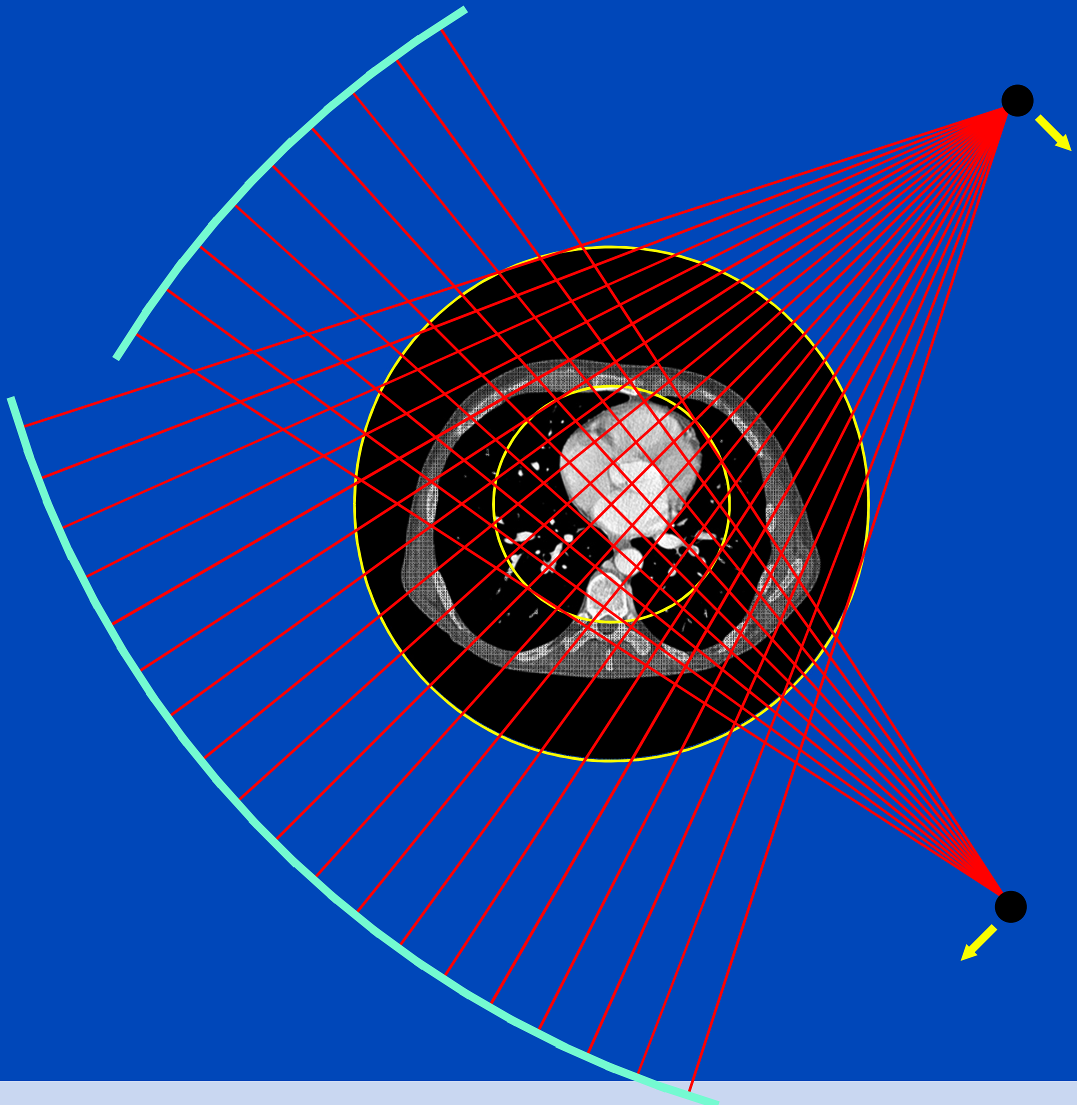
IEC, International Electrotechnical Commision: Medical electrical equipment – 60601 Part 2-44: Particular requirements for the safety of x-ray equipment for computed tomography. Geneva, Switzerland, 1999.

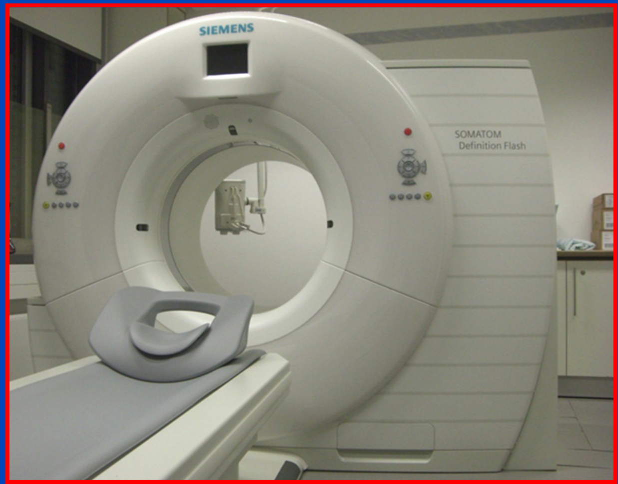
Examples:

- p=1/3=0.333 means that each z-position is covered by 3 rotations (3-fold overlap)
- p=1 means that the acquisition is not overlapping
- $p=p_{max}$ means that each z-position is covered by half a rotation

dkfz.

Multi-Threaded CT Scanners and Dual-Source-CT





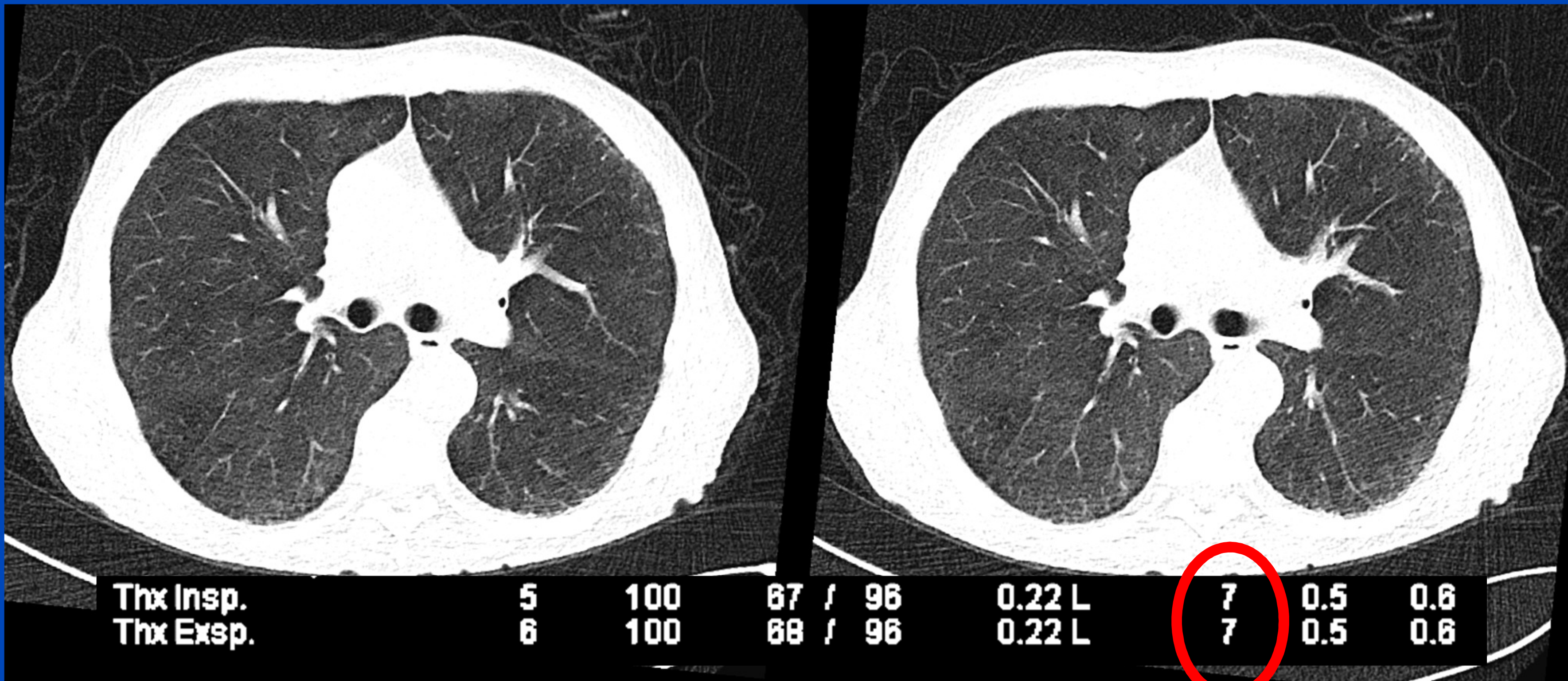
Siemens SOMATOM Definition Flash
dual source cone-beam spiral CT scanner


SIEMENS
300.0
-2000.0
SOMATOM Force


SOMATOM Force

Somatom Force: Ultra Low Dose Lung Imaging

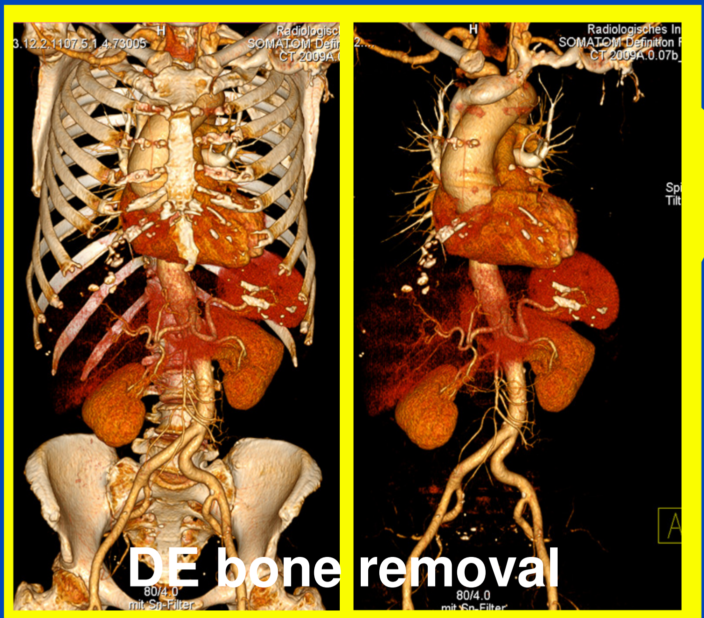
- Atypical pneumonia in inspiration and expiration
- Turbo Flash mode, 737 mm/s, 100 kV Sn
- DLP = 7 mGy cm ≈ 0.1 mSv

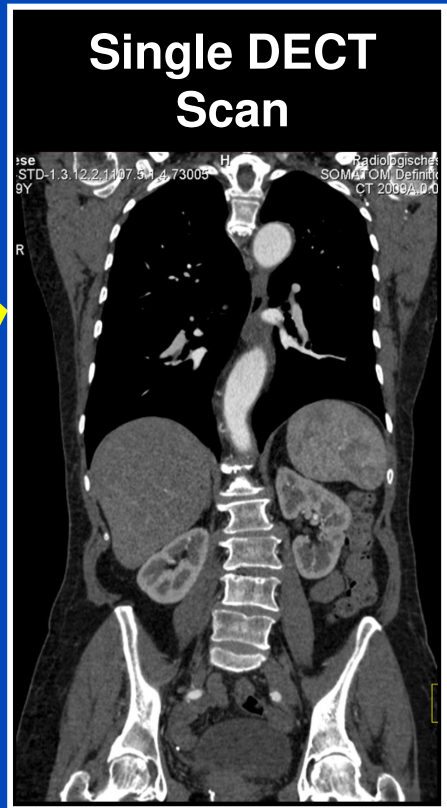


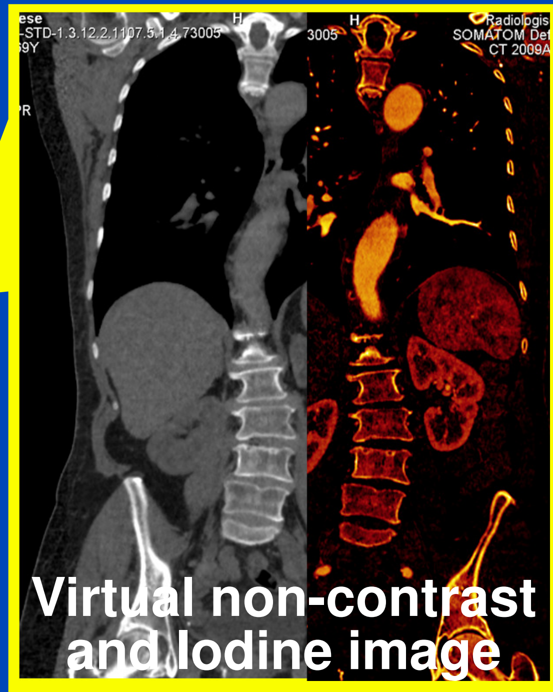
Courtesy University Hospital Mannheim

Dual Source CT = Best Possible Dual Energy CT

- Tube currents can be selected and modulated for each thread independently
- Prefiltration can be optimized for each thread independently
- Optimal sampling





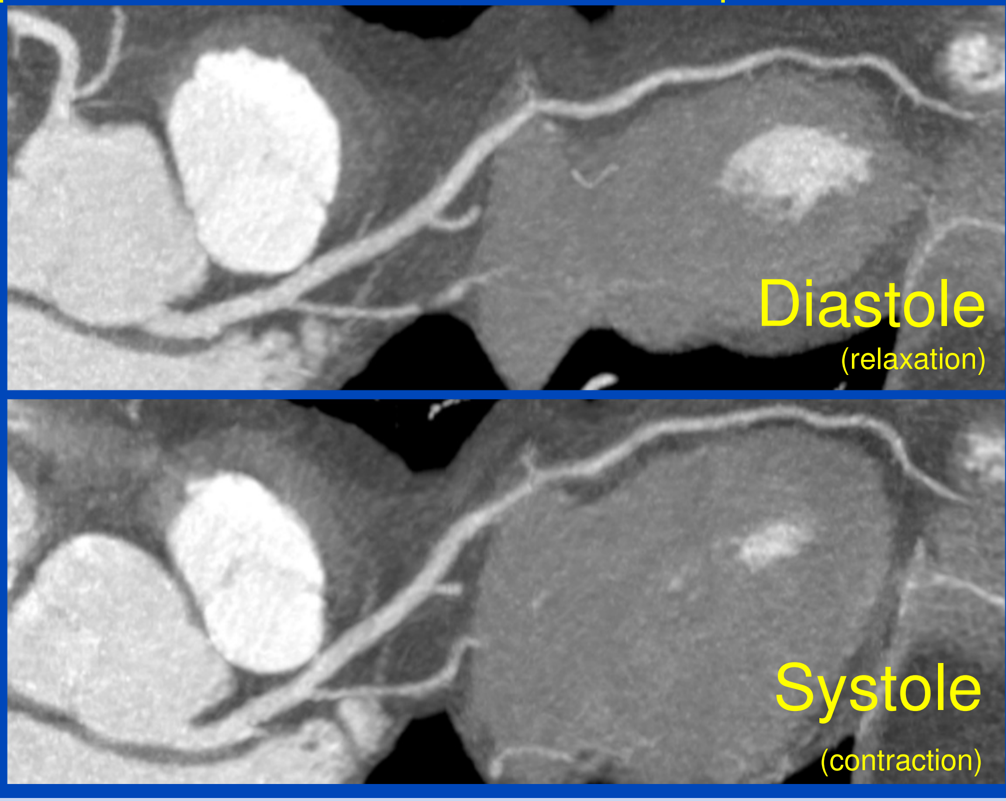


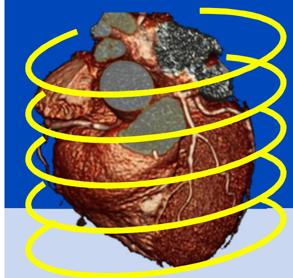
Dual Energy whole body CTA: 100/140 Sn kV @ 0.6mm

Dual Source CT = Best Possible Cardiac CT

- **Extremely high temporal resolution**
- **Nearly free of motion artifacts**

dual source CT, 330 ms rotation,
partial scan reconstruction, 83 ms temporal resolution

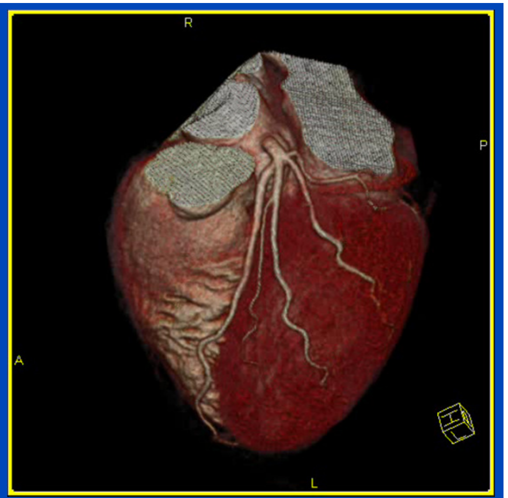




Data courtesy of Stephan Achenbach

Imaging the Heart with CT

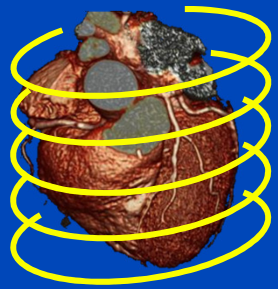
(Cardiac-CT = phase-correlated CT)

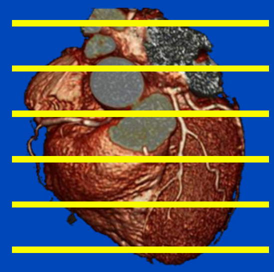


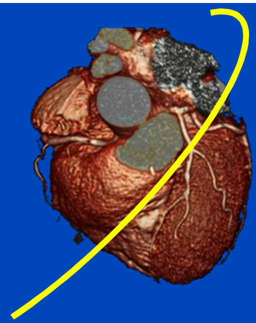
- Periodic motion
- Synchronisation (ECG, Kymogram, …)
- Phase-correlated scanning = Prospective Gating
  - Used in the 80s and 90s with little success.
  - Comes into use again due to large cone-angles.
- Phase-correlated reconstruction = Retrospective Gating
  - Single-phase (partial scan) approaches, e.g. 180°MCD
  - Bi-phase approaches, e.g. ACV (Flohr et al.)
  - Multi-phase Cardio Interpolation methods, e.g. 180°MCI (gold-standard)
  - Generations
    - » Single-slice spiral CT: 180°CD, 180°CI (introduced 1996[1])
    - » Multi-slice spiral CT: 180°MCD, 180°MCI (introduced 1998[2])
    - » Cone-beam spiral CT: ASSR CD, ASSR CI (introduced 2000[3])
    - » Wide cone-beam CT: EPBP (introduced 2002[4])
    - » Multi-source CBCT: EPBP (introduced 2005[5])

[1]Med. Phys. 25(12):2417-2431 (1998), [2]Med. Phys. 27(8):1881-1902 (2000), [3]Proc. Fully 3D-2001:179-182 (2001), [4]Med. Phys. 31(6): 1623-1641 (2004), [5]Med. Phys. 33(7): 2435-2447 (2006)

dkfz.







Retrospective Gating

=

Standard scan + ECG-correlated recon

Standard spiral scan with low pitch value ($p \le f_H \cdot t_{rot}$)

Phase-correlated reconstruction

$p \cdot T_{rot} / 2 \le$ Temp. resolution $\le T_{rot} / 2$

Works also at high heart rates

Dose management: ECG-based TCM

Full phase selectivity

Highly robust (also with arrhythmia)

Good dose usage

Prospective Gating

=

ECG-triggered scan + standard recon

ECG-triggered sequence- or spiral scan with high pitch value

Standard image reconstruction

Temporal resolution = $T_{rot} / 2$

Good at low heart rates

Dose management: inherent

No phase selectivity

Sufficiently robust (not with arrythmia)

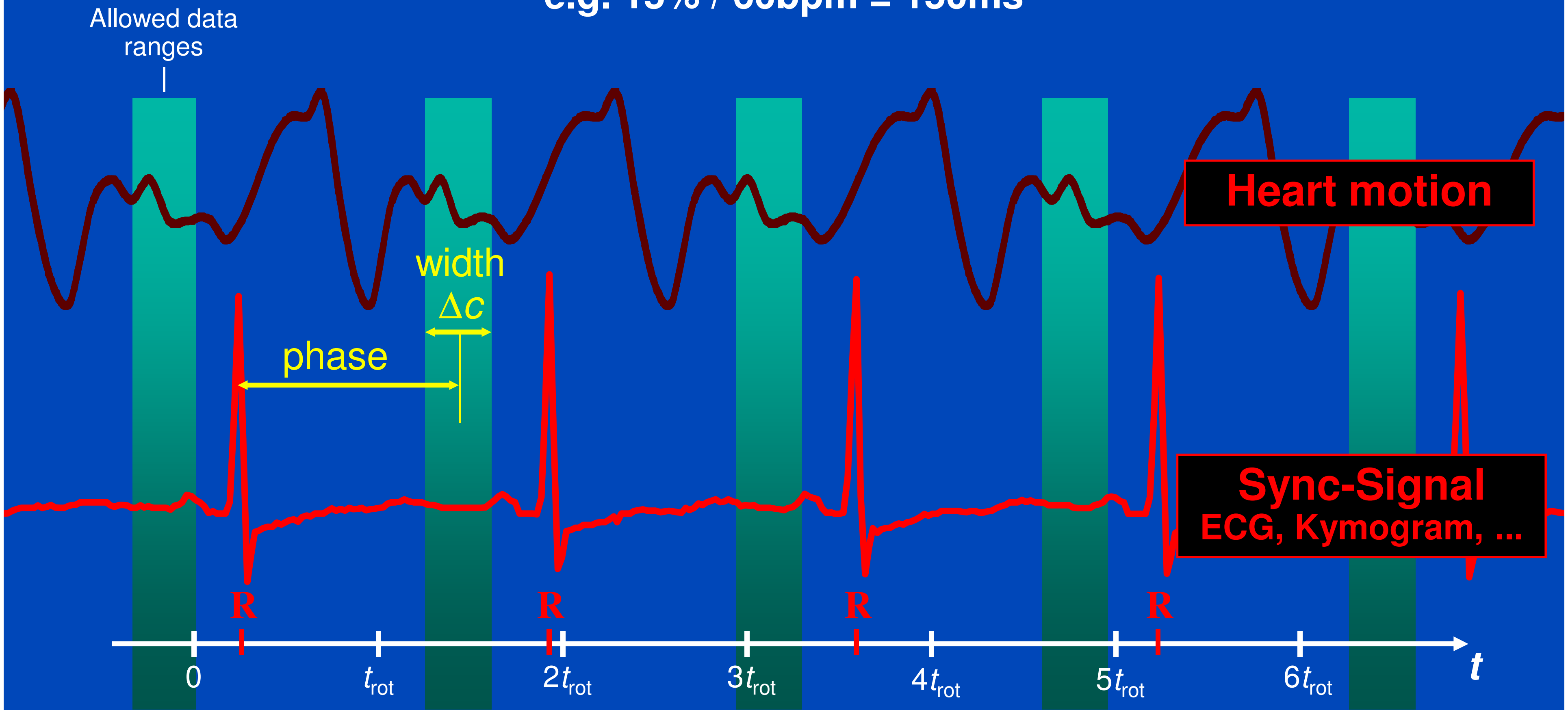
Very good dose usage

dkfz.

Synchronization with the Heart Phase

t_{eff} = width / heart rate

e.g. 15% / 60bpm = 150ms

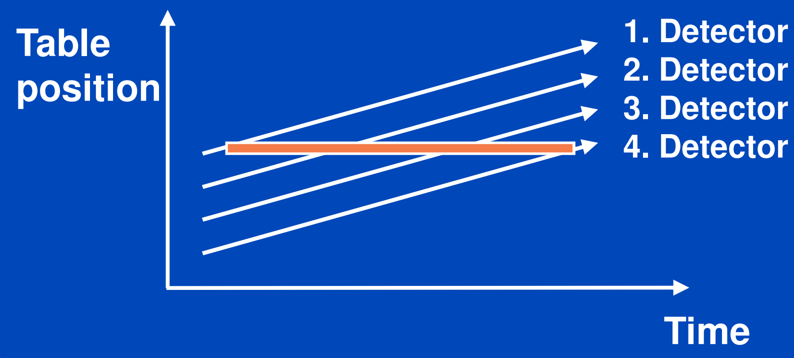


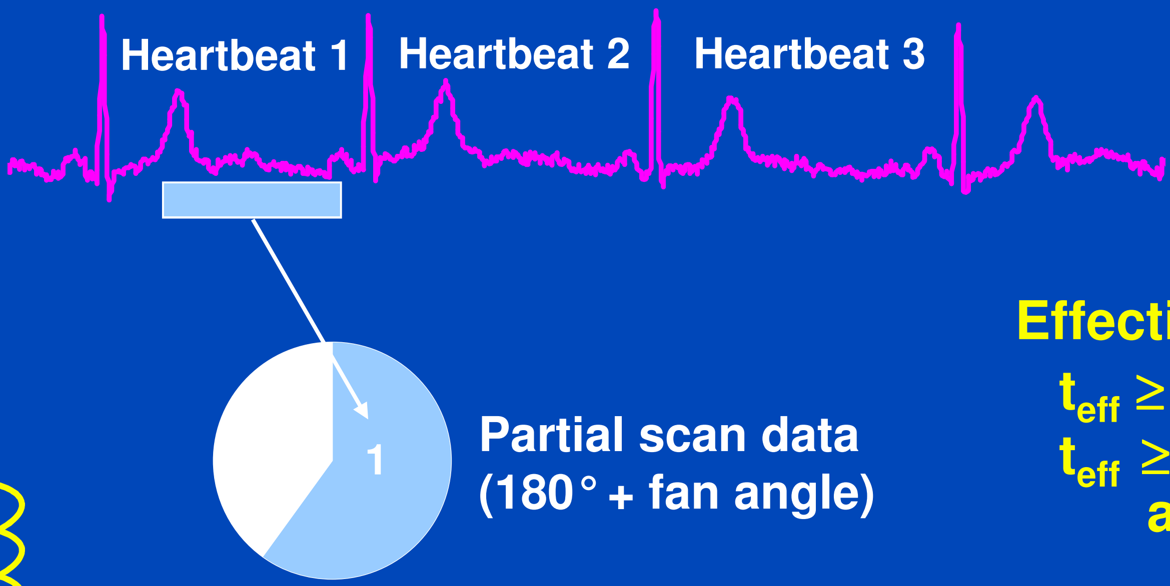
Width, and thus t_{eff}, corresponds to the FWTM of the phase contribution profile.

Kachelrieß et al., Radiology 205(P):215, (1997)

Partial Scan Reconstruction

Use one segment of 180°+δ data of phase-coherent data for a selected heart phase

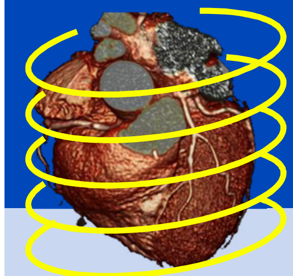




Effective scan time

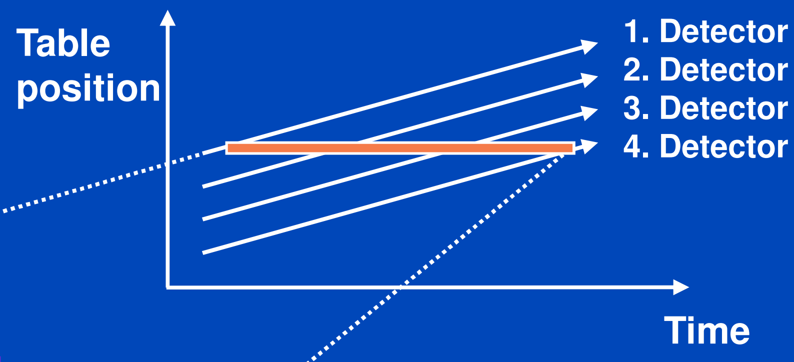
$t_{eff} \geq t_{rot}/2$

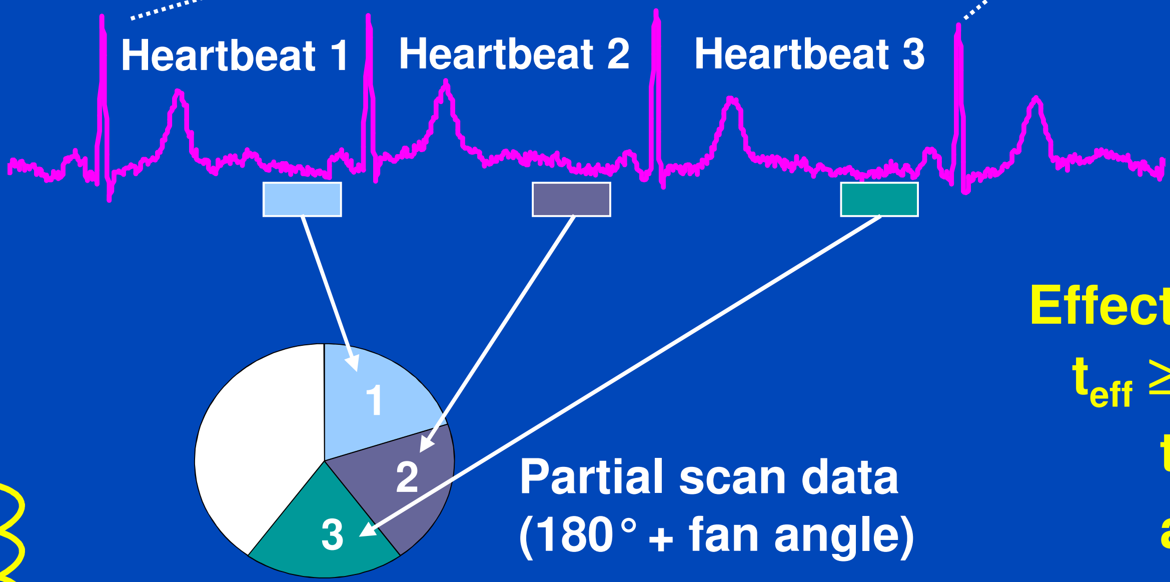
$t_{eff} \geq 200$ ms at $t_{rot} = 0.4$ s



Multi-Segment Reconstruction

Combine n segments
to obtain 180°+δ
of phase-coherent data
for a selected heart phase



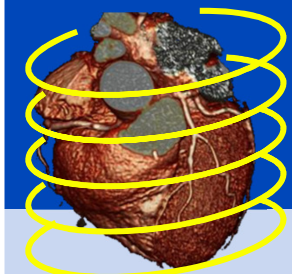


Effective scan time

$t_{eff} \geq 48$ ms

typ. 75-150 ms

at $t_{rot} = 0.4$ s



Kachelrieß, Ulzheimer, Kalender, Med. Phys. 27(8):1881-1902 (2000)

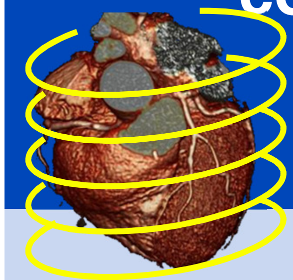
dkfz.

Pitch Value and Full Phase Selectivity

- **Each voxel must be illuminated by the x-rays at least as long as one motion cycle of the heart takes**
- **The table increment per motion cycle must not be larger than the collimation of the scanner**

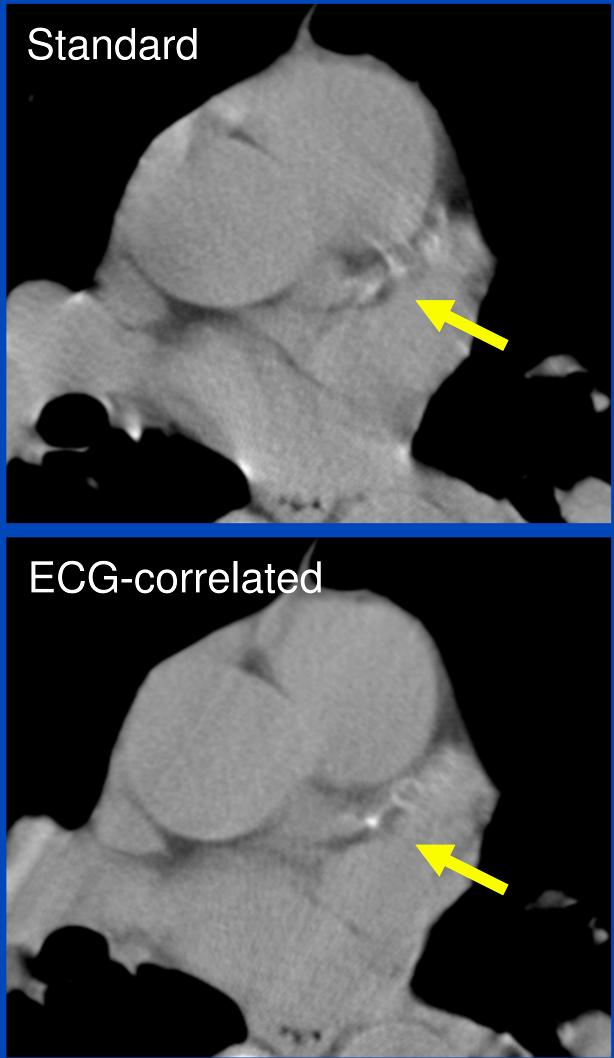
$$p \leq f_{\mathrm{H}} t_{\mathrm{rot}}$$

- **For example $t_{\mathrm{rot}} = 0.5$ s and $f_{\mathrm{H}} = 60$ bpm imply that a pitch value of $p < 0.5$ must be chosen.**
- **The lower the pitch value the more segments can be combined in multi-segment image reconstruction.**



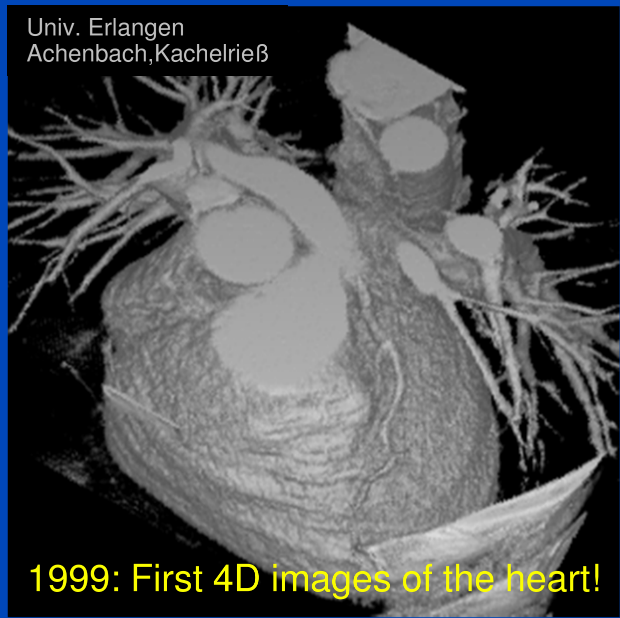
Early Cardiac Spiral CT

Single Slice CT (RSNA 1997)

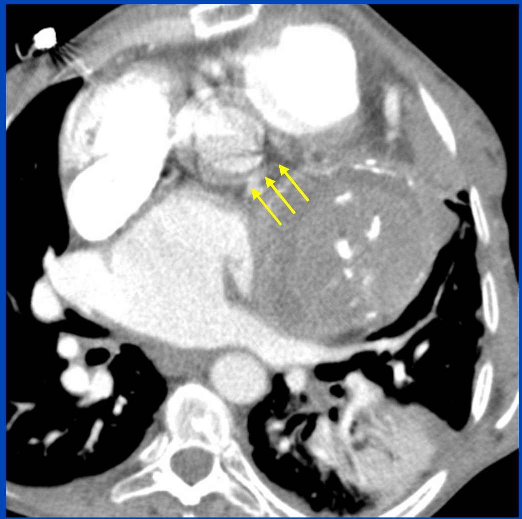


Kachelrieß et al. Electrocardiogram-correlated image reconstruction from subsecond spiral computed tomography scans of the heart. Med. Phys., 25(12):2417-2431, December 1998.

4-Slice CT (RSNA 1999)



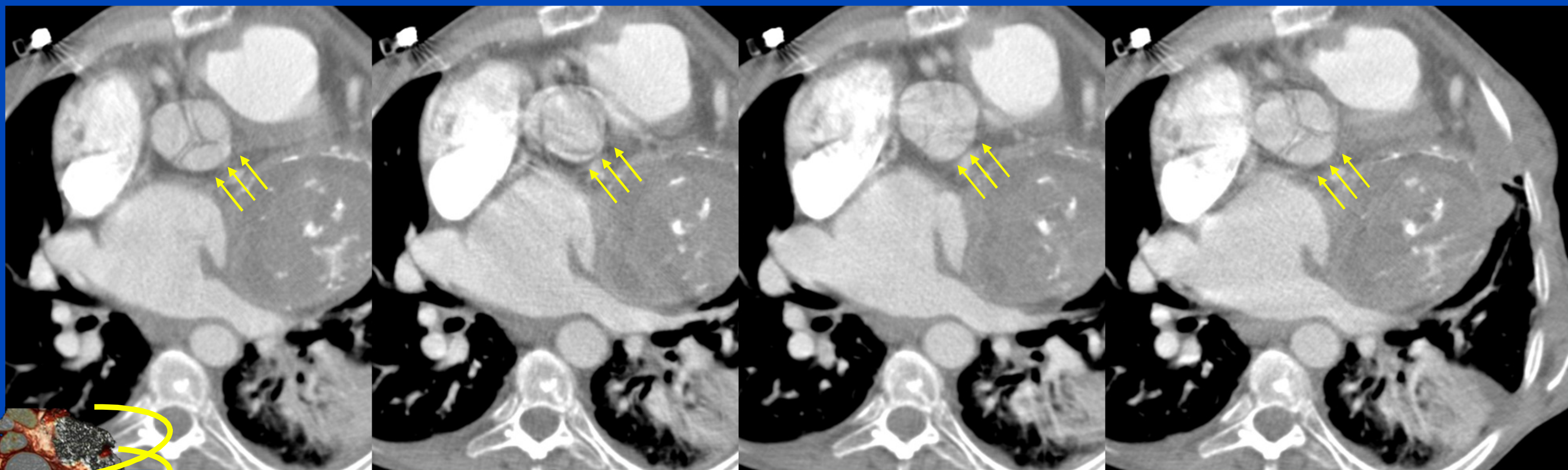
Kachelrieß et al. ECG-correlated imaging of the heart with subsecond multislice spiral CT. IEEE TMI, 19(9):888-901, September 2000.

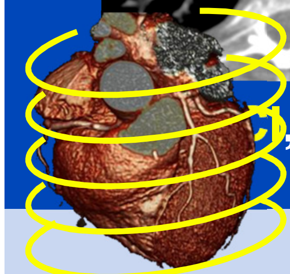


180°MLI

Cardiac CT is Phase-Selective

Volume Zoom, 4 × 2.5 mm, 0.5 s, 1998, f_H = 90 bpm



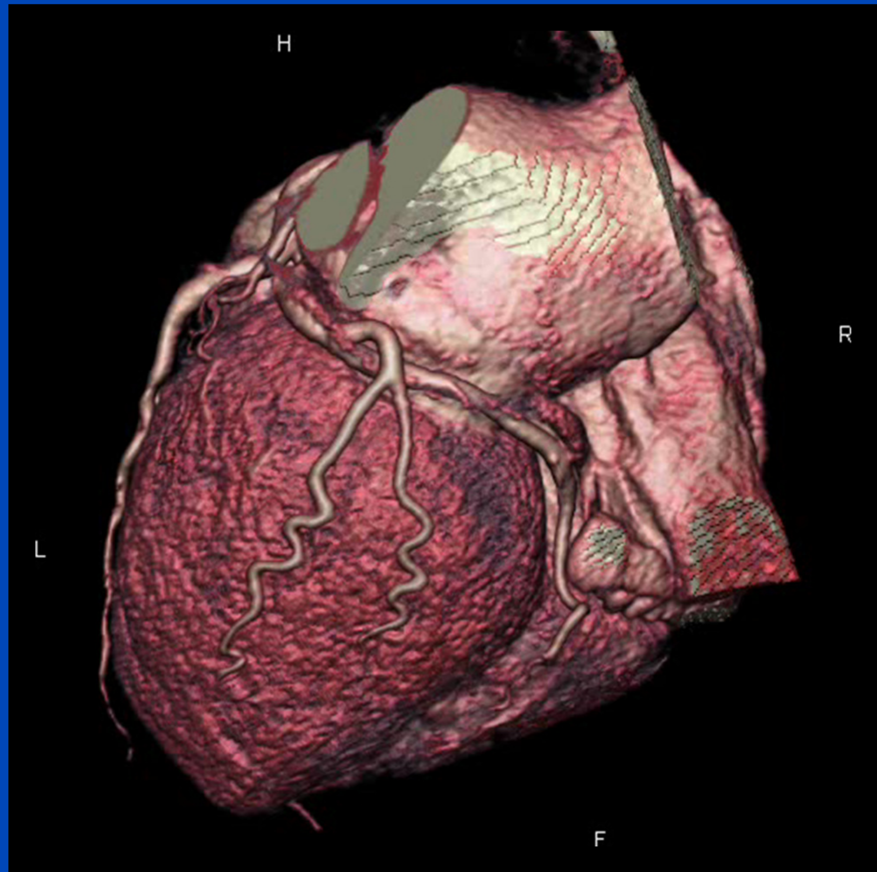


, 0%R-R **25%R-R** **50%R-R** **75%R-R**

Kachelrieß, Ulzheimer, Kalender, Med. Phys. 27(8):1881-1902 (2000)

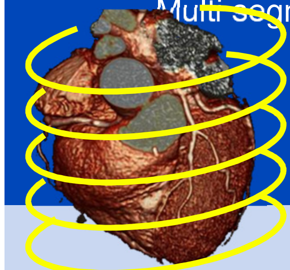
Volume Zoom, 4 × 2.5 mm, 0.5 s, 1998

Multi-segment reconstruction 180°MCI, 90 bpm

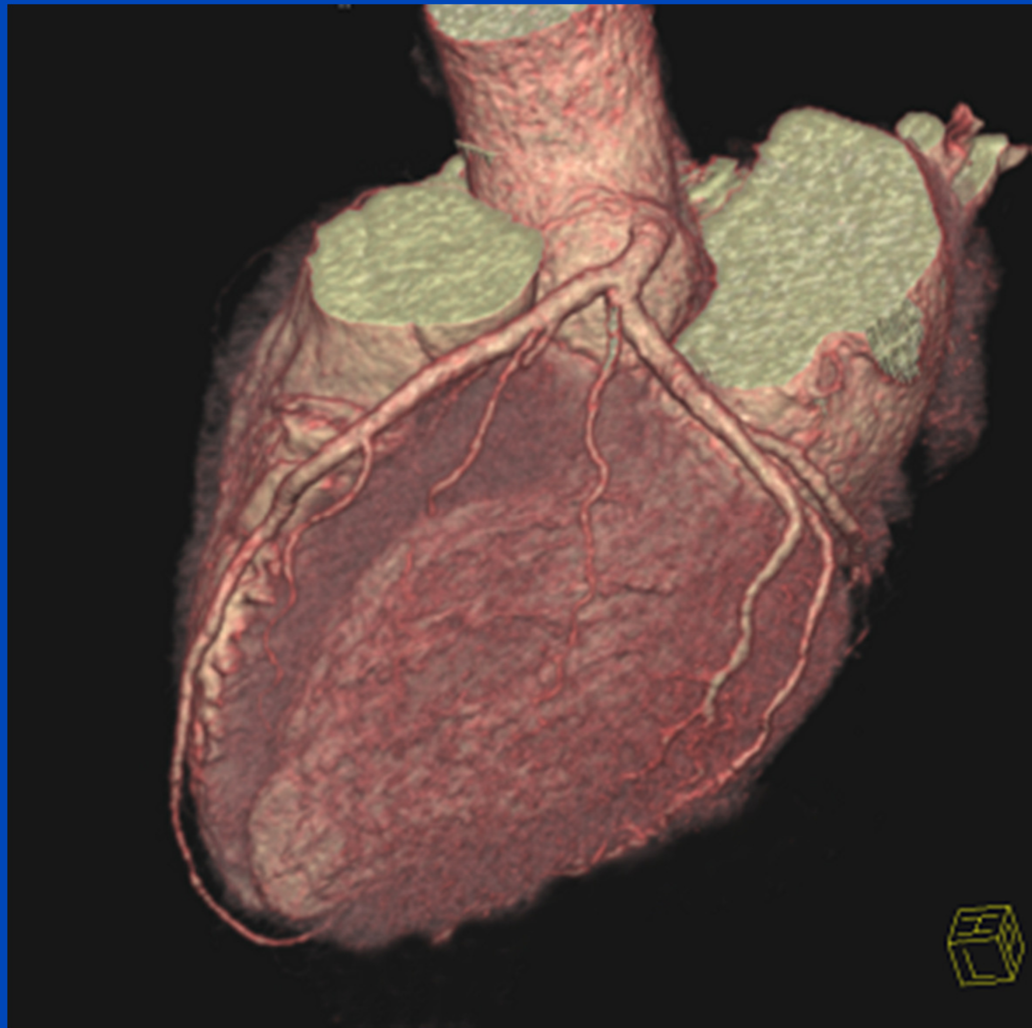


Sensation 64, 2·32 × 0.6 mm, 0.33 s, 2004

Data courtesy of Dr. Stephan Achenbach

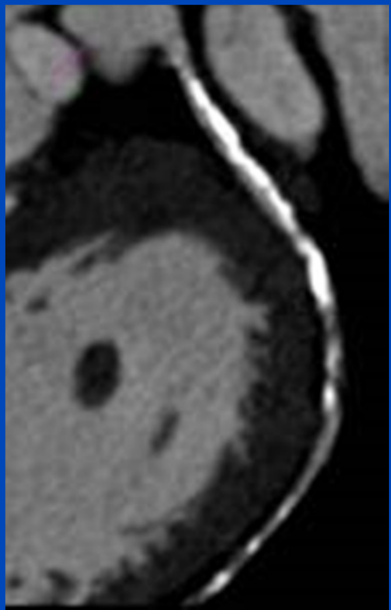


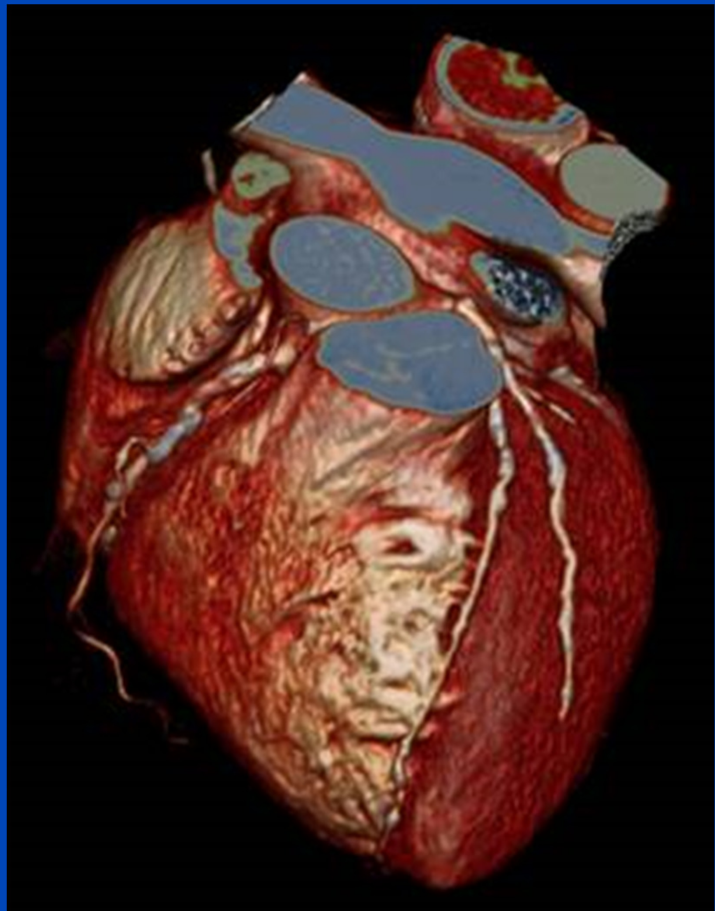
Dual-source-CT, 330 ms rotation, partial scan reconstruction, 83 ms temporal resolution

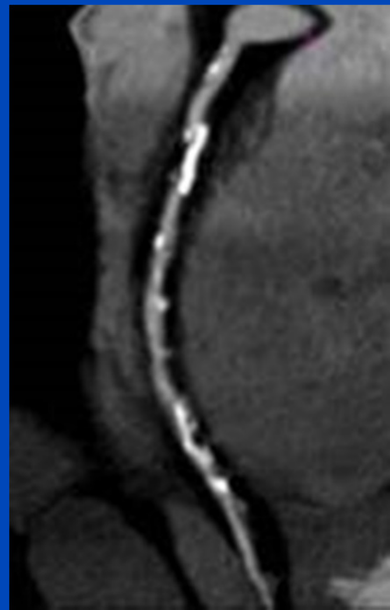


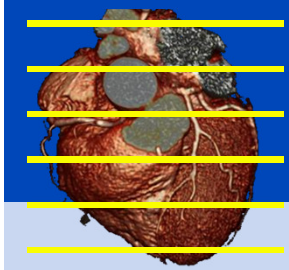
Data courtesy of Dr. Stephan Achenbach, Erlangen, Germany

2·64×0.6 mm, 300 ms rotation, partial scan recon, 150 ms temporal resolution





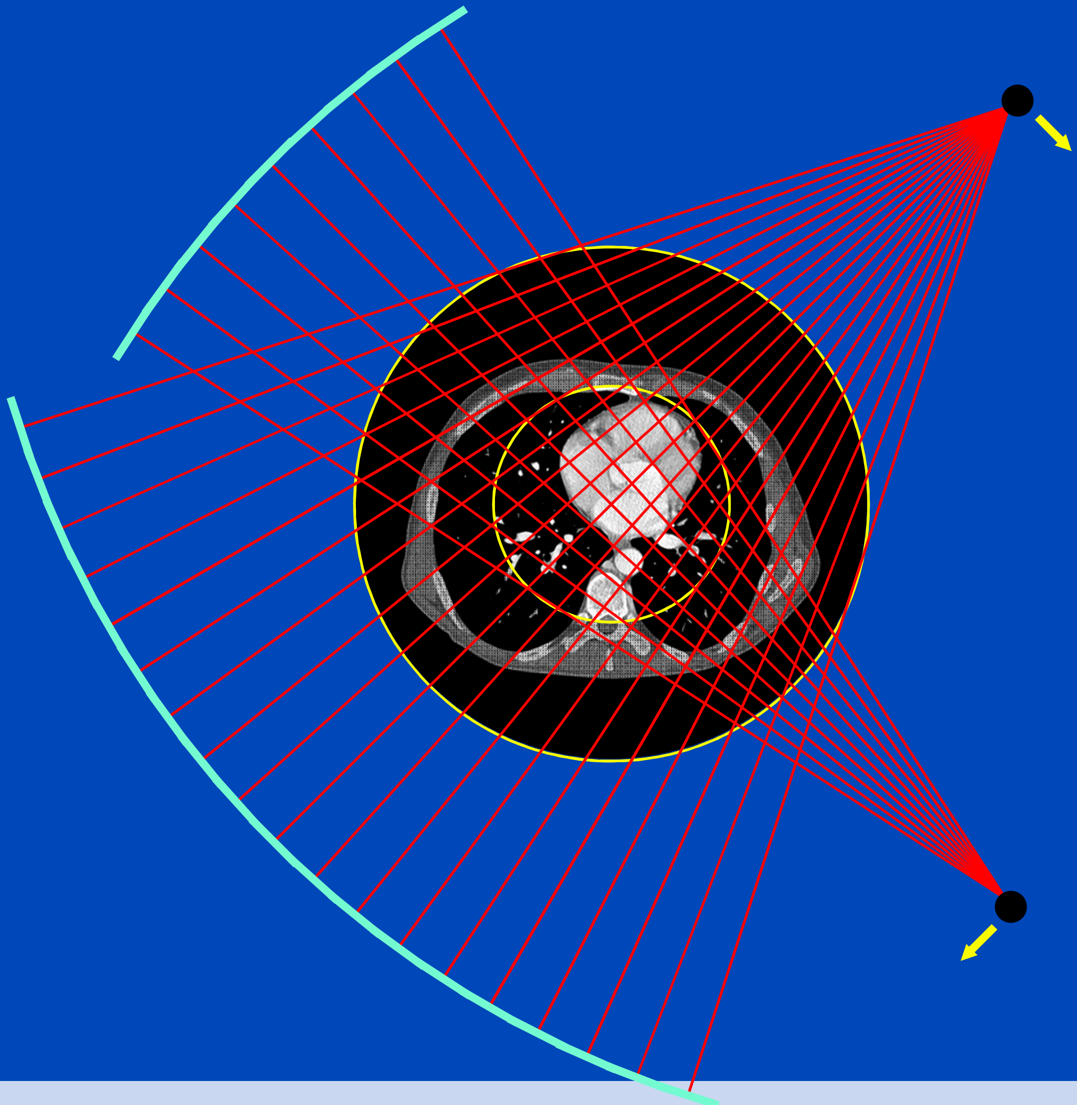


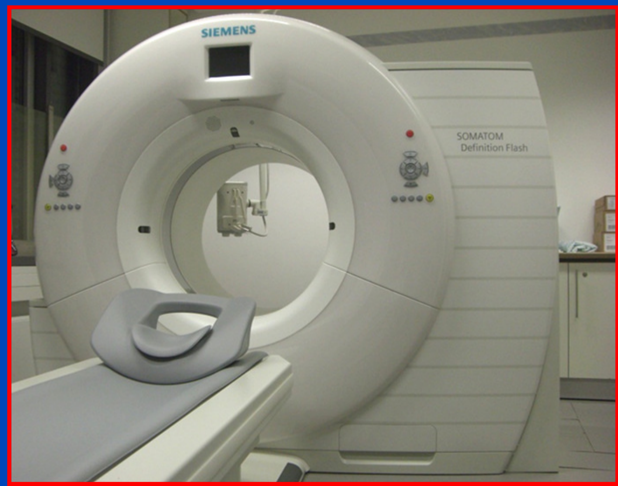


Data courtesy of Dr. Michael Lell, Erlangen, Germany

dkfz.

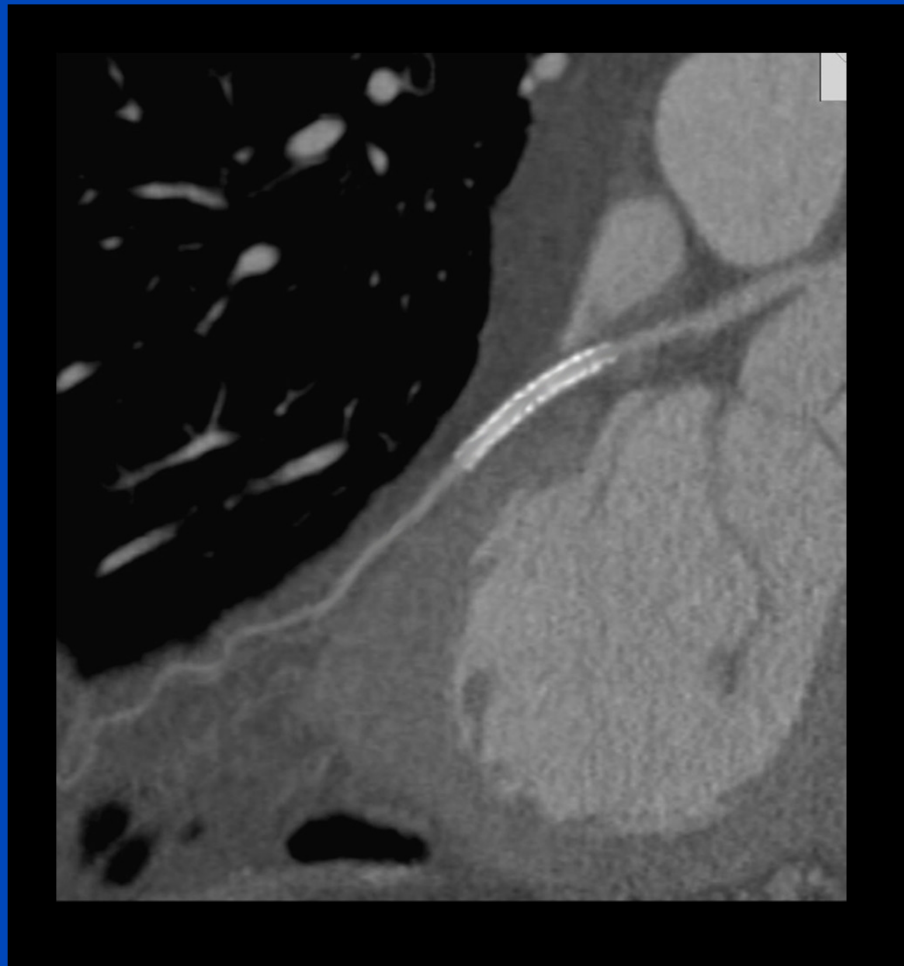
Multi-Threaded CT Scanners and Dual-Source-CT





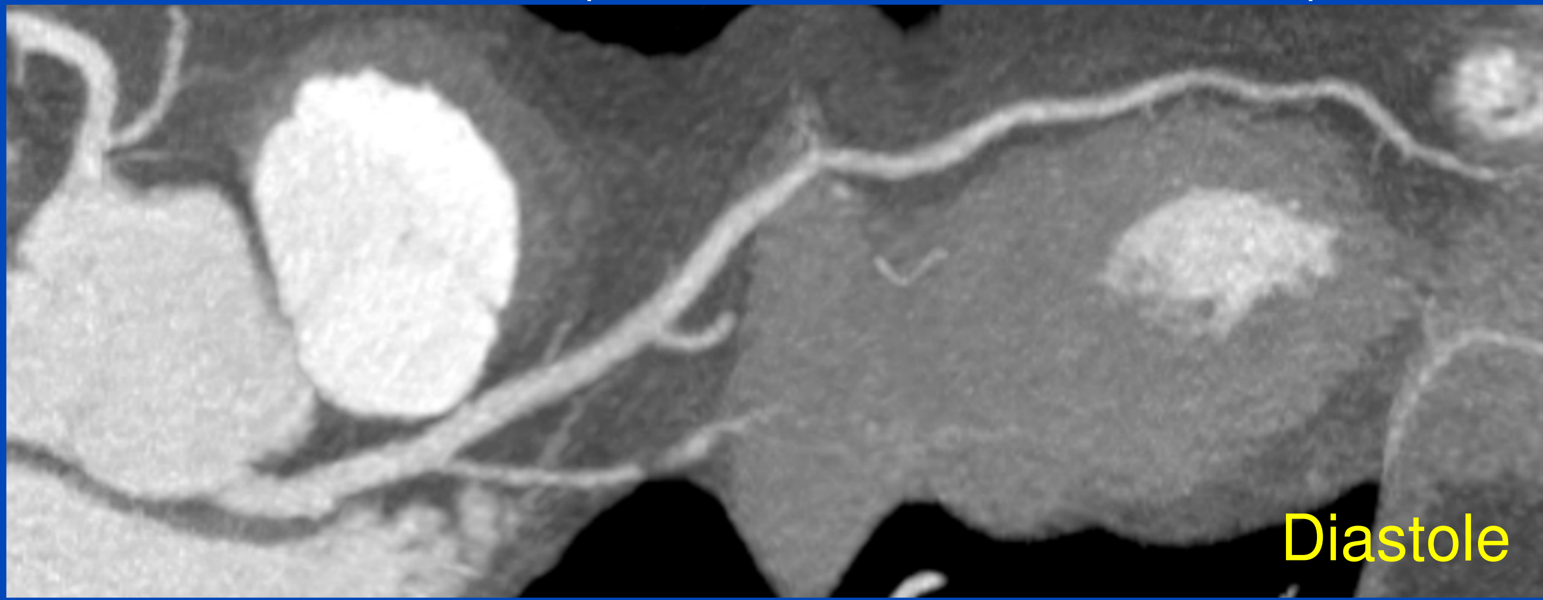
Siemens SOMATOM Definition Flash
dual source cone-beam spiral CT scanner

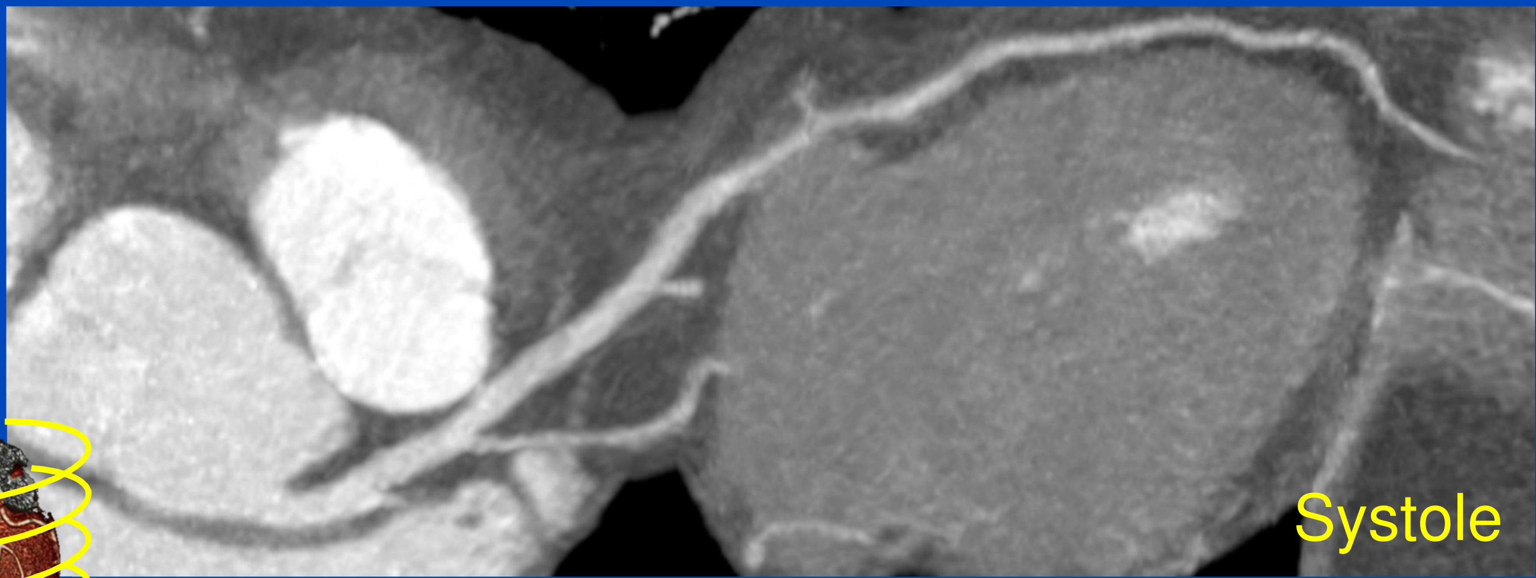
Dual-source-CT, 330 ms rotation, partial scan reconstruction, 83 ms temporal resolution

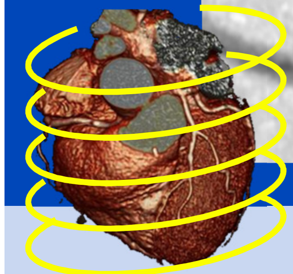


Data courtesy of Dr. Stephan Achenbach, Erlangen, Germany

Dual-source-CT, 330 ms rotation, partial scan reconstruction, 83 ms temporal resolution







Data courtesy of Dr. Stephan Achenbach, Erlangen, Germany

dkfz.

Dual-Source-CT

Flash Mode

280 ms Rotation

Partial scan reconstruction

70 ms temporal resolution

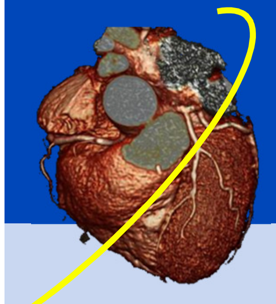
Pitch = 3.2 (43 cm/s)

320 mAs, 100 kV

10.6 cm scan range

DLP = 64 mGy·cm

D_{eff} = 0.89 mSv



Data courtesy of Dr. Stephan Achenbach, Erlangen, Germany

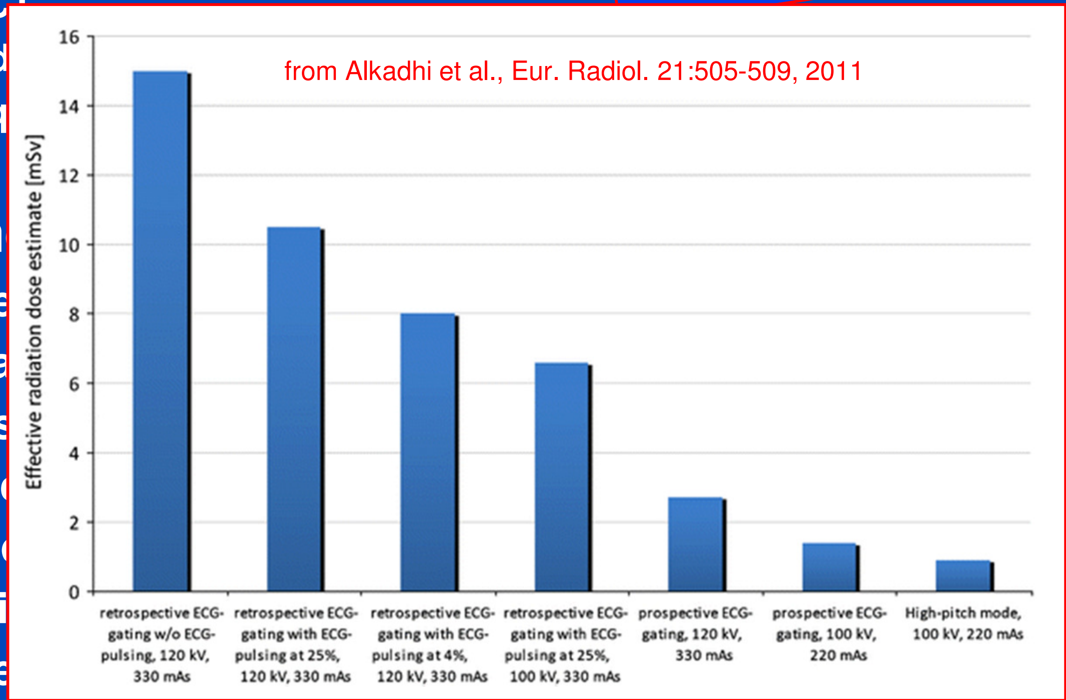
dkfz.

Dose in Cardiac CT Today

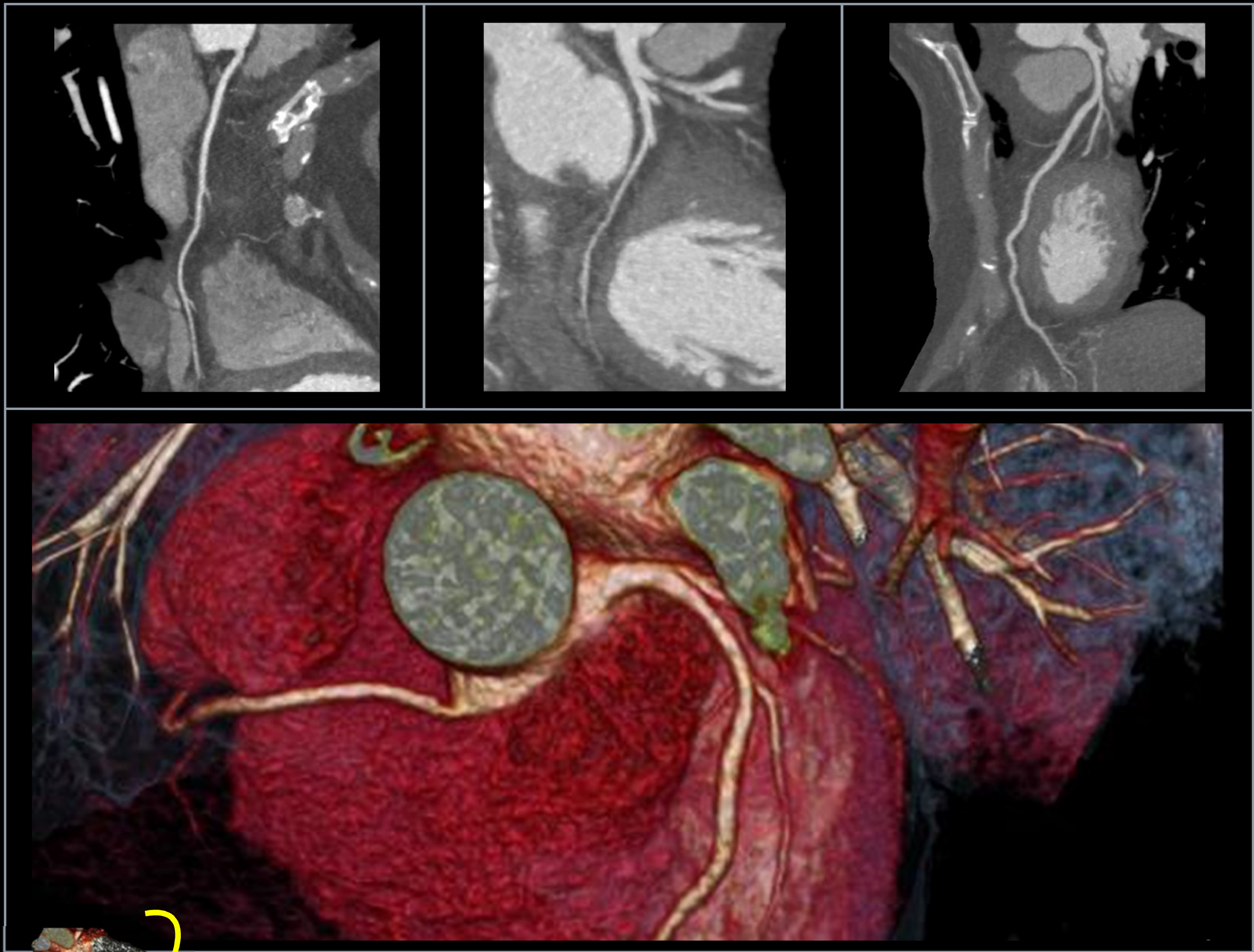
- Reasons for a dose increase
  - Cardiac CT as such
  - Higher spatial resolution
  - More exams due to higher reliability
  - New cardiac CT applications
    - DECT
    - card
    - plaq
    - …
- Counterm
  - Adaptive
  - New x-ra
  - ECG-bas
  - Faster s
  - Improve
  - User trai
  - Optimize

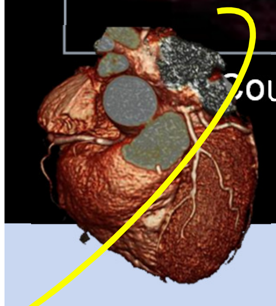
Dose values of up to 30 mSv (site-specific median) per cardiac exam have been reported in a multicenter study carried out 2007[1].

elow 1 mSv per are routinely today[2].



[1]Hausleiter et al., JAMA 301(5):500-507, 2009
[2]Alkadhi et al., Eur. Radiol. 21:505-509, 2011





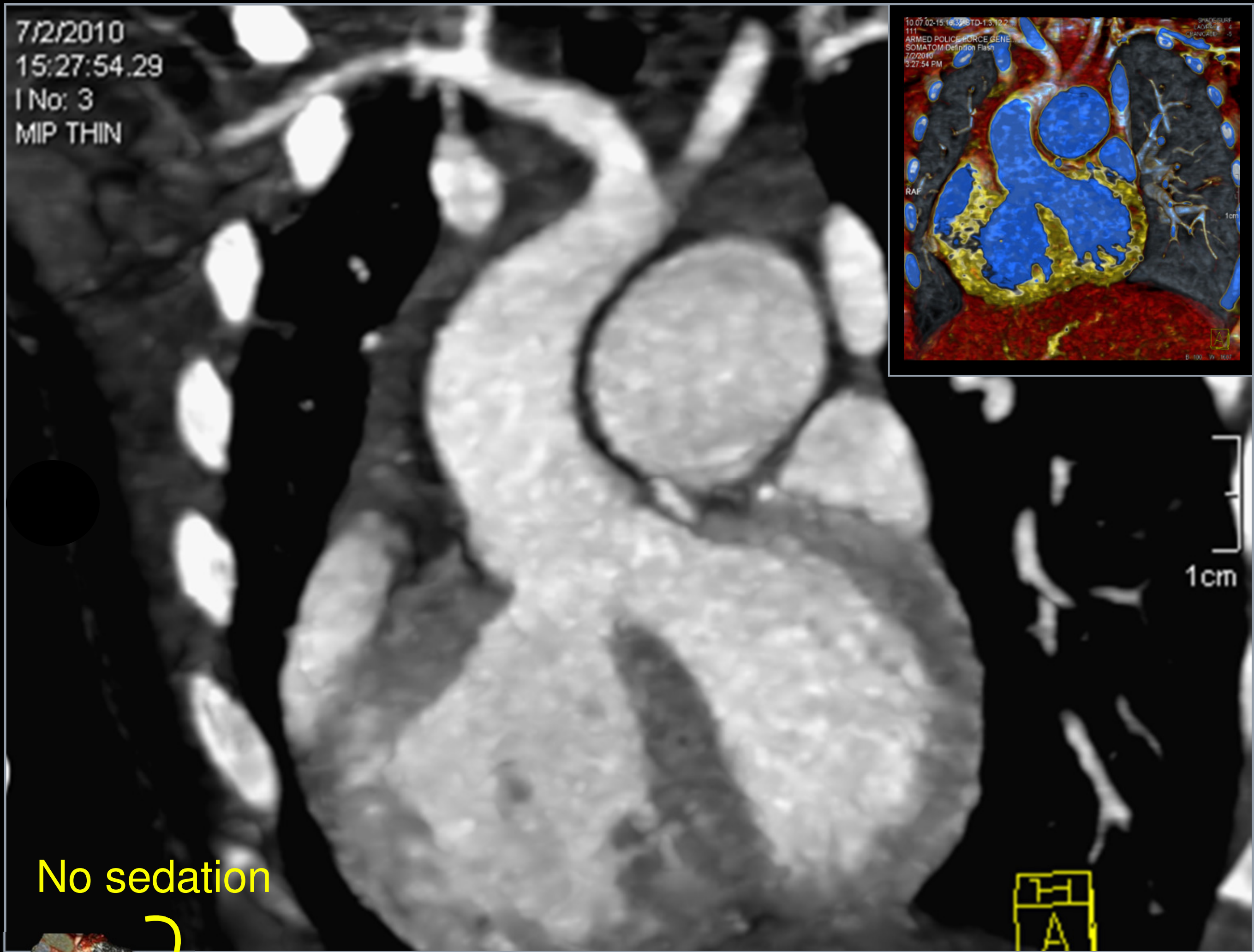
Courtesy of Sir Run Run Shaw University HongKong / HongKong, China

Adult

Temporal resolution: 75 ms
Collimation: 2·64×0.6 mm
Spatial resolution: 0.6 mm
Scan time: 0.28 s
Scan length: 128 mm
Rotation time: 0.28 s
80 kV, 300 mAs / rotation

Flash Spiral

Eff. dose: 0.36 mSv



No sedation

Courtesy of Armed Police Forces Center/ Beijing, China

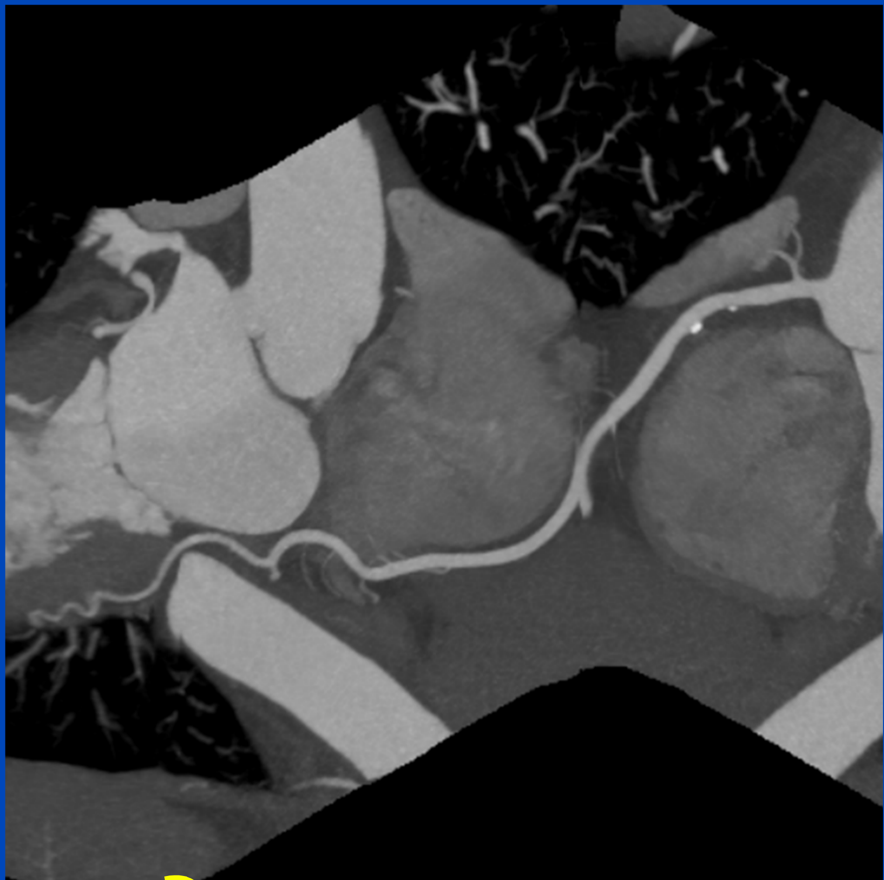
Child, 12 months

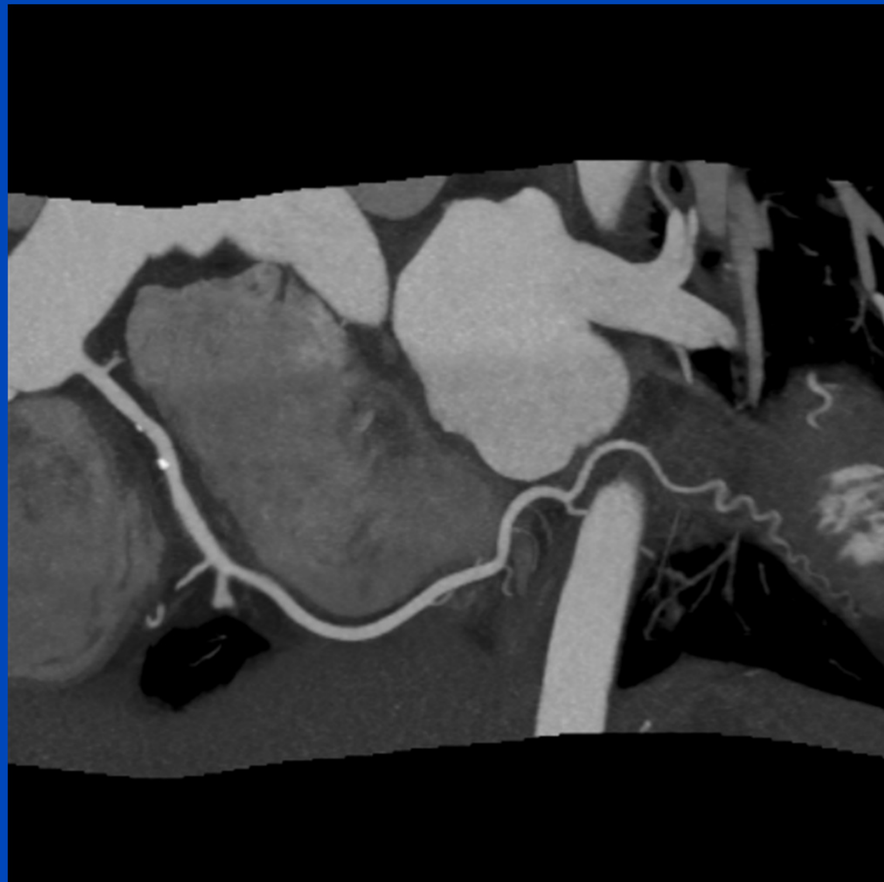
Temporal resolution: 75 ms
Collimation: 2·64×0.6 mm
Spatial resolution: 0.6 mm
Scan time: 0.23 s
Scan length: 78 mm
Rotation time: 0.28 s
80 kV, 36 mAs / rotation

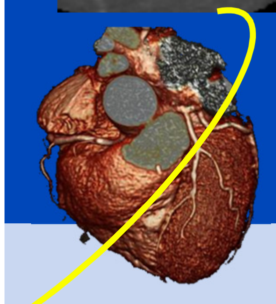
Flash Spiral

Eff. dose: 0.05 mSv

Dual Source CT, Turbo Flash Mode
70 kV, DLP: 39 mGy cm ≈ 0.5 mSv, calcified RCA







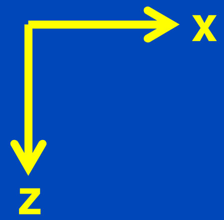
Data courtesy of Dr. Stephan Achenbach, Erlangen, Germany

dkfz.

How are Scans Conducted?

- Patient registration, incl. patient history, obtain patient consent
- Positioning of the patient on the CT table (laser localizer, ECG leads, contrast agent access, power injector, beta blocker, …)
- Definition of the scan procedure
  - X-ray overview (topogram, scout view, scanogram, …) parameters
  - CT scan parameters
  - Patient instructions (typ. breathing instructions)
  - Contrast agent volume and injection speed
  - Test bolus or bolus tracking parameters (e.g. z_{Bolus}, interscan delay, …)
  - Cardiac CT parameters (e.g. diastolic at about 70% of R-R, …)
  - Reconstruction parameters
- Scanning
  - Automatically, according to the previously defined plan
  - Manual updates, manual interrupts

Topogram (a.p. view)



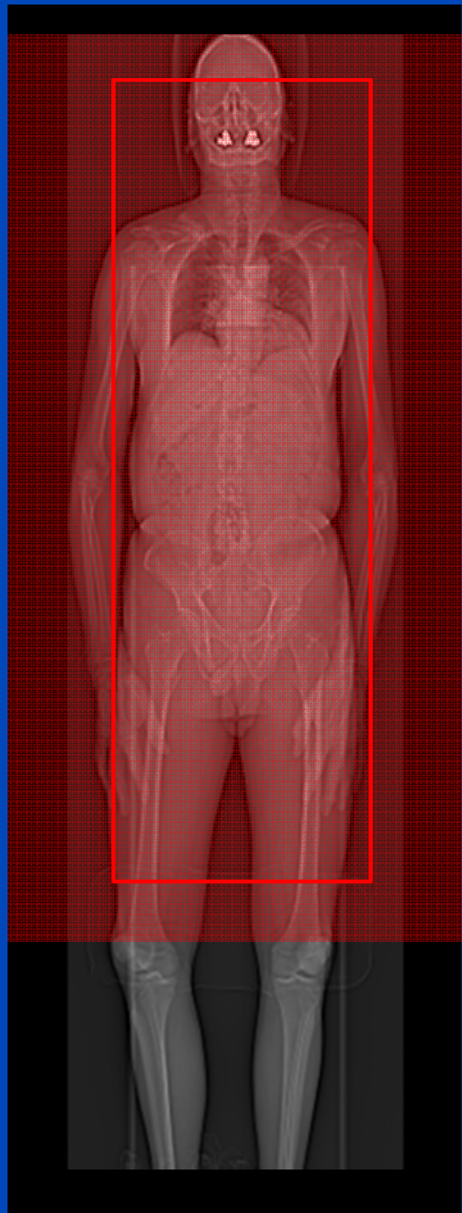


Image courtesy of Dr. Migle Sumkauskaite, Heidelberg, Germany

Typical Scan Parameters

- Scan directions (caudo cranial or cranio caudal)
- Scan length (0 – 200 cm)
- Tube voltage (70 – 140 kV)
- Trajectory (circle, sequence, spiral, shuttle, bolus tracking, multiple circle for dynamic CT, …)
- Effective tube current time product mAs_{eff}
- Rotation time (0.28 – 1.0 s)
- Pitch value (spiral scan), scan increment (sequence scan), …
- Slice thickness (0.5 – 10 mm)
- Special parameters
  - Contrast agent volume and speed (1 – 4 mL/s)
  - Scan delays
  - Patient instructions
  - Tube current modulation
  - …

Bolus Tracking

- **Device parameters (fixed):**
  - **delay to move table**
  - **delay to start scan**
- **Scan parameters (user-selectable):**
  - **target vessel**
  - **threshold**
  - **interscan delay**

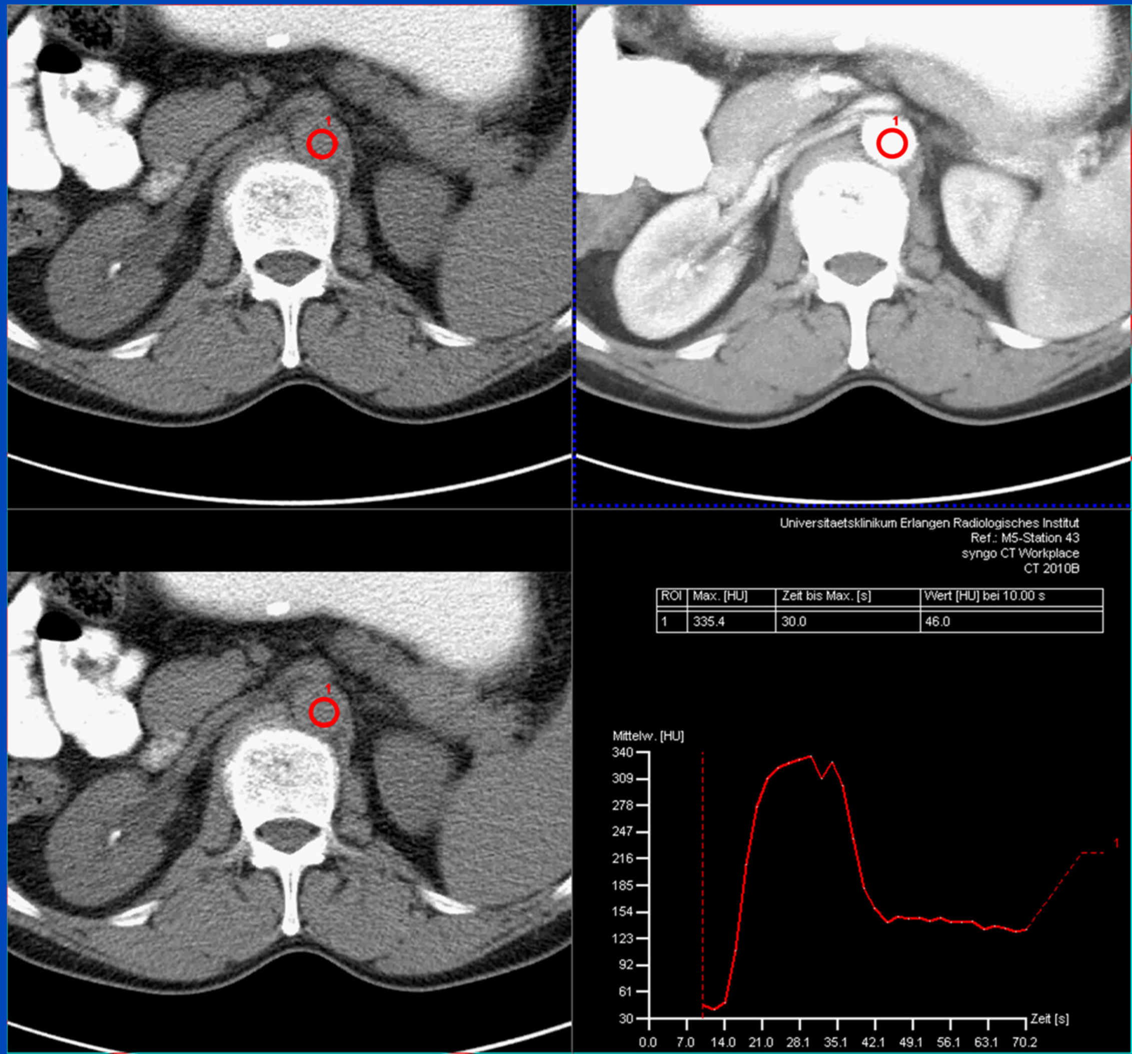


Image courtesy of Prof. Dr. Michael Lell, Erlangen, Germany

Test Bolus Method

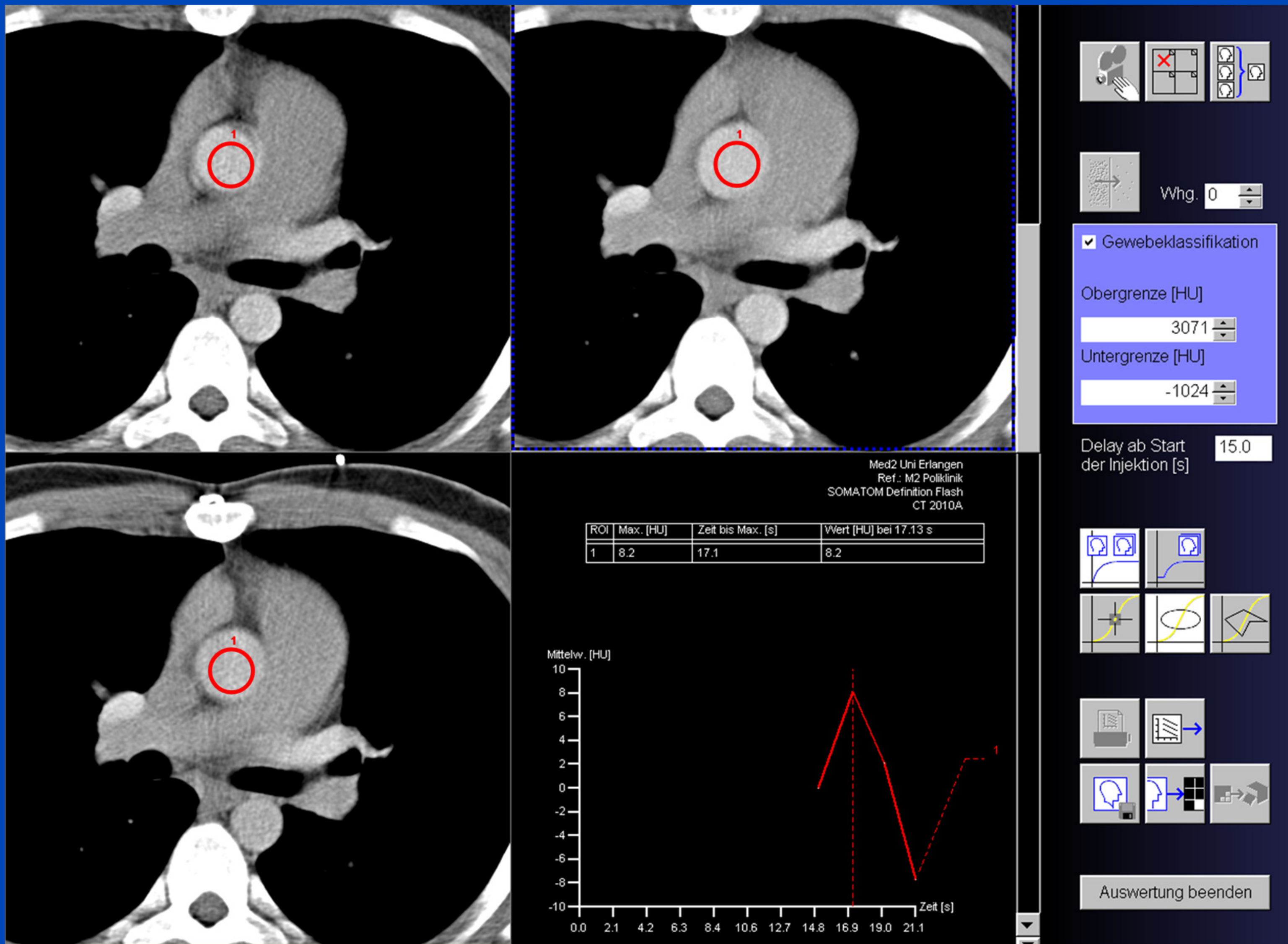


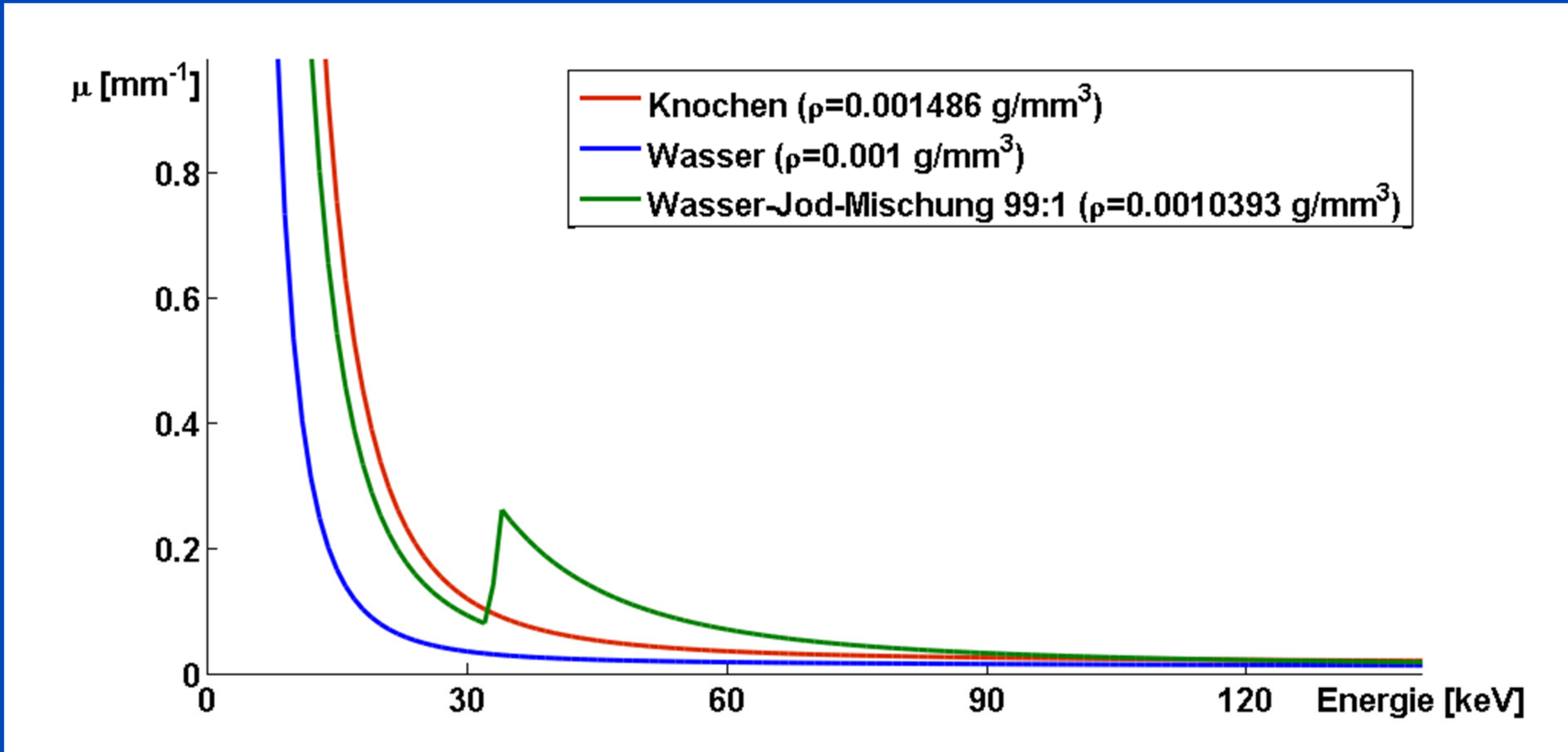
Image courtesy of Prof. Dr. Michael Lell, Erlangen, Germany

Typical Reconstruction Parameters

- Reconstruction kernel (soft, standard, high resolution)
- Body region (abdomen, head, adult, child)
- Effective slice thickness S_{eff} (0.5 mm – 10 mm)
- Slice increment Δz (0.1 mm – 10 mm)
- Lateral FOV size (100 mm – 500 mm)
- Lateral FOV position x_c, y_c
- Longitudinal FOV position z_{Start}, z_{End}
- Standard window (lung, soft tissue, bone, …)
- Reconstruction algorithm (analytical, iterative)

Typical Values for the Tube Voltage *U*

- Normal adults: 120 kV
- Obese adults: 140 kV
- Slim adults: 100 kV or 80 kV
- Children: 80 kV or 70 kV
- Toddlers: 70 kV, less would be desirable but is not provided
- Optimization of iodine contrast: 100 kV or 80 kV
- Avoid metal artifacts or photon starvation: 140 kV
- Comments
  - Adapt the threshold for bolus tracking to the selected tube voltage! The threshold should be typically reduced for increasing tube voltage.
  - Adapt the mAs_{eff} to the selected tube voltage! The effective mAs should be typically reduced for increasing tube voltage.
  - The available mAs-values depend on the tube voltage. If necessary, the pitch value must be decreased.



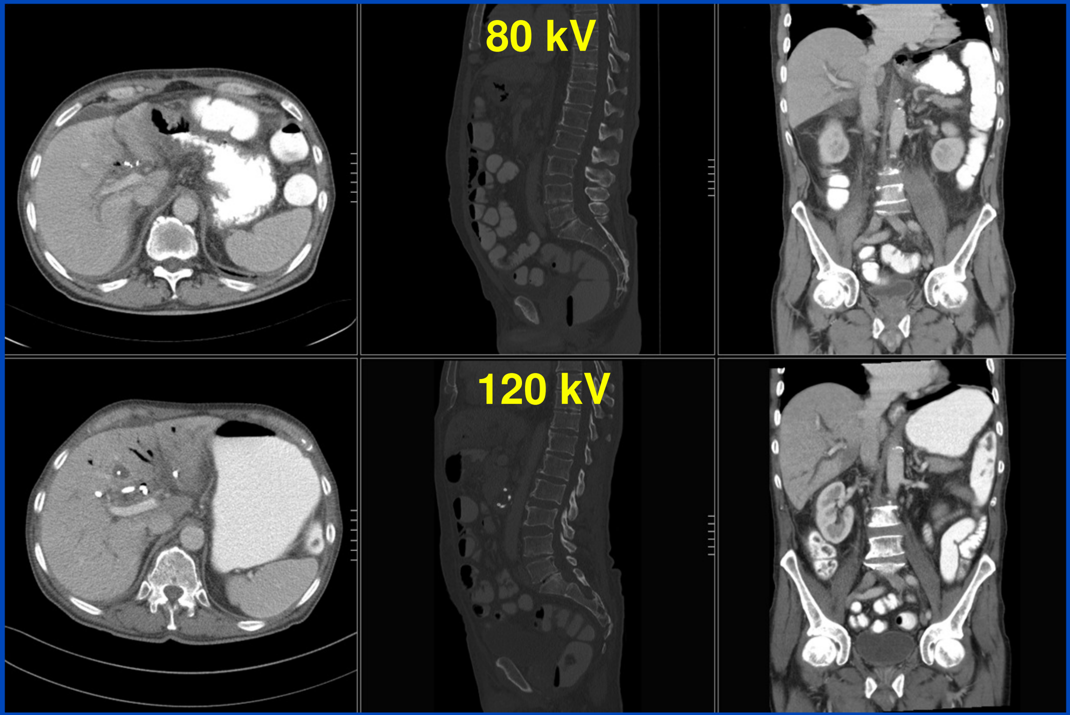
μ [mm⁻¹]
0.8
0.6
0.4
0.2
0
0
30
60
90
120
Energie [keV]
Knochen (ρ=0.001486 g/mm³)
Wasser (ρ=0.001 g/mm³)
Wasser-Jod-Mischung 99:1 (ρ=0.0010393 g/mm³)

Tube Voltage

- Low kV
  - higher iodine contrast
  - improved soft tissue contrast in small patients and children
  - higher absorption (inadequate for large and obese patients)
  - increased metal artifacts
  - increased beam hardening artifacts
- High kV
  - lower iodine contrast
  - improved soft tissue contrast in large patients
  - less metal artifacts
- In any case the tube voltage and the tube current must be selected to maximize the contrast-to-noise ratio at unit dose (CNRD)!

Scans at Low Tube Voltage

- **Properties**
  - More iodine contrast
  - Higher image noise
- **Solution**
  - Adapt mAs-value
- **Iodine CNRD increases with decreased kV for small and medium patients**



At same mAs: $E_{80} = 0.36 \times E_{120}$, $CTDI_{vol80} = 0.62 \times CTDI_{vol120}$

Take Home Messages

- Today, all clinical CT systems are 3rd generation CTs.
- CT requires an angular coverage of 180° or more.
- Today‘s x-ray tube power is up to 120 kW.
- Typical tube voltages are between 70 kV and 150 kV.
- CT‘s x-ray detectors are of energy integrating type.
- The spiral trajectory is the one that is most often used.
- Dual source CT systems double the temporal resolution.
- CT often requires the administration of contrast agents.


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.