Technical Advances in Paediatric Dose Reduction
(joint EANM/EFOMP session)

Dose Reduction in Paediatric CT

Marc Kachelrieß

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

DEUTSCHES KREBSFORSCHUNGSZENTRUM IN DER HELMHOLTZ-GEMEINSCHAFT

Aortic dissection during pregnancy. Image courtesy of PD Dr. Matthias May, University of Erlangen-Nürnberg, Germany

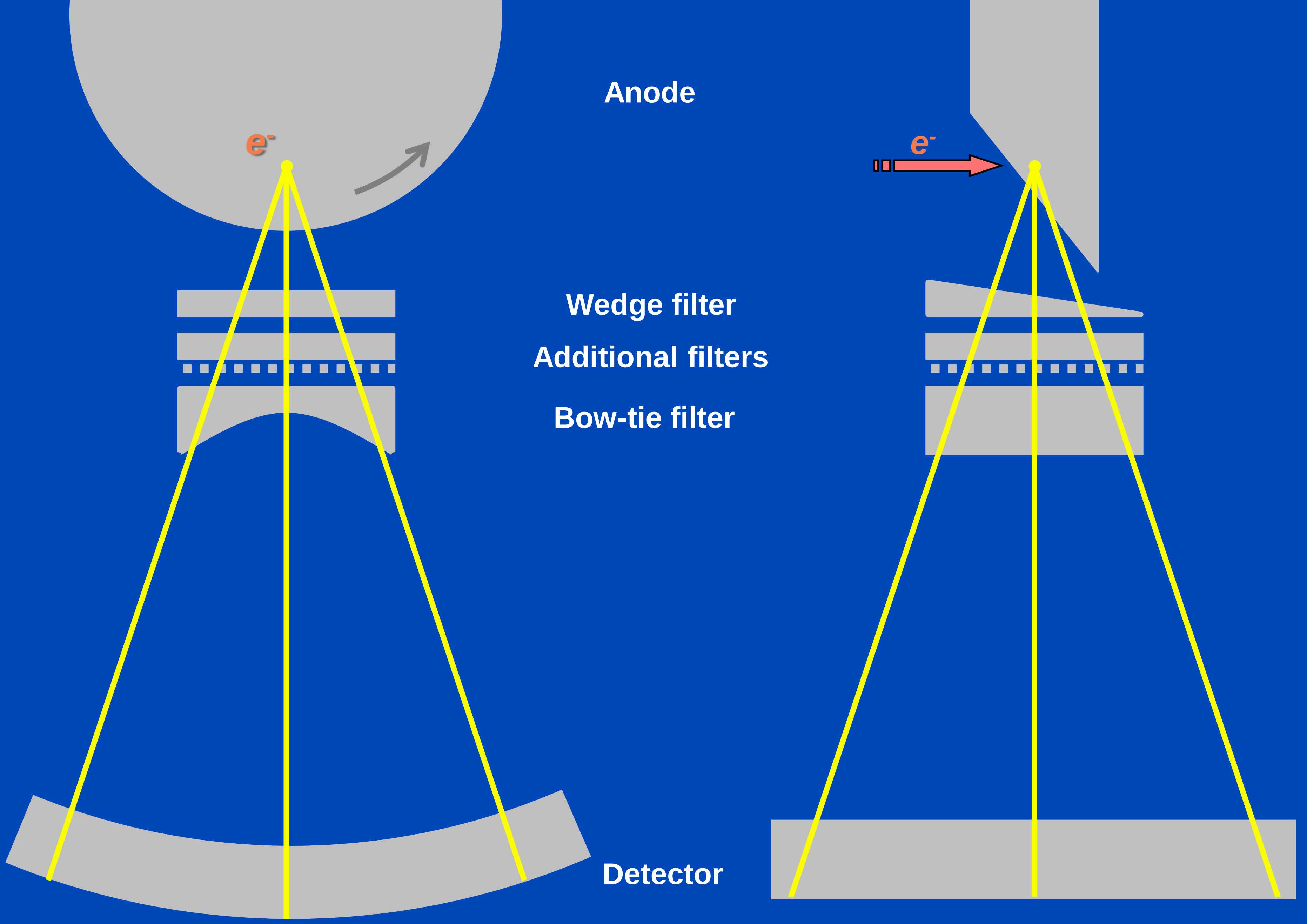

Figure not drawn to scale. Type and order of prefiltration may differ from scanner to scanner.
Depending on the selected protocol filters are changed automatically (e.g. small bowtie for pediatric scans).

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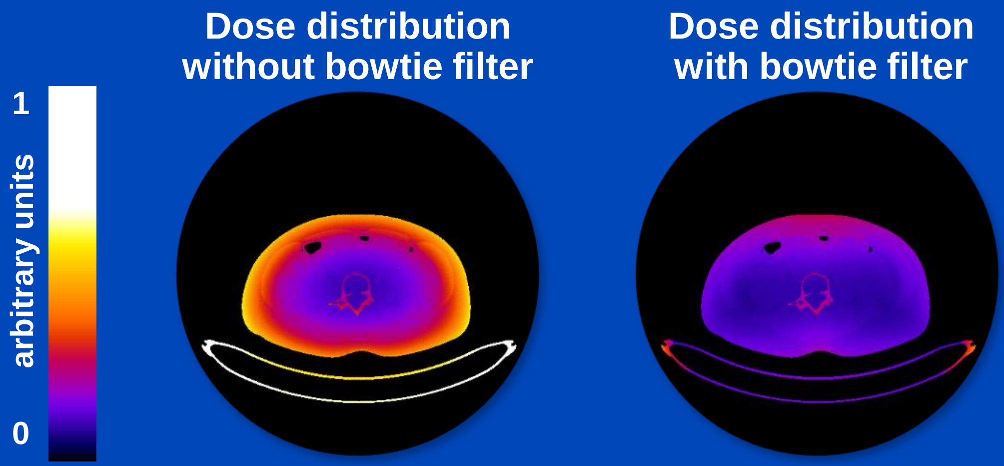
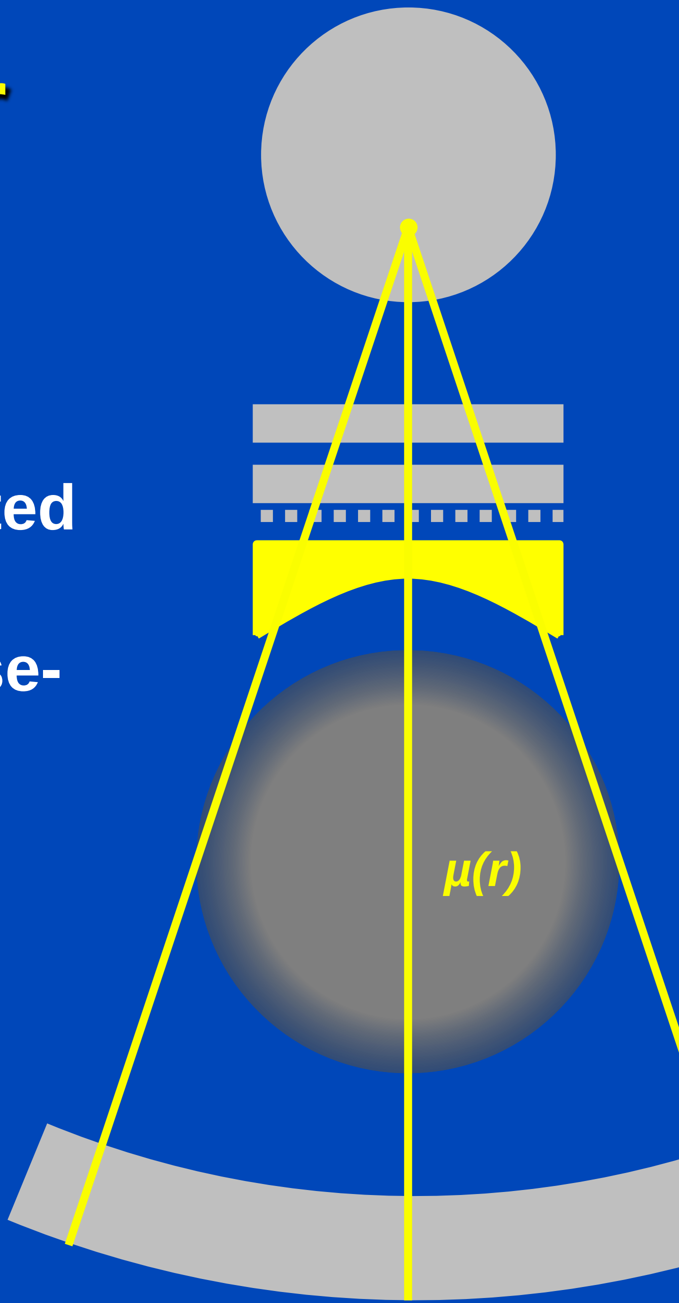
Bowtie Filter

- Also known as shaped filter or as form filter
- Optimized for a certain patient size
- Paediatric imaging requires dedicated (narrow) bowtie filter.
- Filter changer thus required for dose-efficient paediatric CT.





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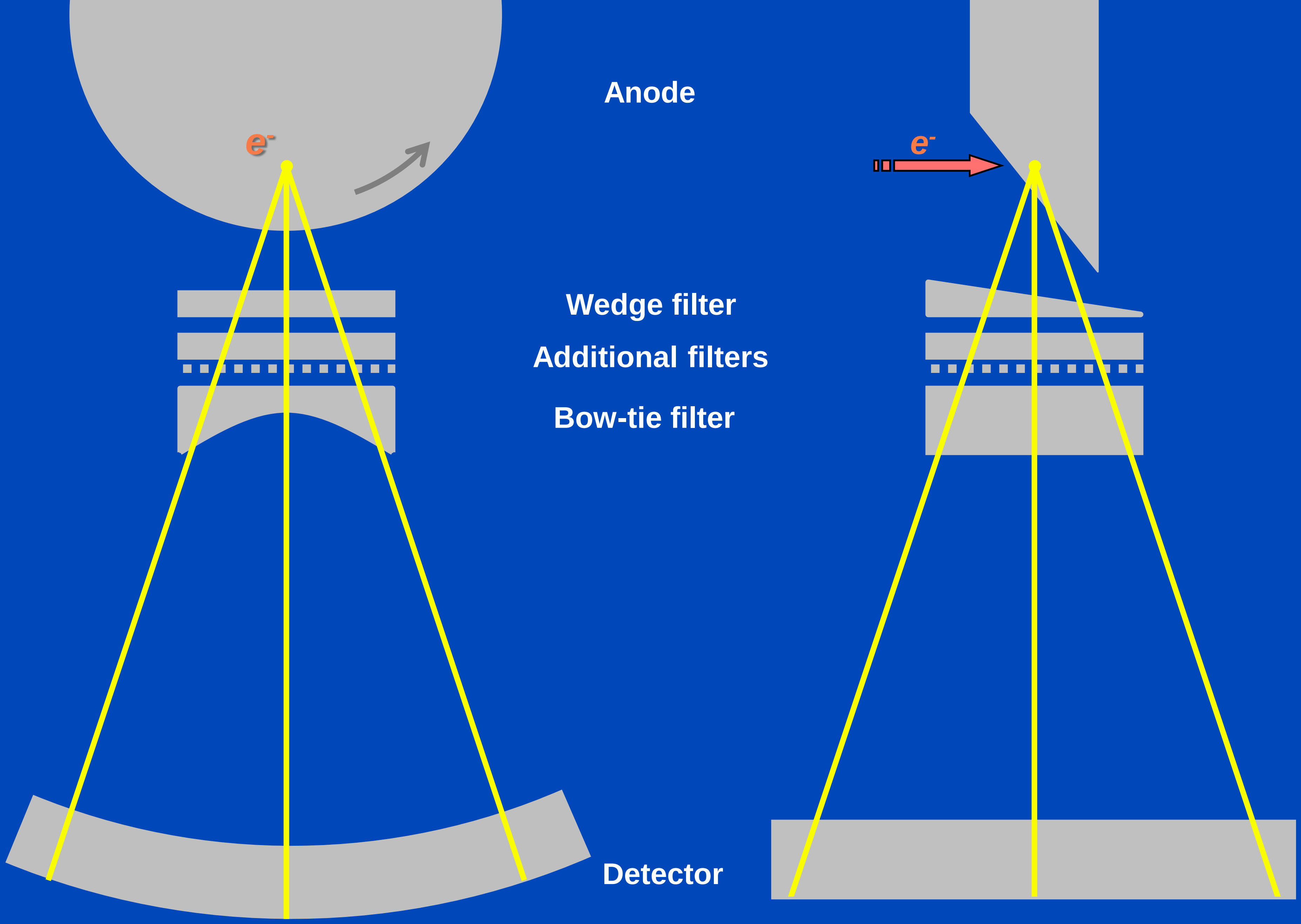

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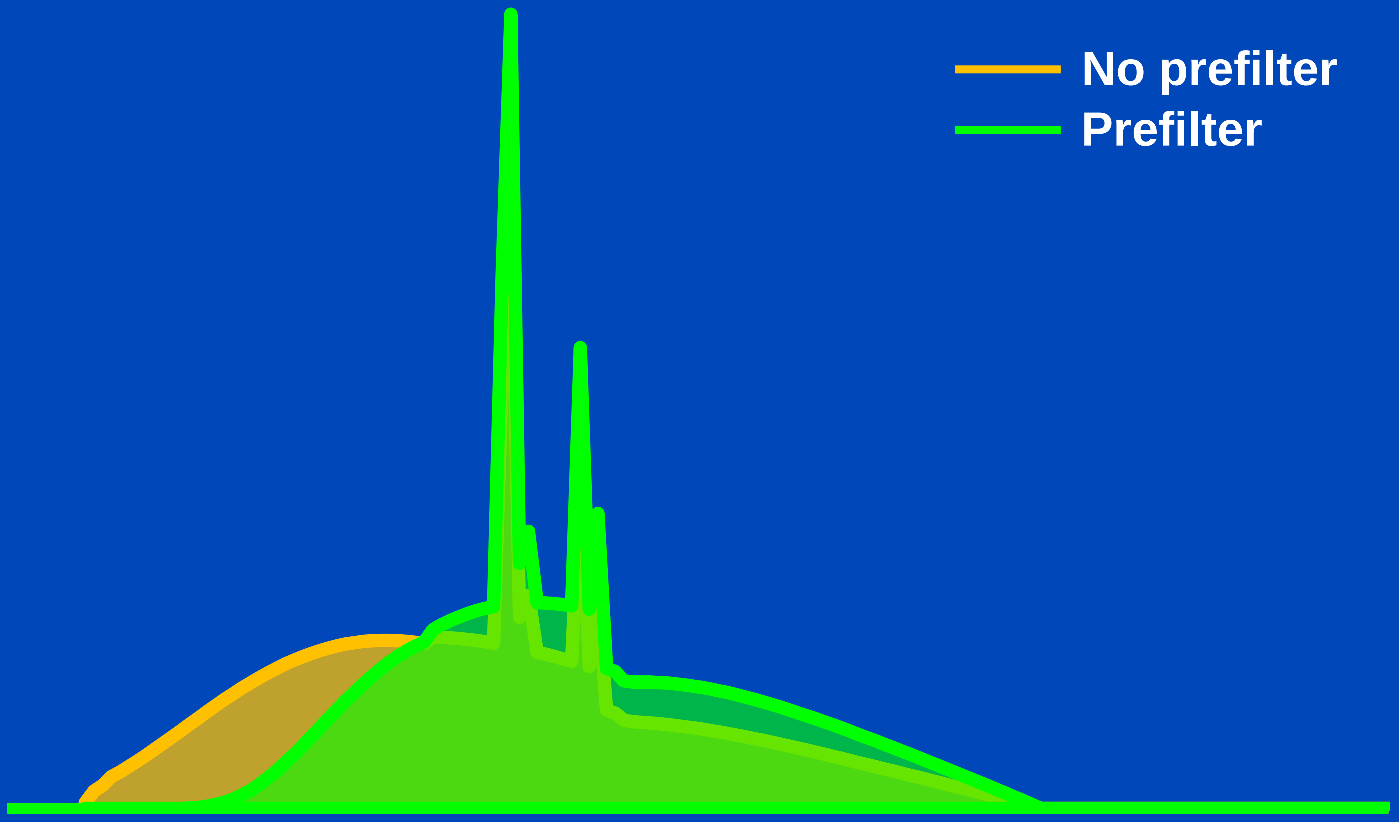
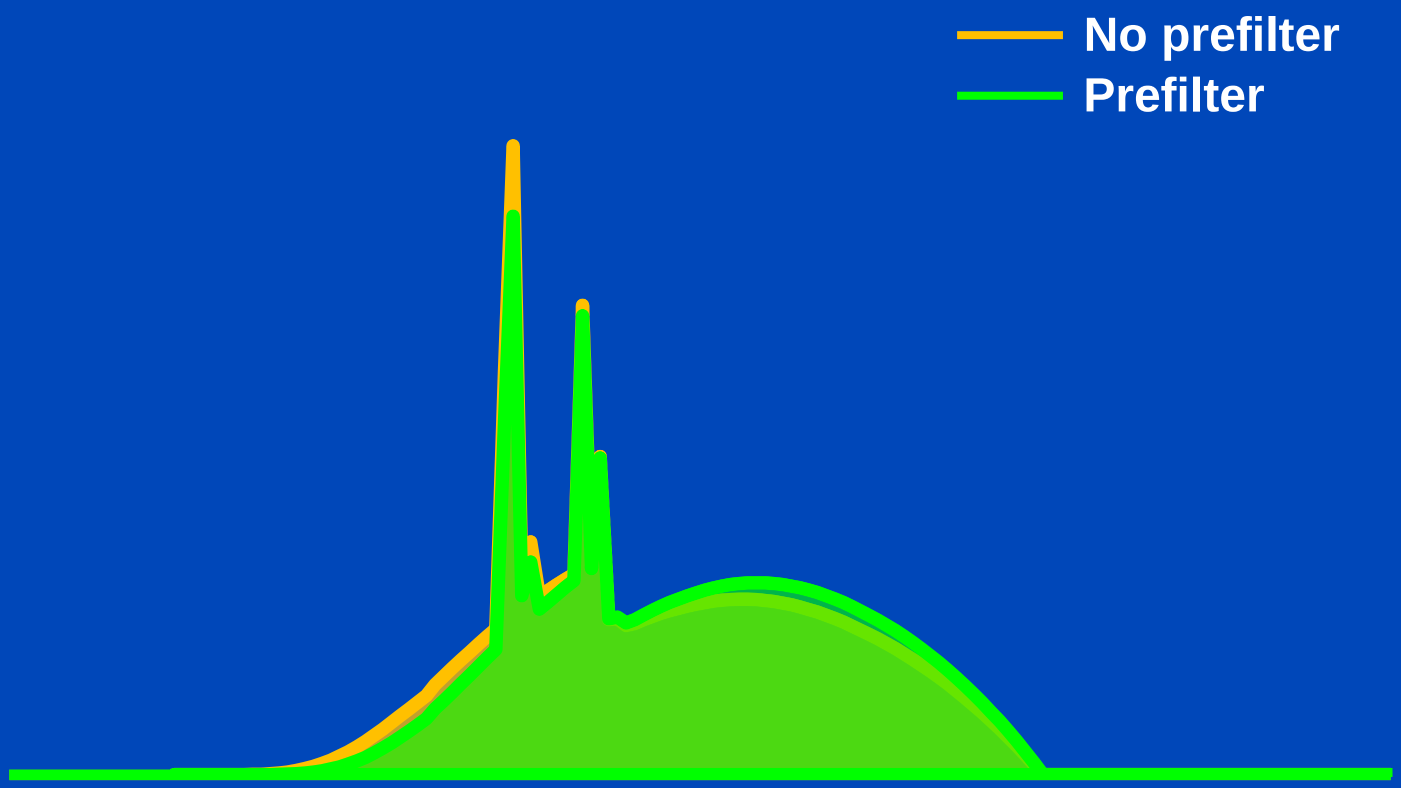
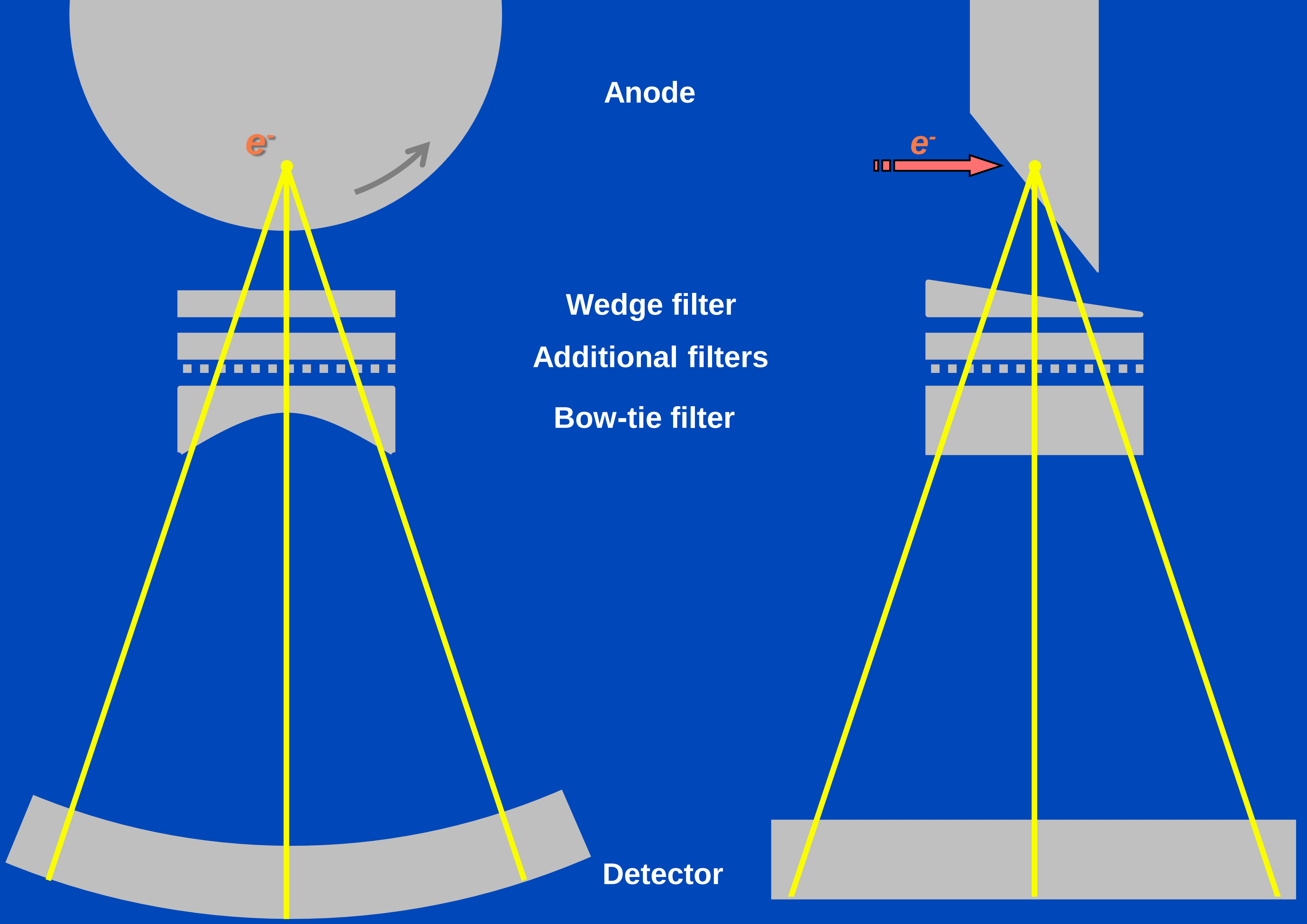
120 kV + 0 mm water with and without prefilter



120 kV + 320 mm water with and without prefilter





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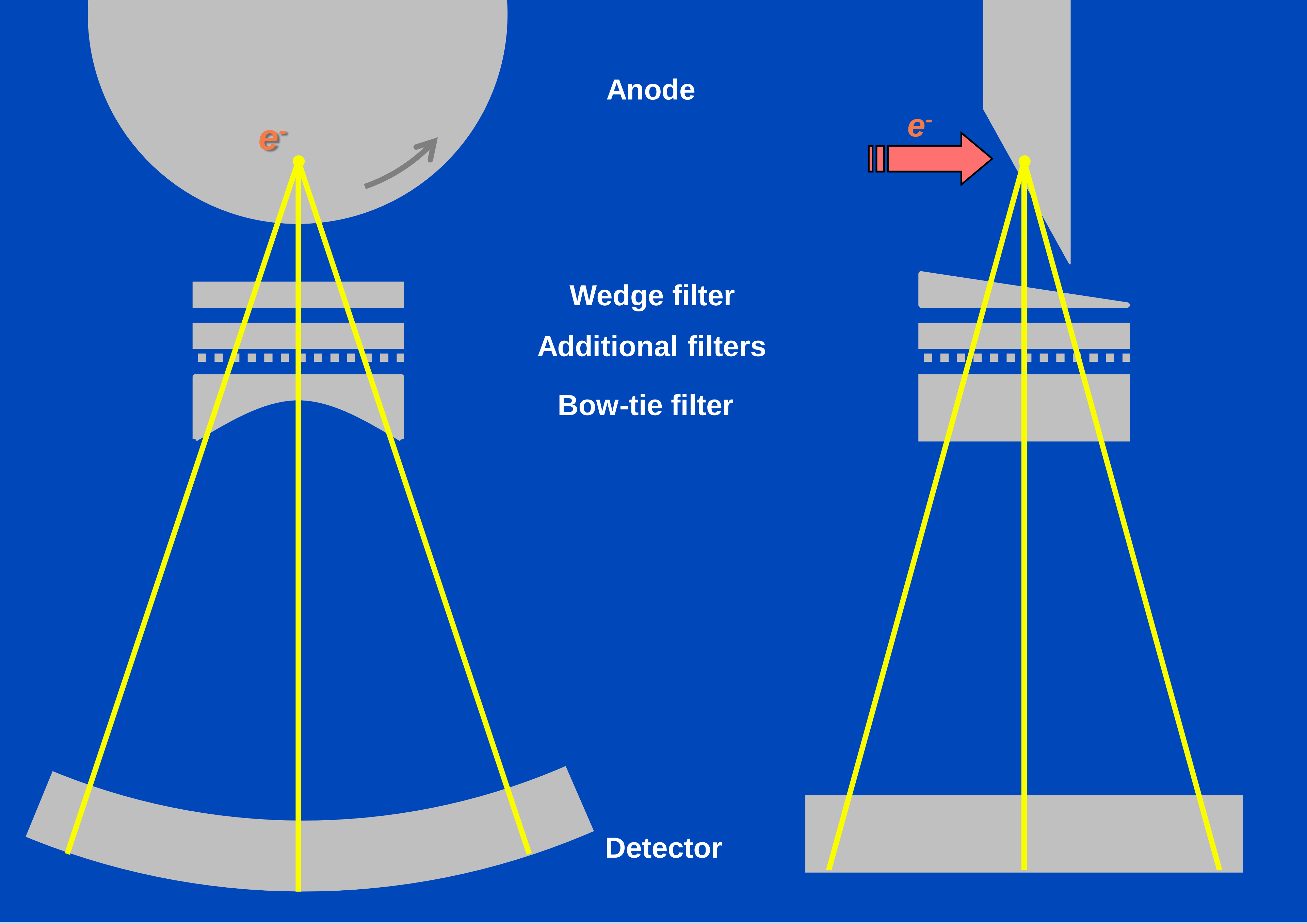
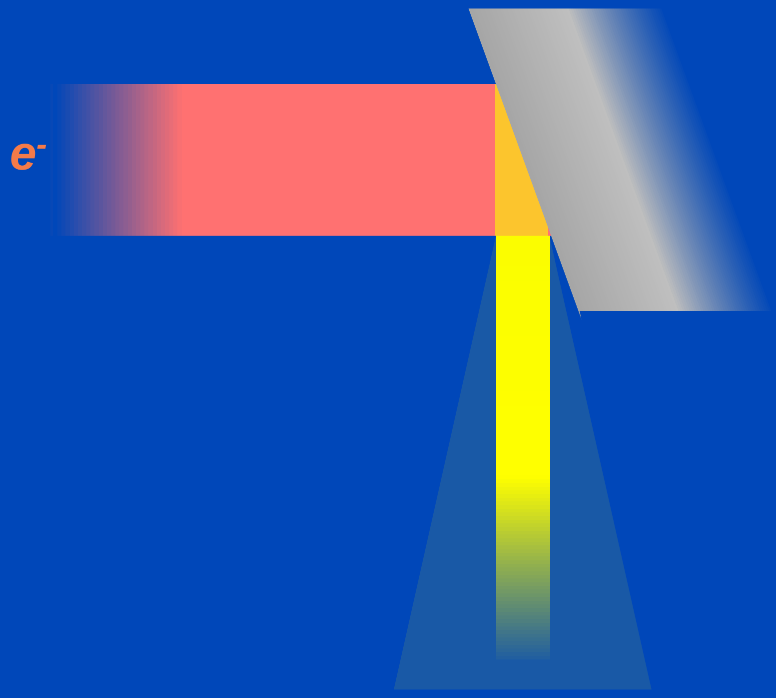
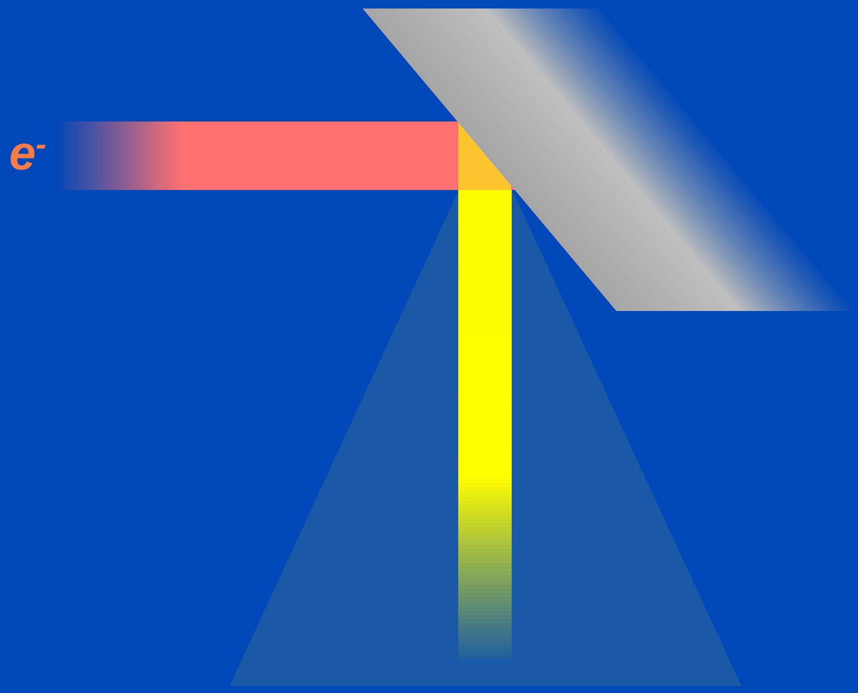


Figure not drawn to scale. Type and order of prefiltration may differ from scanner to scanner.
Depending on the selected protocol filters are changed automatically (e.g. small bowtie for pediatric scans).

Narrow Cone = High Tube Power

Wide Cone = Low Tube Power





… at the same spatial resolution

Onset of target melting (rule of thumb)[1]: 1 W/µm

[1] D.E. Grider, A. Writh, and P.K. Ausburn. Electron Beam Melting in Microfocus X-Ray Tubes. J. Phys. D: Appl. Phys 19:2281-2292, 1986

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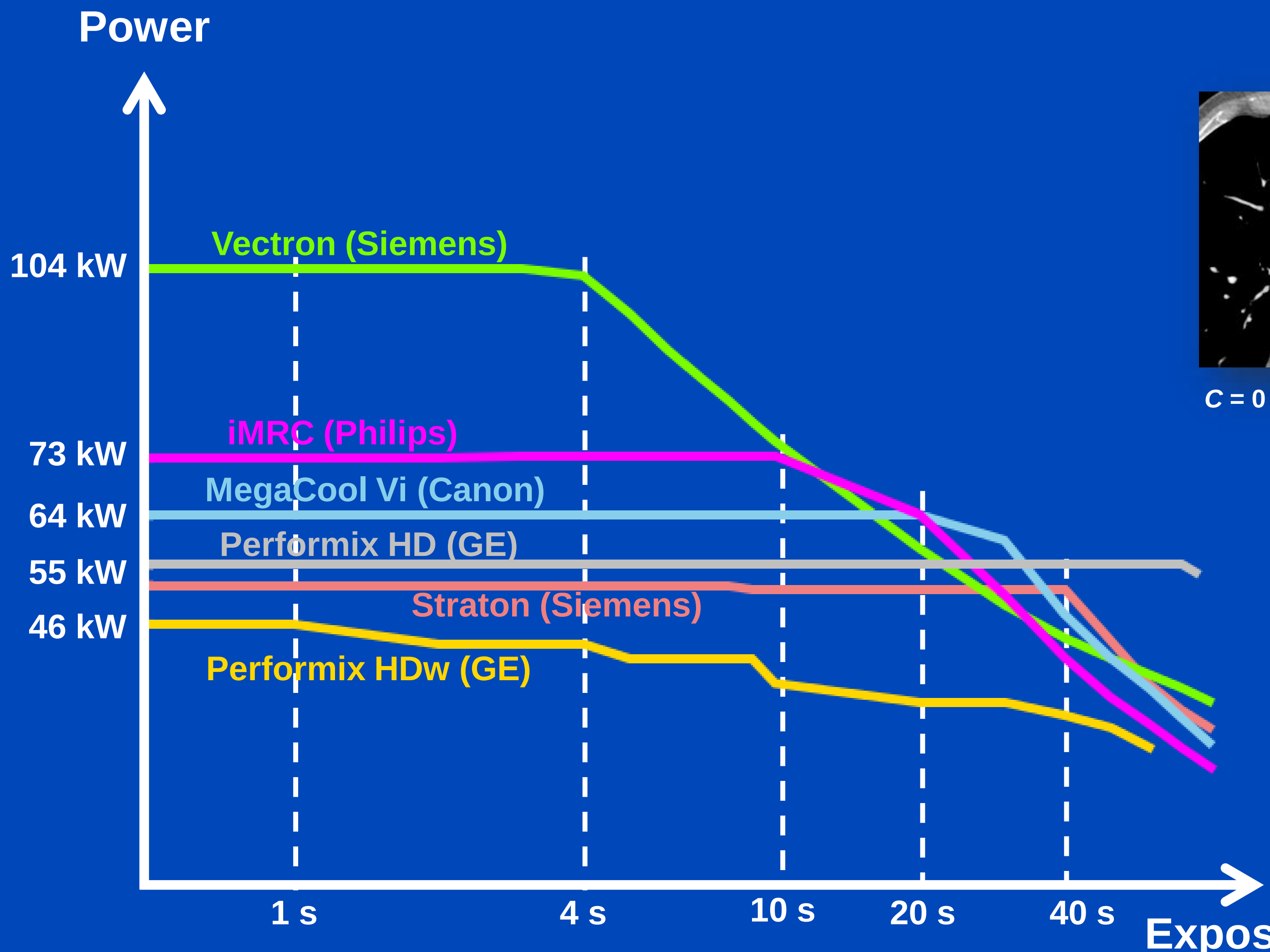
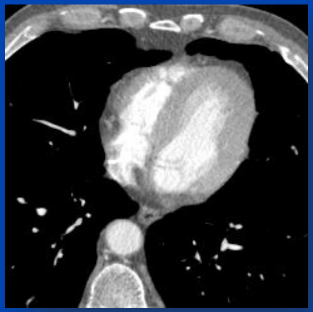
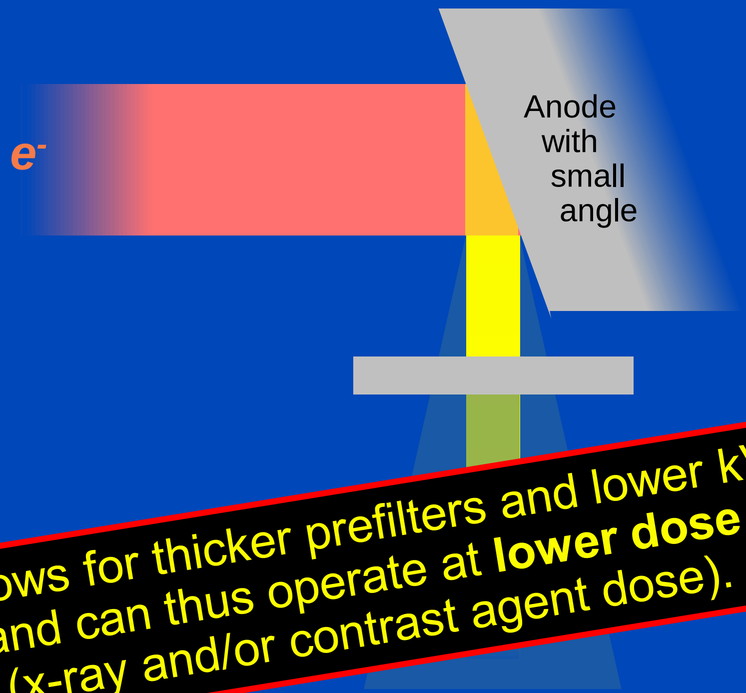
Tube Voltage 80 kV





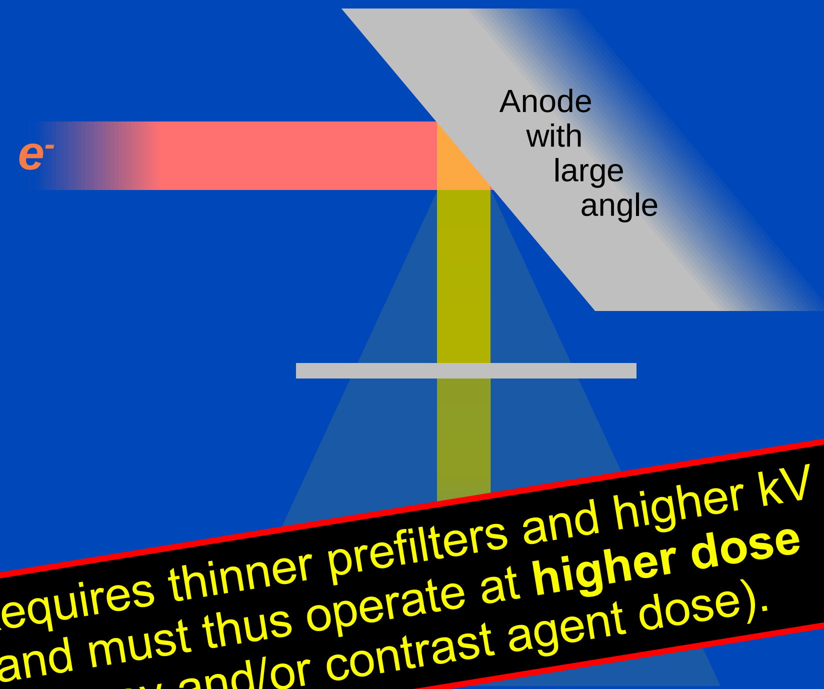
C = 0 HU, *W* = 700 HU

Narrow Cone = High Tube Power



Allows for thicker prefilters and lower kV and can thus operate at **lower dose** (x-ray and/or contrast agent dose).

Wide Cone = Low Tube Power



Requires thinner prefilters and higher kV and must thus operate at **higher dose** (x-ray and/or contrast agent dose).

… at the same spatial resolution

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LUNG CANCER SCREENING CT (selected SIEMENS scanners, continued)

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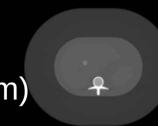
TOPOGRAM: PA; scan from top of shoulder through mid-liver.

SIEMENS	**Definition DS (Dual source 64-slice)**	**Somatom Drive (Dual source 128-slice)**	**Definition Flash (Dual source 128-slice)**	**Definition Force** (Dual source 192-slice)
Software version	VA44	VB10	VB10	VB10
Scan Mode	Spiral	Spiral	Spiral	Spiral
Rotation Time (s)	0.5	0.5	0.5	0.5
Detector Configuration	*64 × 0.6 mm (32 x 0.6 mm =19.2 mm)	*128 × 0.6 mm (64 x 0.6 mm = 38.4 mm)	*128 × 0.6 mm (64 x 0.6 mm = 38.4 mm)	*192 × 0.6 mm (96 x 0.6 mm = 57.6 mm)
Pitch	1.2	1.2	1.2	1.2
kV	120	100Sn	120	100Sn
Quality ref. mAs	20	81	20	101
CARE Dose4D	ON	ON	ON	ON
CARE kV	ON	ON	ON	ON
CTDIvol***	1.4 mGy	0.6mGy	1.3 mGy	0.4 mGy

RECON 1

Type	Axial	Axial	Axial	Axial
Kernel	B31f	Bf37, strength = 3**	Bf37, strength = 3**	Br40, strength = 3**
Slice (mm)	5.0	5.0	5.0	5.0
Increment (mm)	5.0	5.0	5.0	5.0

Dose Reduction by Patient-Specific Tin or Copper Prefilters[1,2]
1000 mAs Limit, 70-150 kV, 10 kV steps

	Child (15 cm × 10 cm) 	**Adult** (30 cm × 20 cm) 	**Obese** (50 cm × 40 cm) 
Soft tissue (basis)	30 mAs, 90 kV	100 mAs, 130 kV	600 mAs, 150 kV
Soft tissue, Sn	0.6 mm, 1000 mAs, 80 kV **14%** → 19%	1.0 mm, 1000 mAs, 120 kV **32%** → 36%	0.2 mm, 870 mAs, 150 kV **25%** → 57%
Soft tissue, Cu	1.6 mm, 1000 mAs, 70 kV **17%** → 19%	3.1 mm, 1000 mAs, 120 kV **31%** → 36%	0.8 mm, 1000 mAs, 150 kV **29%** → 57%
Iodine (basis)	50 mAs, 70 kV	120 mAs, 90 kV	720 mAs, 120 kV
Iodine, Sn	0 mm, 50 mAs, 70 kV **0%**	0.1 mm, 1000 mAs, 70 kV **40%**	0.0 mm, 1000 mAs, 110 kV **26%** → 79%
Iodine, Cu	0.1 mm, 58 mAs, 70 kV **3%**	0.4 mm, 1000 mAs, 70 kV **44%**	0.1 mm, 1000 mAs, 110 kV **28%** → 80%

[1]Steidel, Maier, Sawall, Kachelrieß. Tin or Copper Prefilters for Dose Reduction in Diagnostic Single Energy CT? RSNA 2020.
[2]Steidel, Maier, Sawall, Kachelrieß. Dose Reduction through Patient-Specific Prefilters in Diagnostic Single Energy CT. RSNA 2020.

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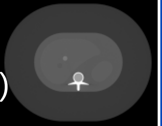
	Child (15 cm × 10 cm) 	**Adult** (30 cm × 20 cm) 	**Obese** (50 cm × 40 cm) 
Soft tissue (basis)	30 mAs, 90 kV	100 mAs, 130 kV	600 mAs, 150 kV
Soft tissue, Sn	0.6 mm, 1000 mAs, 75 kV **15%** → 19%	1.0 mm, 1000 mAs, 120 kV **32%** → 36%	0.2 mm, 1000 mAs, 150 kV **25%** → 57%
Soft tissue, Cu	1.6 mm, 1000 mAs, 70 kV **17%** → 19%	3.4 mm, 1000 mAs, 125 kV **31%** → 36%	0.8 mm, 1000 mAs, 150 kV **29%** → 57%
Iodine (basis)	50 mAs, 70 kV	120 mAs, 90 kV	720 mAs, 120 kV
Iodine, Sn	0 mm, 210 mAs, 50 kV **39%**	0.1 mm, 1000 mAs, 70 kV **40%** → 53%	0.0 mm, 1000 mAs, 105 kV **39%** → 81%
Iodine, Cu	0.4 mm, 1000 mAs, 50 kV **57%** → 67%	0.2 mm, 1000 mAs, 65 kV **49%** → 68%	0.0 mm, 1000 mAs, 105 kV **39%** → 89%

[1]Steidel, Maier, Sawall, Kachelrieß. Tin or Copper Prefilters for Dose Reduction in Diagnostic Single Energy CT? RSNA 2020.
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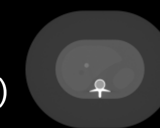
Child (15 cm × 10 cm) 			Adult (30 cm × 20 cm) 			Obese (50 cm × 40 cm) 		
	90 kV (basis)	optimal voltage		130 kV (basis)	optimal voltage		150 kV (basis)	optimal voltage
no filter (basis)	0%	0%	no filter (basis)	0%	1%	no filter (basis)	0%	0%
optimal Sn/Cu filter	12% / 12%	15% / 17%	optimal Sn/Cu filter	31% / 30%	32% / 31%	optimal Sn/Cu filter	25% / 29%	25% / 29%
	70 kV (basis)	optimal voltage		90 kV (basis)	optimal voltage		120 kV (basis)	optimal voltage
no filter (basis)	0%	39%	no filter (basis)	0%	40%	no filter (basis)	0%	26%
optimal Sn/Cu filter	0% / 3%	39% / 57%	optimal Sn/Cu filter	0%	40% / 49%	optimal Sn/Cu filter	0%	26% / 28%

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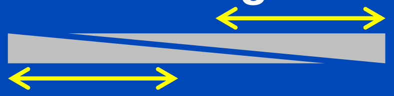
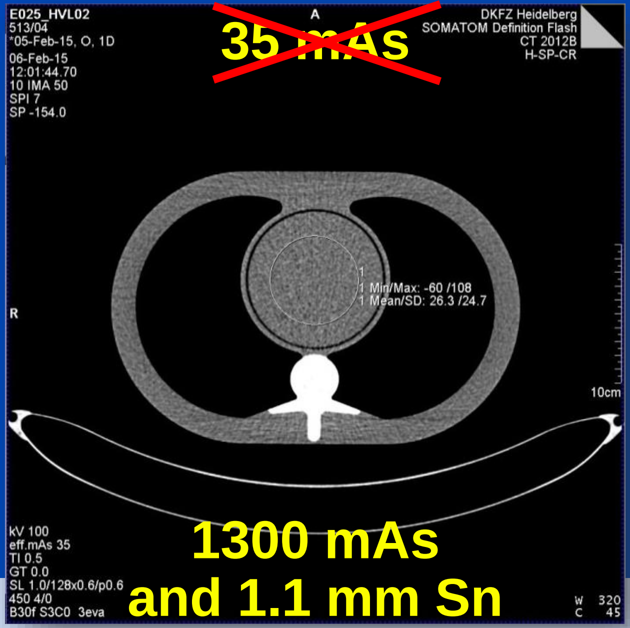
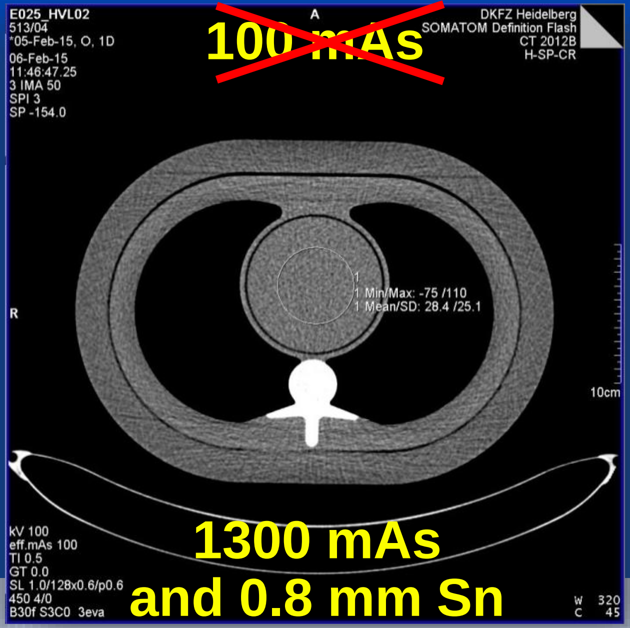
Prefilters

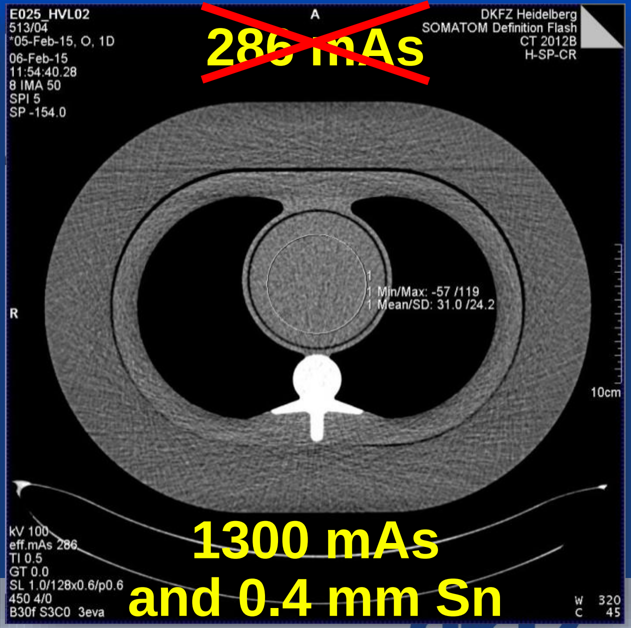
- **We want**
  - a filter changer with, say, 10 different filters, or a sliding double wedge
  - tubes with much higher power and lower kV
  - to always operate the tube close to its power limit
  - to adjust the filter thickness and kV to the patient, not the mAs
  - copper instead of tin



- **We get**
  - a significant dose reduction
  - improved image quality





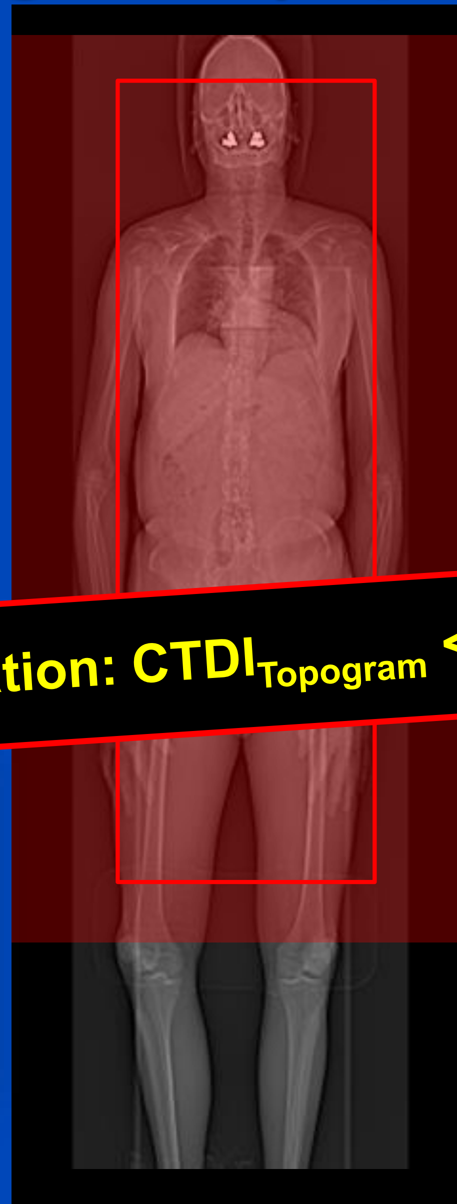


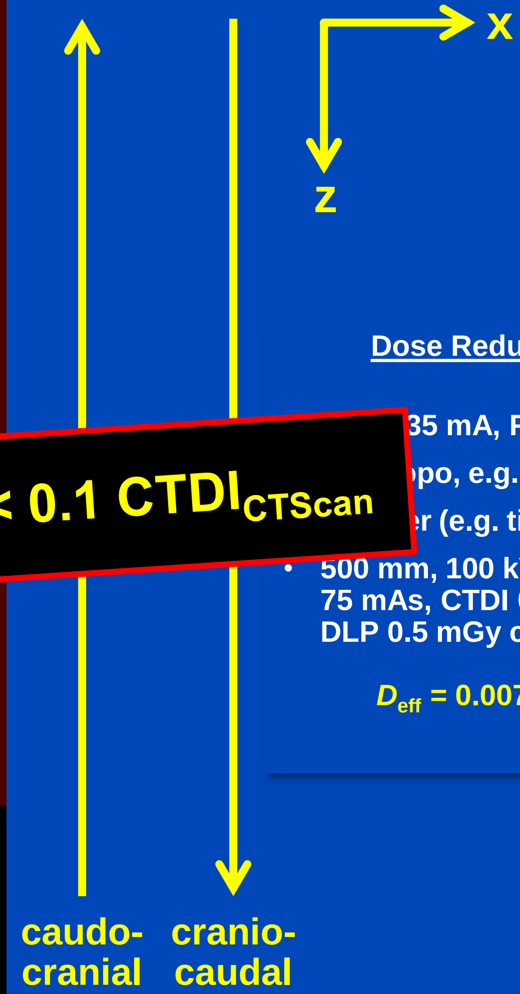
Topogram (a.p. view)

Dose consideration:

- 10 cm/s table speed and 6×0.6 mm collimation imply 36 ms exposure per z-position.
- At 120 kV and 6×0.6 mm the Flash 32 cm CTDI is 11 mGy/100 mAs.
- With 35 mA tube current and 36 ms exposure we obtain 1.3 mAs and 0.14 mGy CTDI.
- Assume a scan length of 50 cm to get DLP = 7 mGy cm.
- With *k* = 0.014 mSv/mGy/cm (chest) we obtain an effective dose of 0.1 mSv.

Protocol type	Head		
Shaped filter	Standard	Standard	Narrow
Phantom size	Ø 16 cm	Ø 32 cm	Ø 32 cm
	$CTDI_{vol}$ µGy/mA	$CTDI_{vol}$ µGy/mA	$CTDI_{vol}$ µGy/mA
70 kV	1.7	0.7	0.6
80 kV	2.6	1.2	0.9
100 kV	5.2	2.4	2.0
120 kV	8.3	4.0	3.3
140 kV	11.9	5.8	5.1





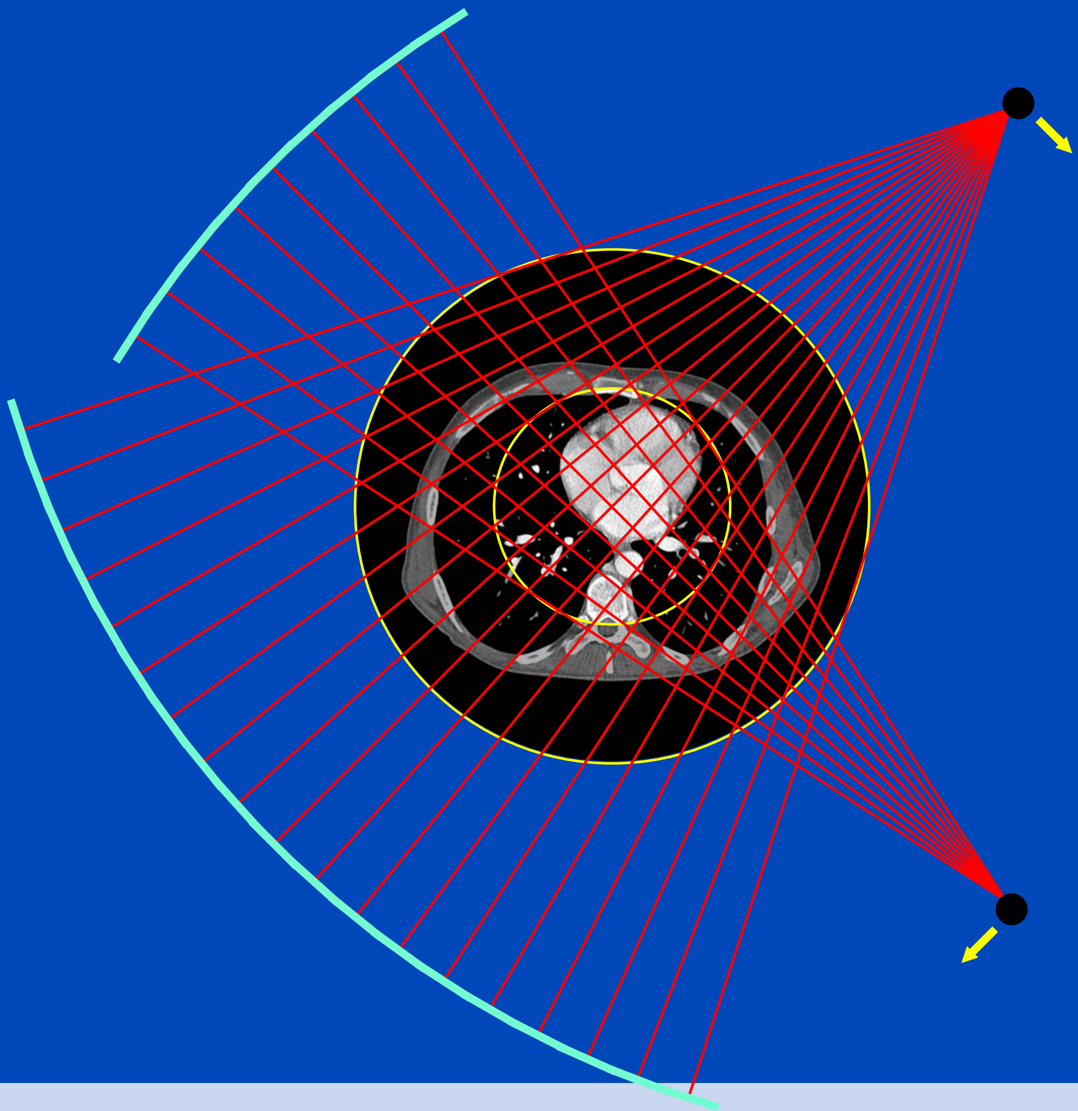
My Recommendation: $CTDI_{Topogram} < 0.1\ CTDI_{CTScan}$

Dose Reduction?

35 mA, Force 20 mA
po, e.g. 20 cm/s
r (e.g. tin)
- 500 mm, 100 kV Sn, 75 mAs, CTDI 0.01 mGy, DLP 0.5 mGy cm:

D_{eff} = 0.007 mSv

Multi-Threaded CT Scanners and Dual-Source-CT



Siemens SOMATOM Force
dual source cone-beam spiral CT

Very Fast Scanning: no Sedation, no Motion Artifacts

Procedure:
Transcatheter aortic valve implantation (TAVI)

Patient age: 80 years

Tube voltage: 80 kV
Current: 340 ref mAs/rot

Rotation time: 0.25 s
Pitch: 3.2
Slice thickness: 0.75 mm
Scan length: 557 mm
Scan time: 0.76 s
Scan speed: 737 mm/s

Kernel : B40
Recon: ADMIRE 3

CTDIvol: 2.7 mGy
DLP: 162 mGy·cm
Effective dose: 2.3 mSv

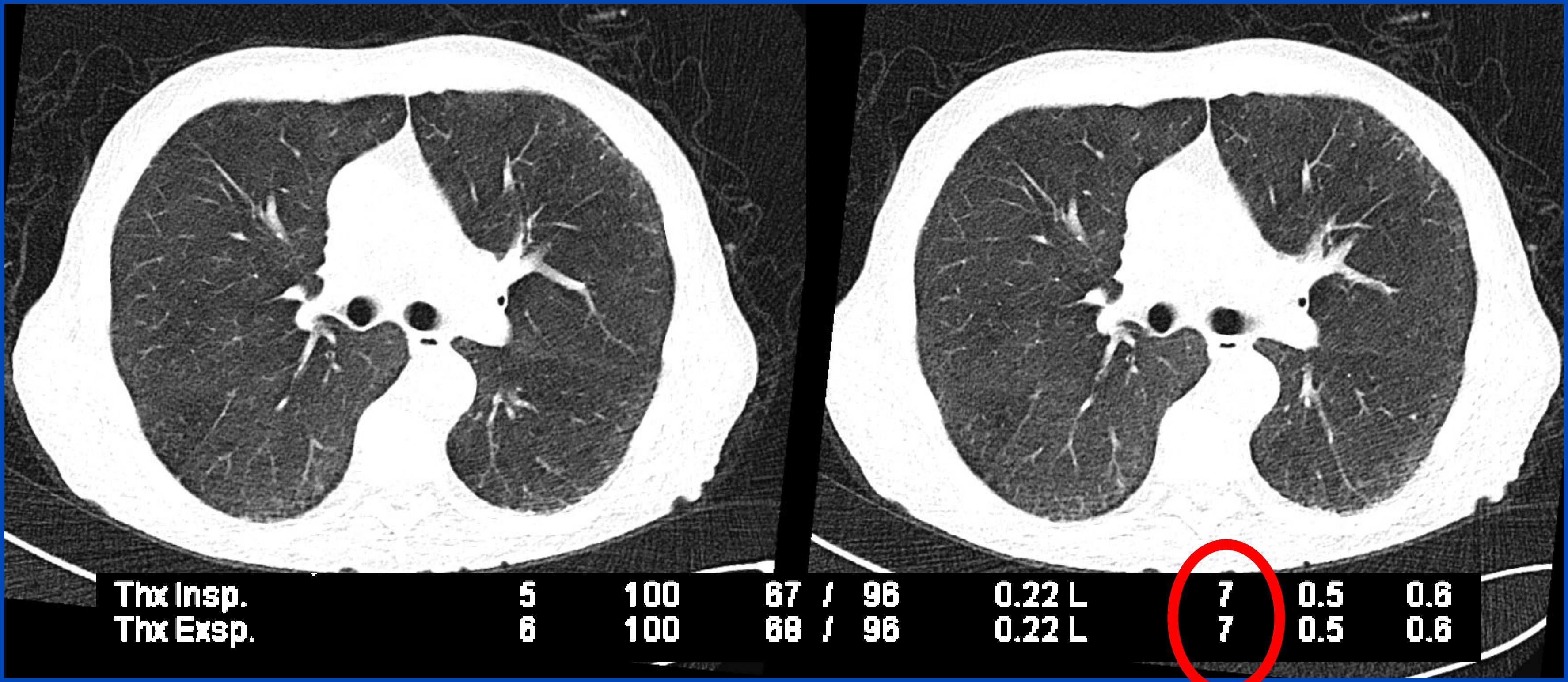
Case information

Axial slices, *C* = 0 HU, *W* = 1500 HU

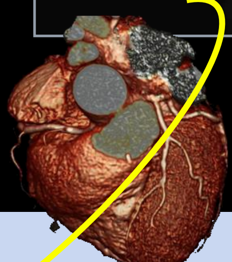
Volume rendering

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 per scan



Courtesy of University Hospital Mannheim



Courtesy of Armed Police Forces Center/ Beijing, China

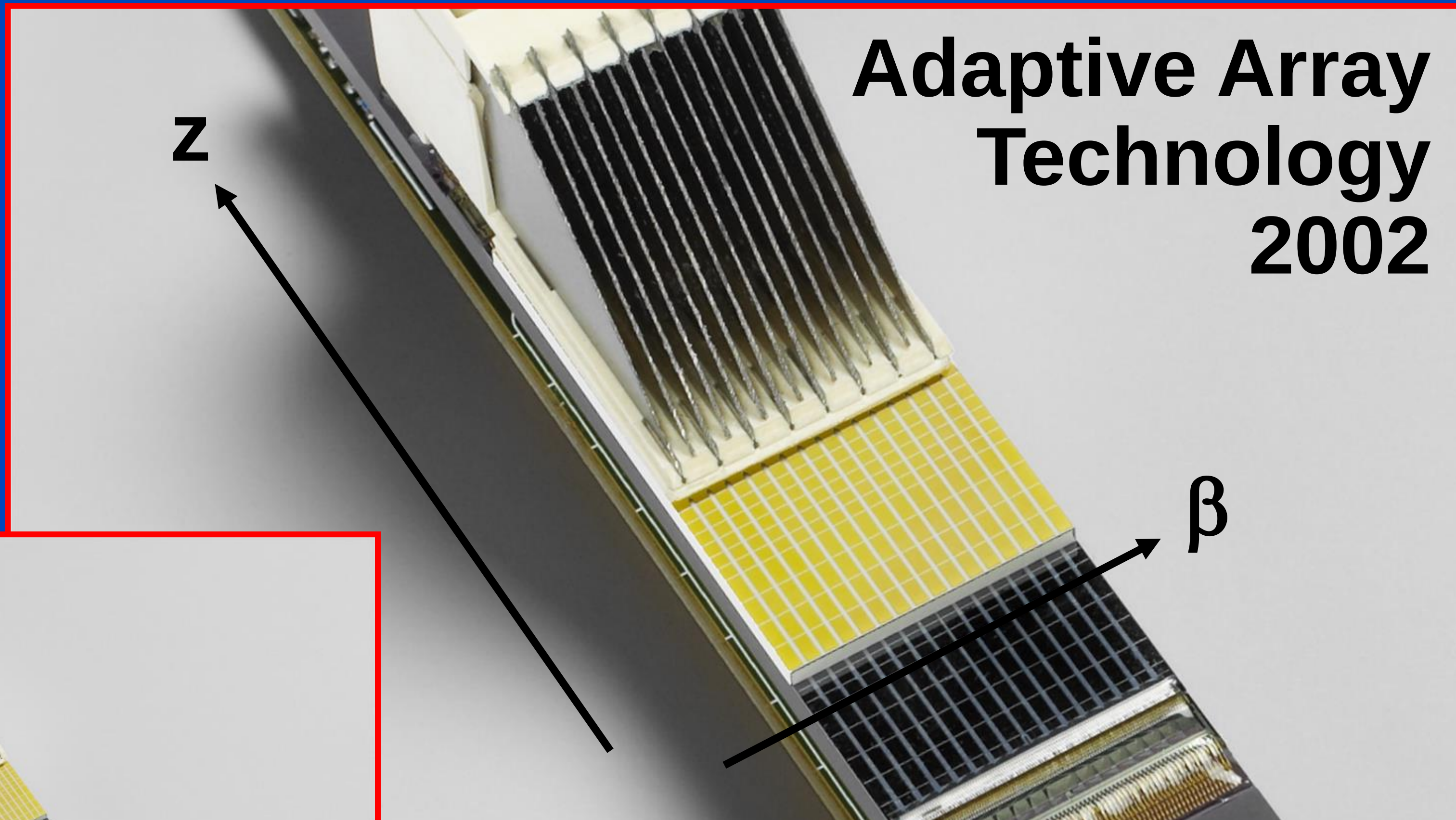
Child, 12 months

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

Adaptive Array Technology 2002



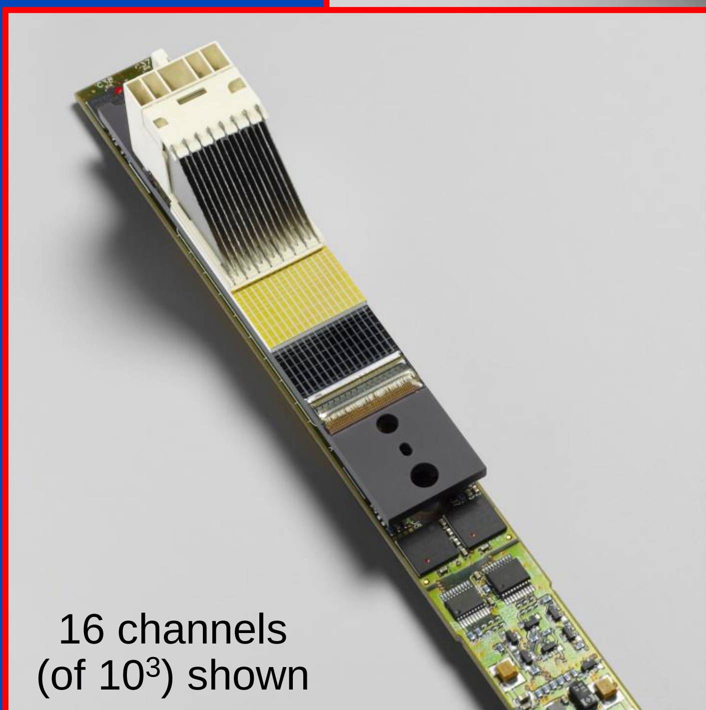
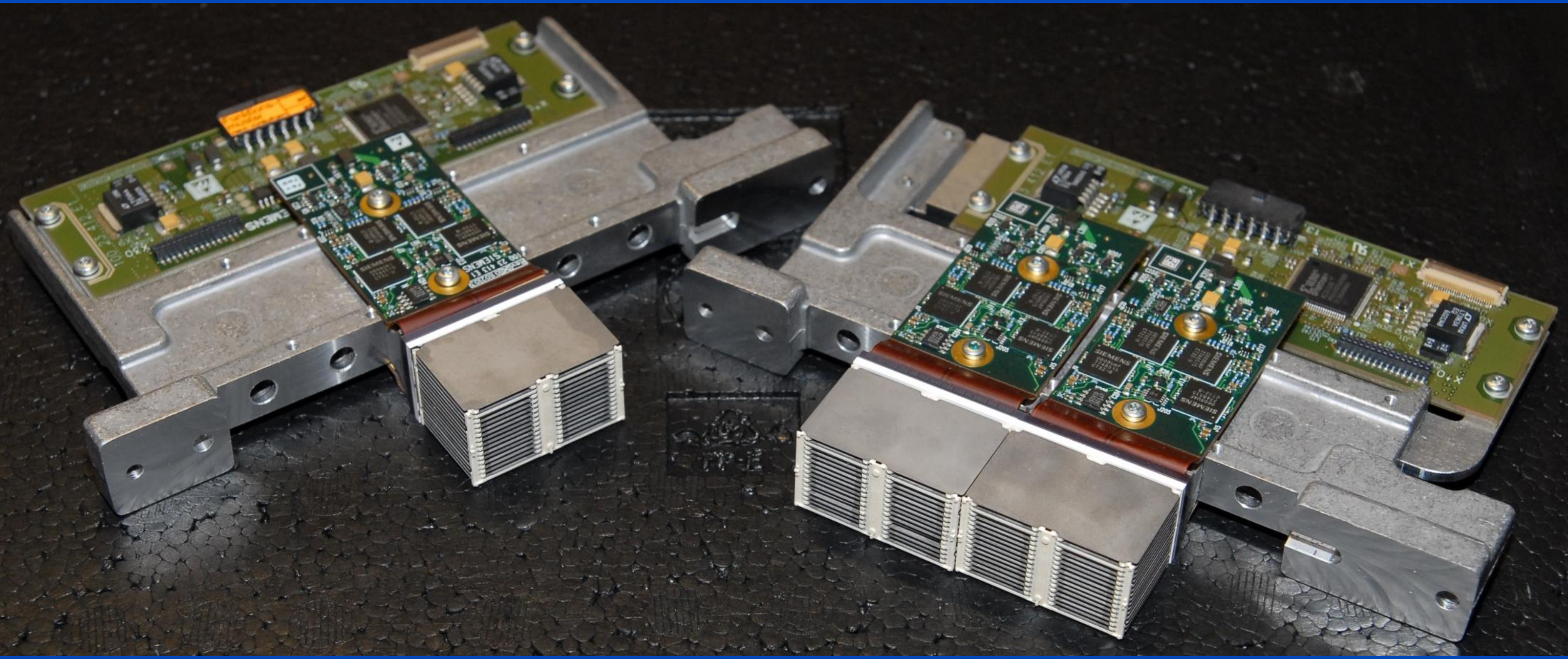


Photo courtesy of Siemens Healthcare, Forchheim, Germany

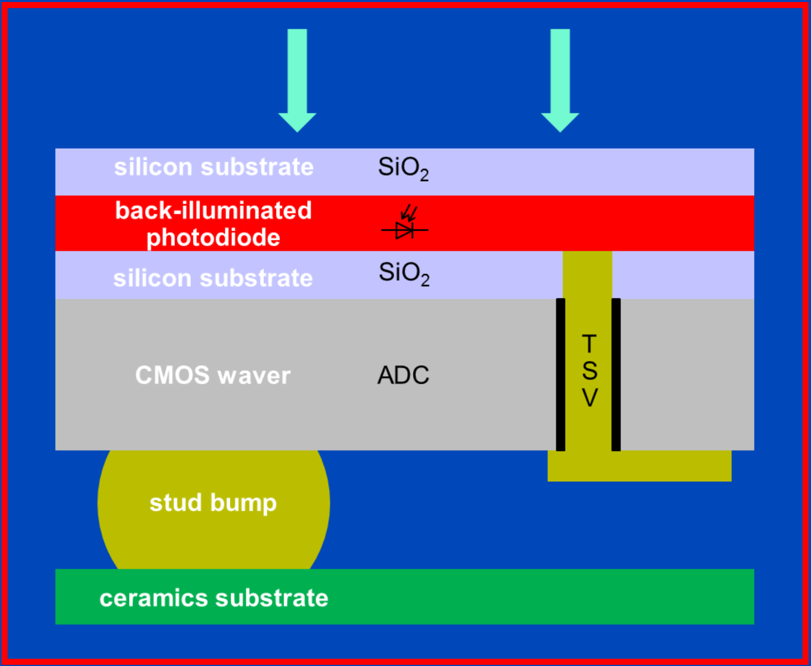


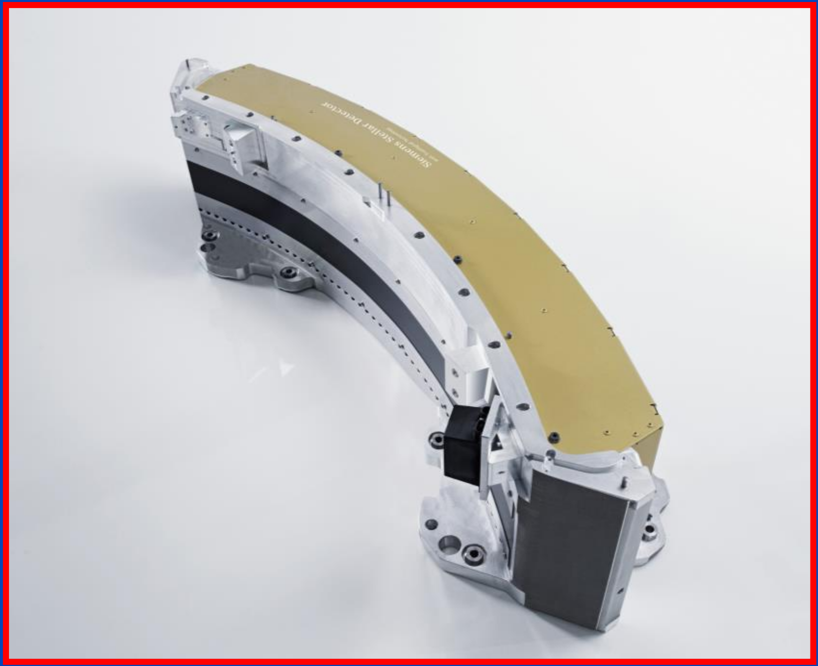
modular and 2D tileable, 1D anti-scatter grid,
modules arranged on the surface of a cylinder segment
(Photo courtesy by Siemens)

dkfz.

Fully Integrated Detector Electronics

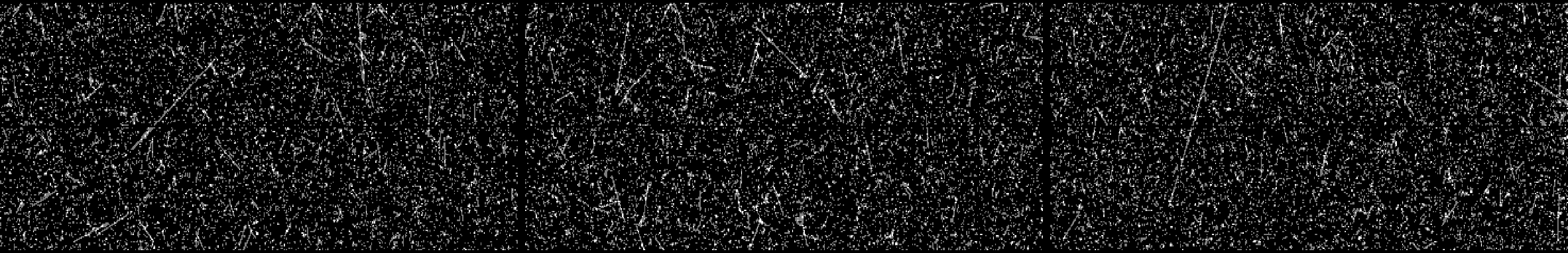
- Electronics fully integrated into detector
- Very low electronic noise
- Less dose for infants, better images for obese





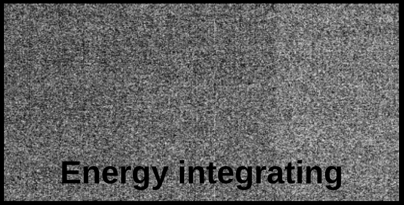
“Stellar detector”, modular and 2D tileable, focussed 2D anti scatter grid. Photo courtesy by Siemens.

Photon Counting Detectors

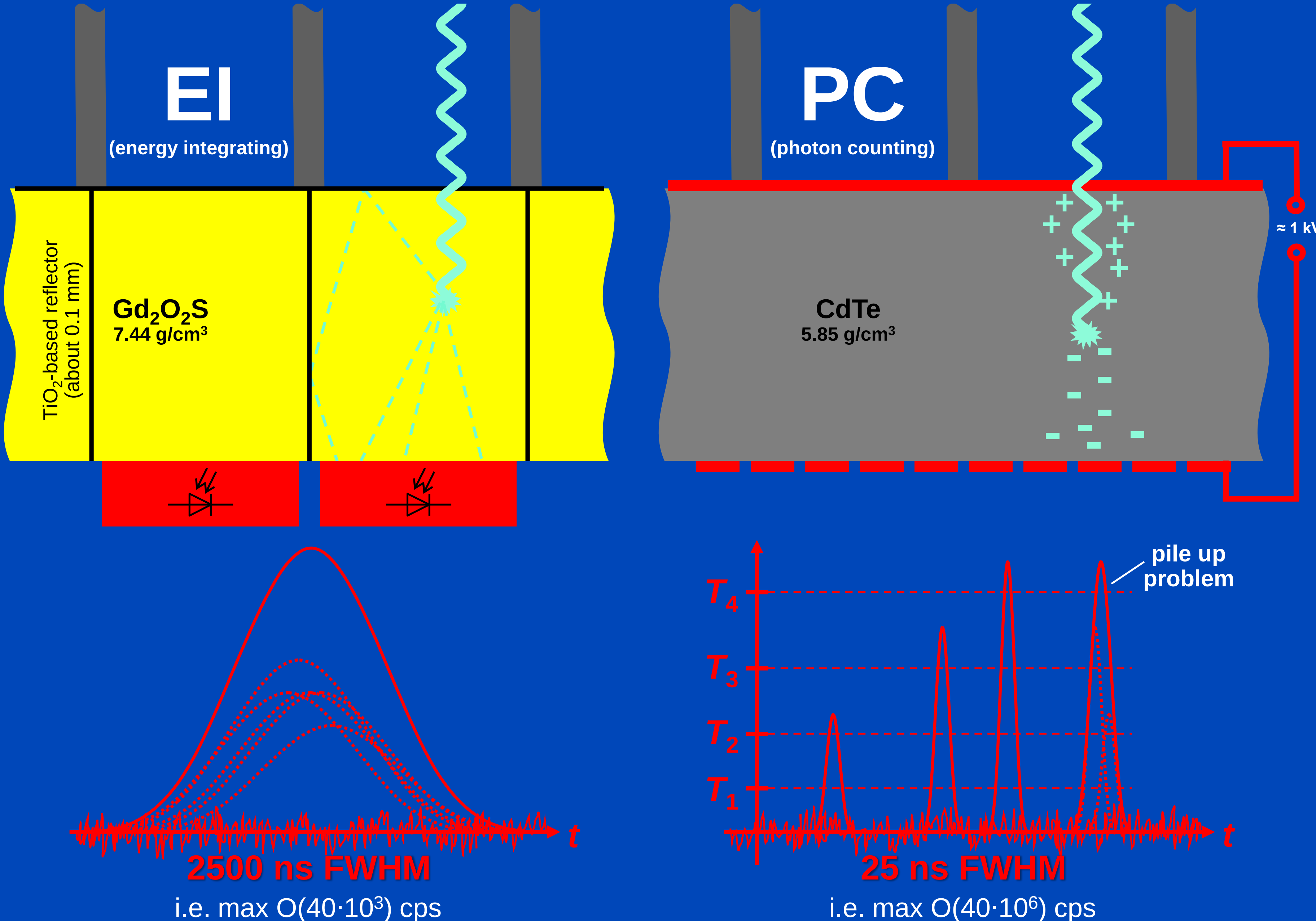


Photon counting (here: Dectris detector), C/W=1 cnts/2 cnts

X-rays are off!



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.

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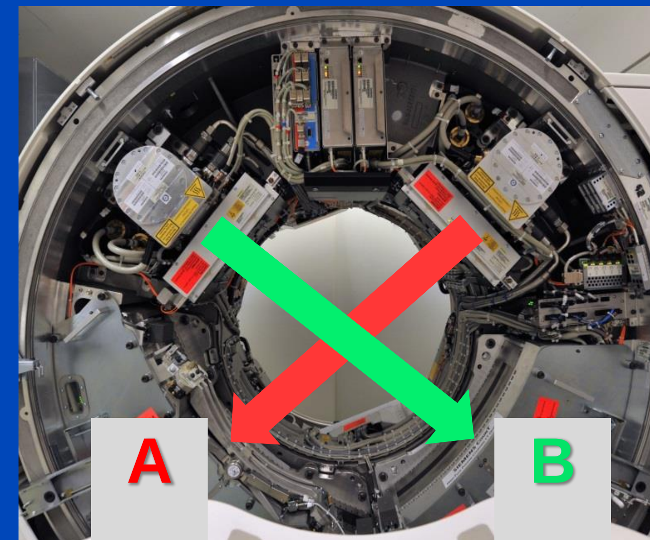
Siemens CounT CT System

Gantry from a clinical dual source scanner

A: conventional CT detector (50.0 cm FOV)

B: Photon counting detector (27.5 cm FOV)

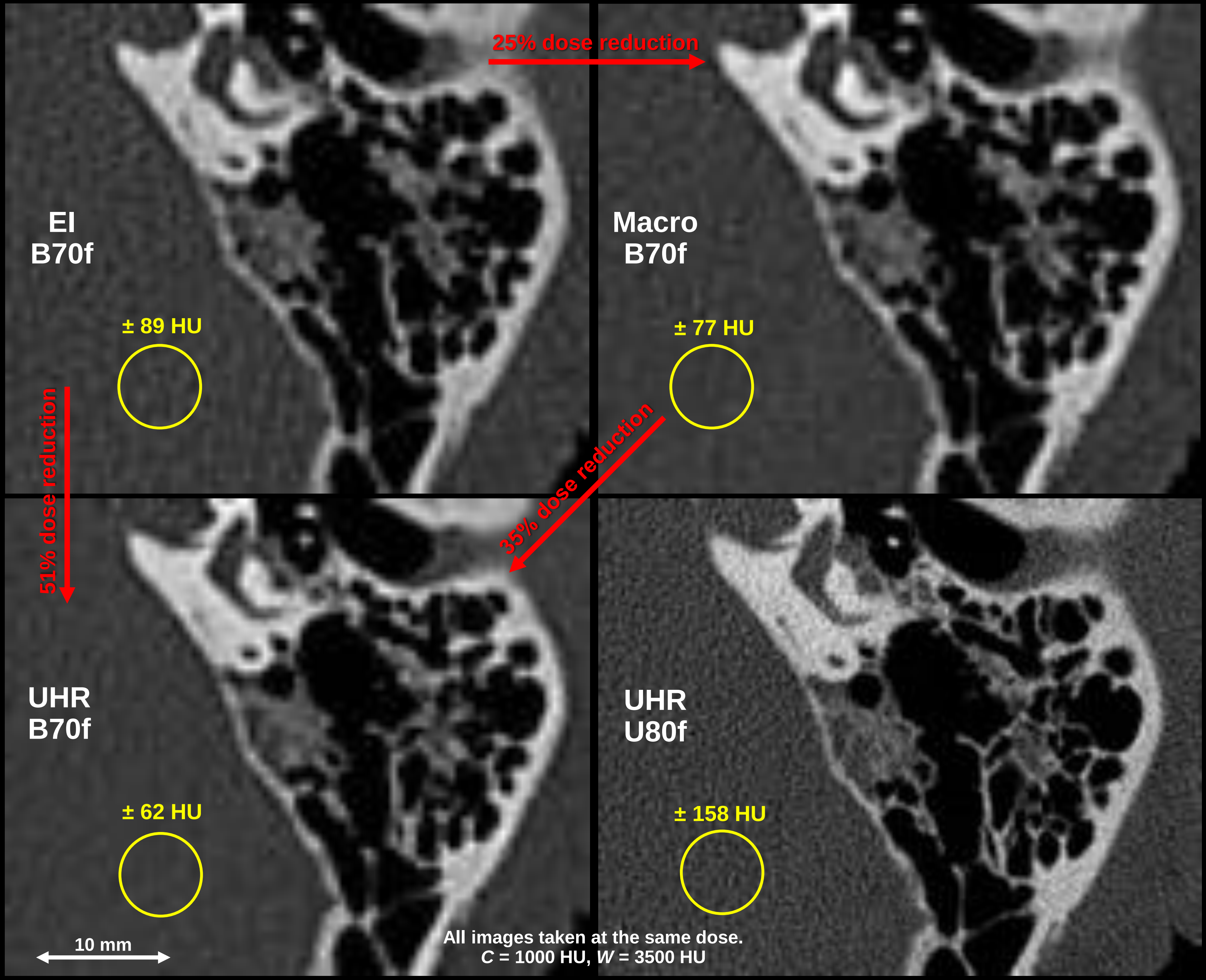


Readout Modes of the CounT

PC-UHR Mode	**PC-Macro Mode**	**EI detector**
0.25 mm pixel size	0.50 mm pixel size	0.60 mm pixel size

Advantages of Photon Counting CT

- No reflective gaps between detector pixels
  - Higher geometrical efficiency
  - Less dose
- No electronic noise
  - Less dose for infants
  - Less noise for obese patients
- Counting
  - Swank factor = 1 = maximal
  - "Iodine effect" due to higher weights on low energies
- Energy bin weighting
  - Lower dose/noise
  - Improved iodine CNR
- Smaller pixels (to avoid pileup)
  - Higher spatial resolution
  - "Small pixel effect" i.e. lower dose/noise at conventional resolution
- Spectral information on demand
  - Dual Energy CT (DECT)
  - Multi Energy CT (MECT)

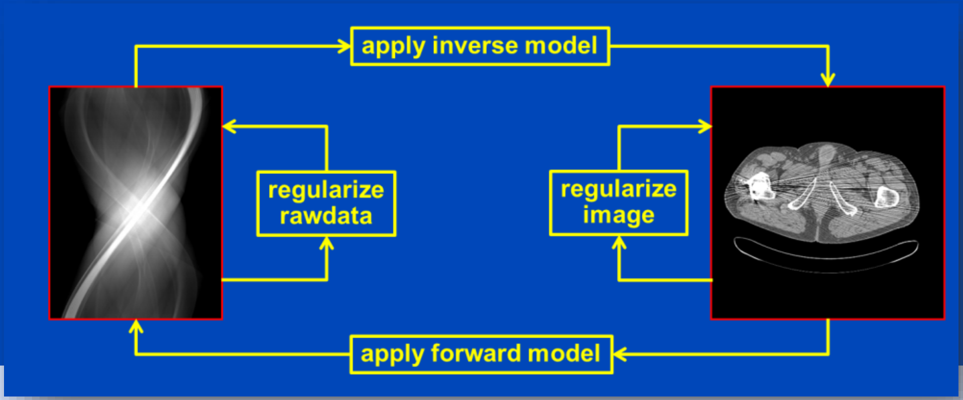

25% dose reduction
EI
B70f
± 89 HU
Macro
B70f
± 77 HU
51% dose reduction
35% dose reduction
UHR
B70f
± 62 HU
UHR
U80f
± 158 HU
10 mm
All images taken at the same dose.
C = 1000 HU, W = 3500 HU

Iterative Reconstruction

- Aim: less artifacts, lower noise, lower dose
- Iterative reconstruction
  - Reconstruct an image.
  - Does the image correspond to the rawdata?
  - If not, reconstruct a correction image and continue.
- CT product implementations
  - AIDR 3D (adaptive iterative dose reduction, Canon)
  - ASIR (adaptive statistical iterative reconstruction, GE)
  - iDose (Philips)
  - IRIS (image reconstruction in image space, Siemens)
  - FIRST (forward projected model-based iterative reconstruction solution, Canon)
  - VEO, MBIR (model-based iterative reconstruction, GE)
  - IMR (iterative model reconstruction, Philips)
  - SAFIRE, ADMIRE (advanced modeled iterative reconstruction, Siemens)

Premium Recon Algorithms 2018/2019

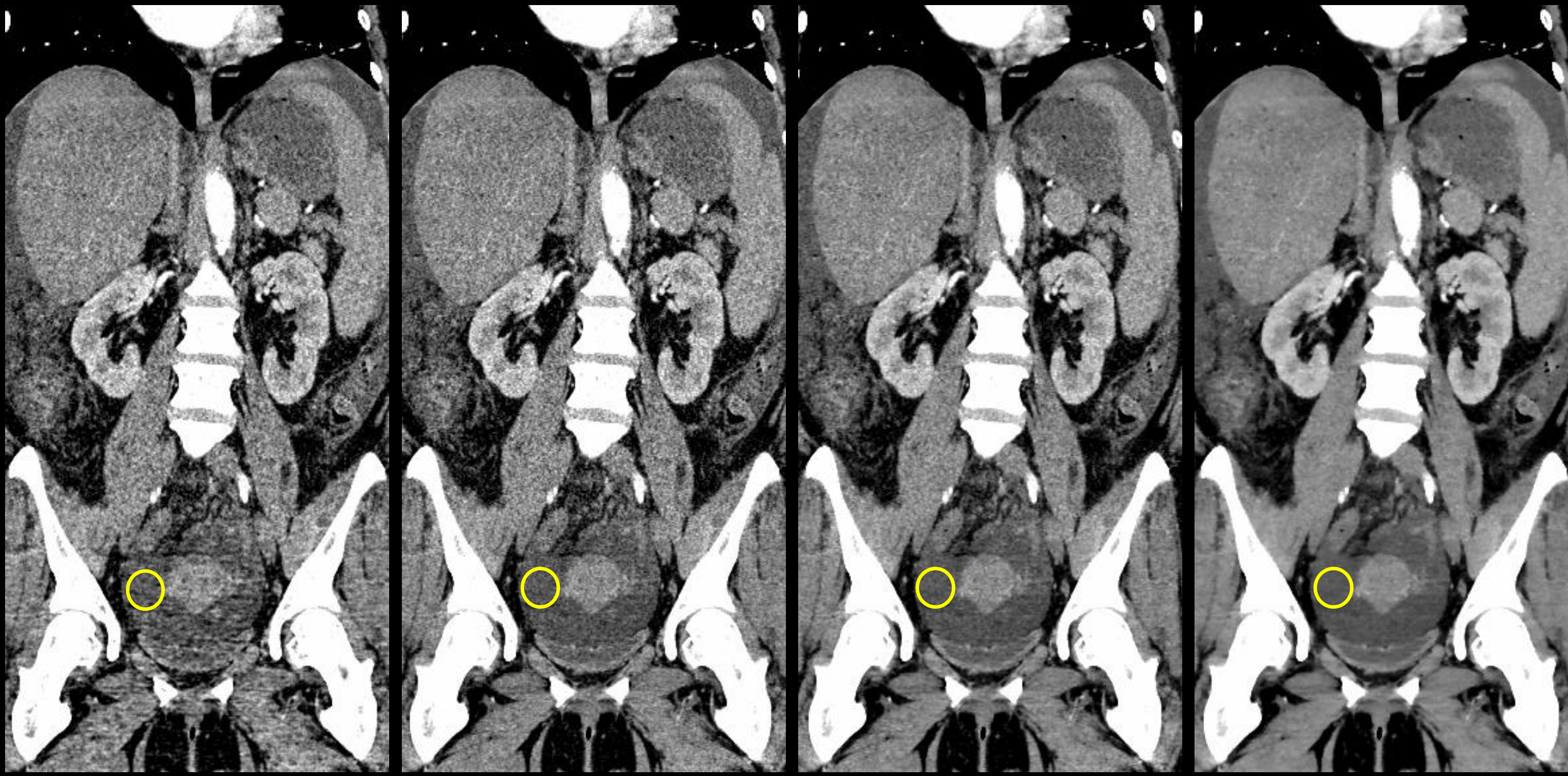
Vendor	Algorithm	Additional parameters	Sinogram restoration	Image restoration	Full iterations	Deep learning
all	FBP	-	✓	-	-	-
Canon	AIDR-3D enhanced FIRST AiCE	Body, Bone, Brain, Cardiac, Lung each with Mild, Standard, or Strong	✓ ✓ ?	✓ ✓ ✓	- ✓ -	- - ✓
GE	ASIR, ASIR-V True Fidelity	0 – 100% (e.g. ASIR 30%) ???	✓ ?	✓ ✓	- -	- ✓
Philips	iDose IMR	Levels 1 – 7 Soft, Routine, or SharpPlus	✓ ?	✓ ?	- ?	- -
Siemens	IRIS SAFIRE ADMIRE	Strength 1 – 5 Strength 1 – 5 Strength 1 – 5	✓ ✓ ✓	✓ ✓ ✓	- ✓ ✓	- - -



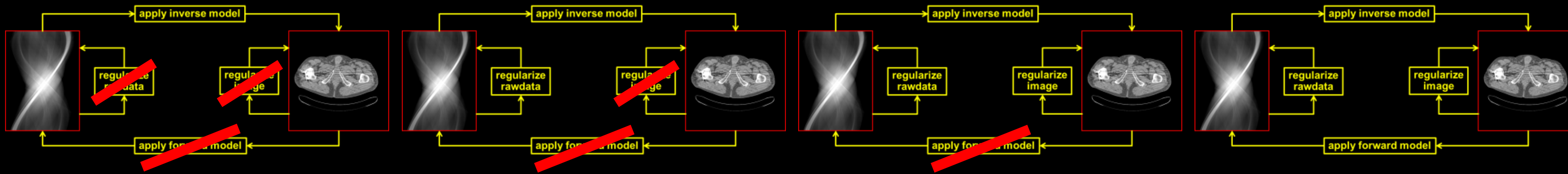
M. Lell and M. Kachelrieß. Recent and upcoming technological developments in CT. Invest. Radiol. Feb. 2020

dkfz.

Plain FBP	Siemens Standard	IRIS VA34	SAFIRE VA40

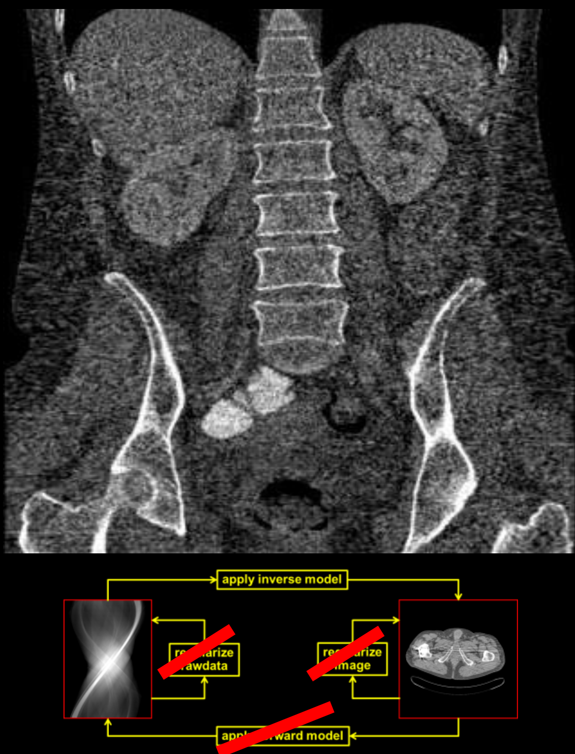


σ = 26.8 HU	σ = 17.6 HU	σ = 12.3 HU	σ = 7.8 HU

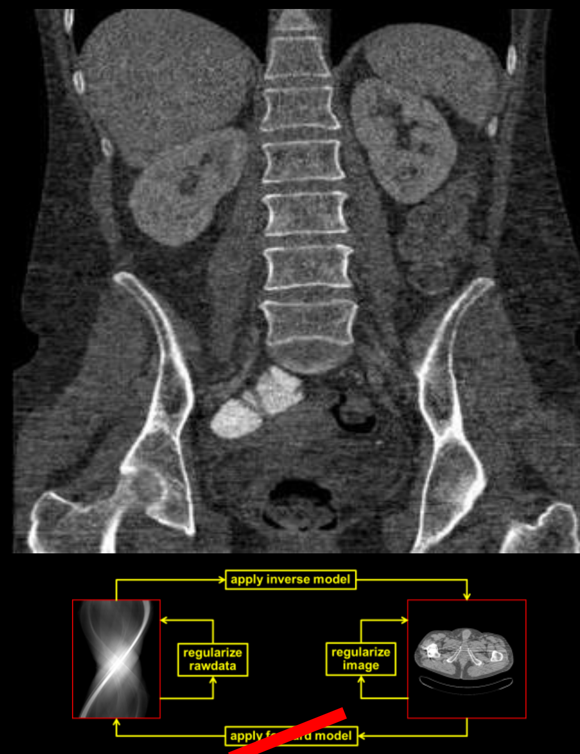


CT images provided by Siemens Healthcare, Forchheim, Germany

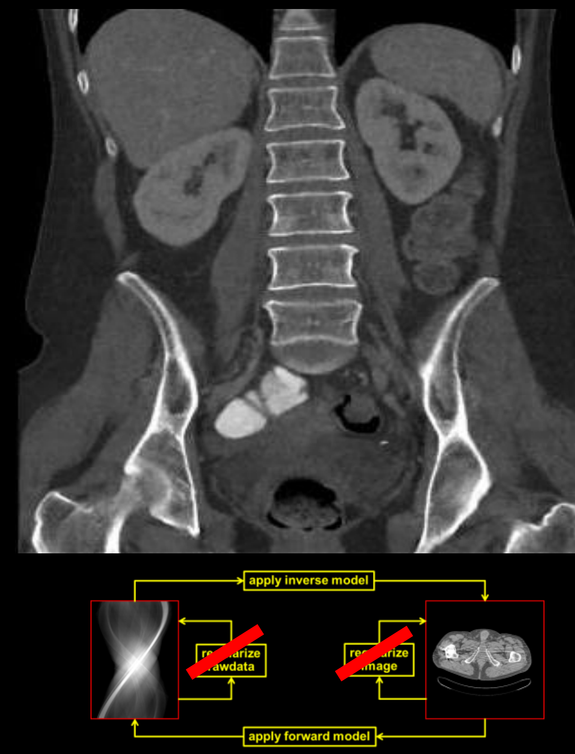
FBP


apply inverse model

ASIR


apply inverse model
regularize rawdata
regularize image

Veo


apply inverse model
apply forward model

Deep Learning Reconstruction: Canon‘s AiCE

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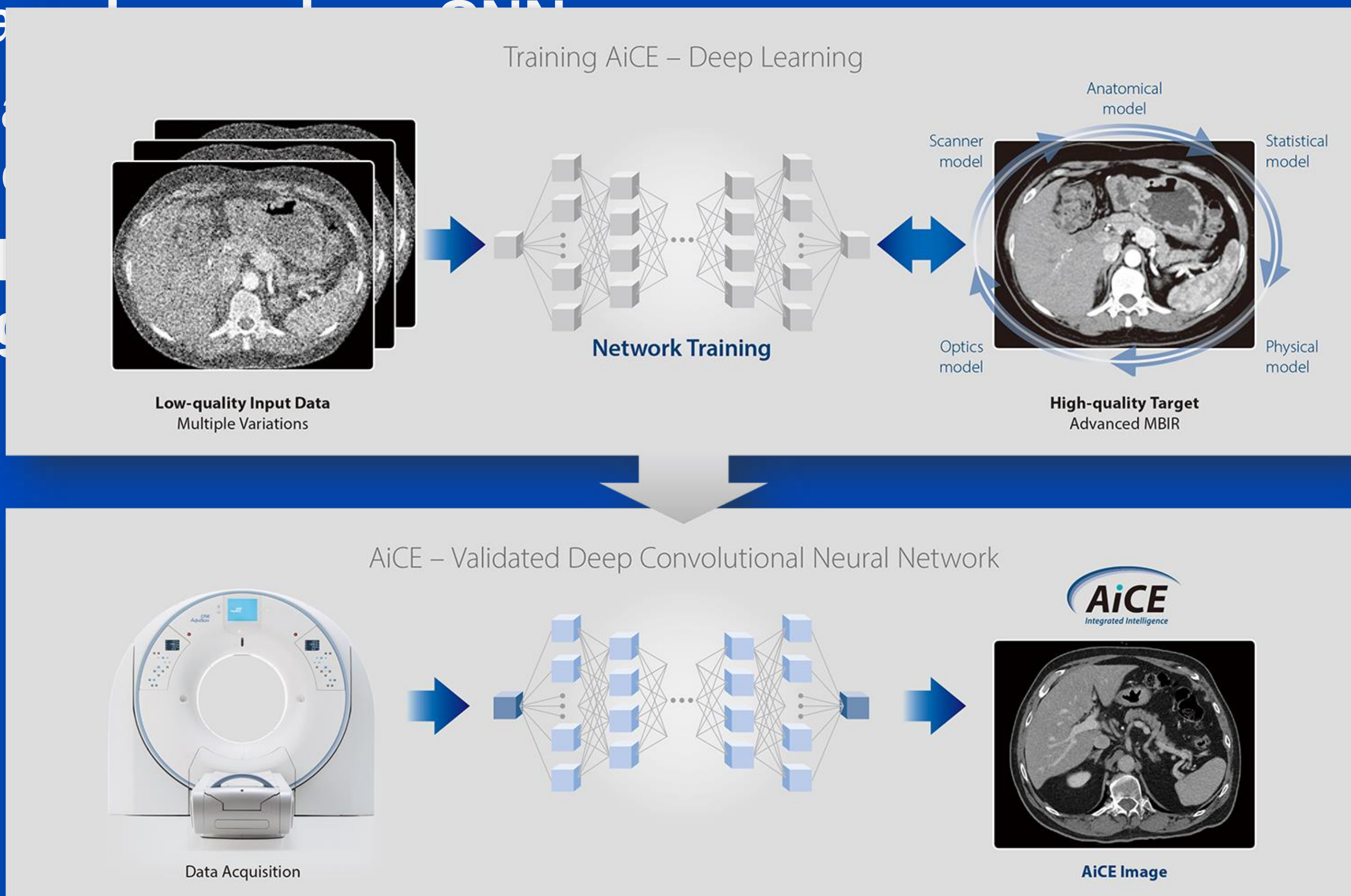

Information taken from https://global.medical.canon/products/computed-tomography/aice_dlr

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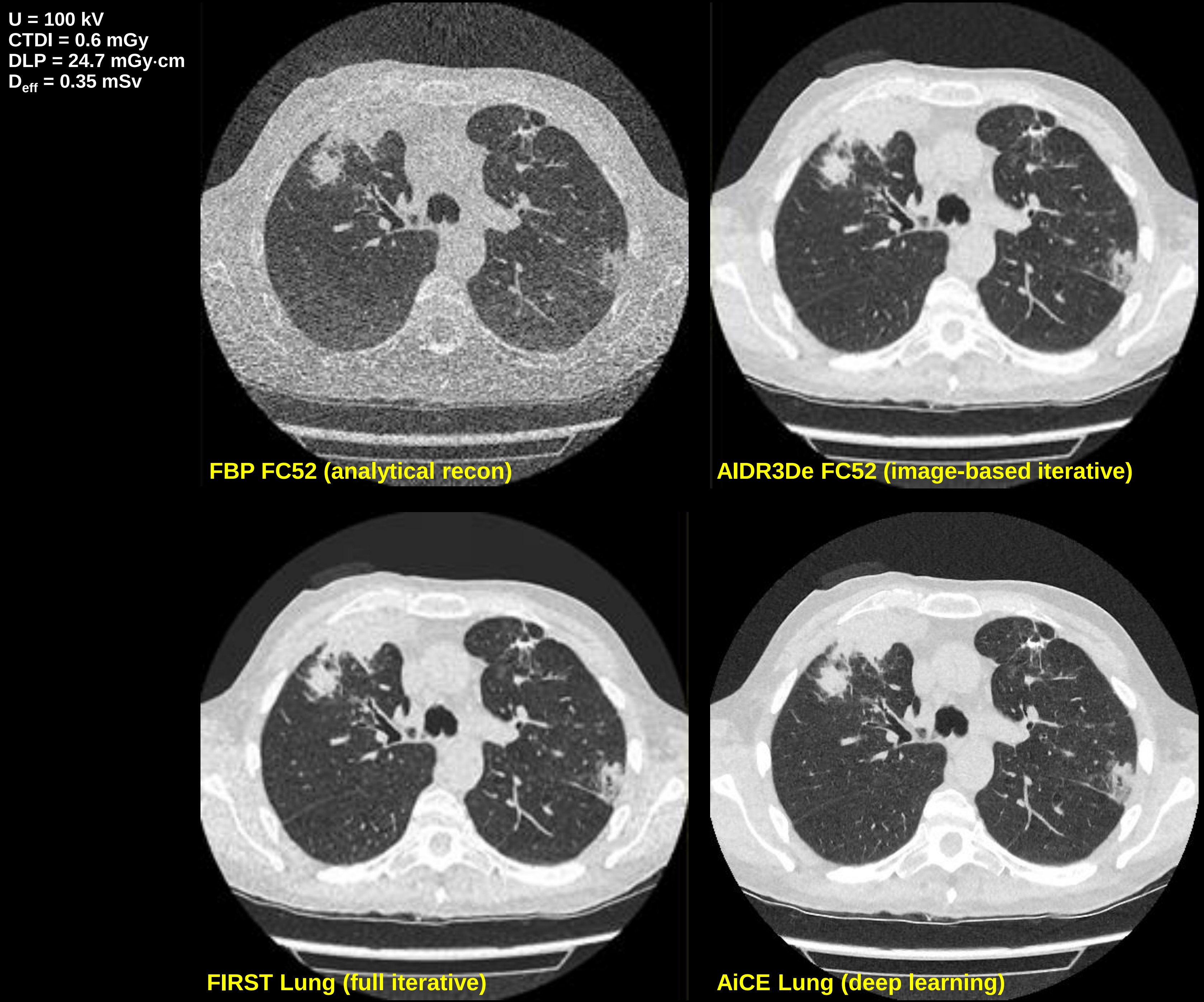


Courtesy of Radboudumc, the Netherlands

Deep Learning Reconstruction: GE's True Fidelity

- Based on a deep CNN
- Trained to restore low-dose CT data to match the properties of Veo, the model-based IR of GE.
- No information can be obtained in how the training is conducted for the product implementation.

2.5D DEEP LEARNING FOR CT IMAGE RECONSTRUCTION USING A MULTI-GPU IMPLEMENTATION

Amirkoushyar Ziabari⋆*, Dong Hye Ye*⋆ †*, Somesh Srivastava*‡*, Ken D. Sauer*⊕
Jean-Baptiste Thibault‡*, Charles A. Bouman*⋆

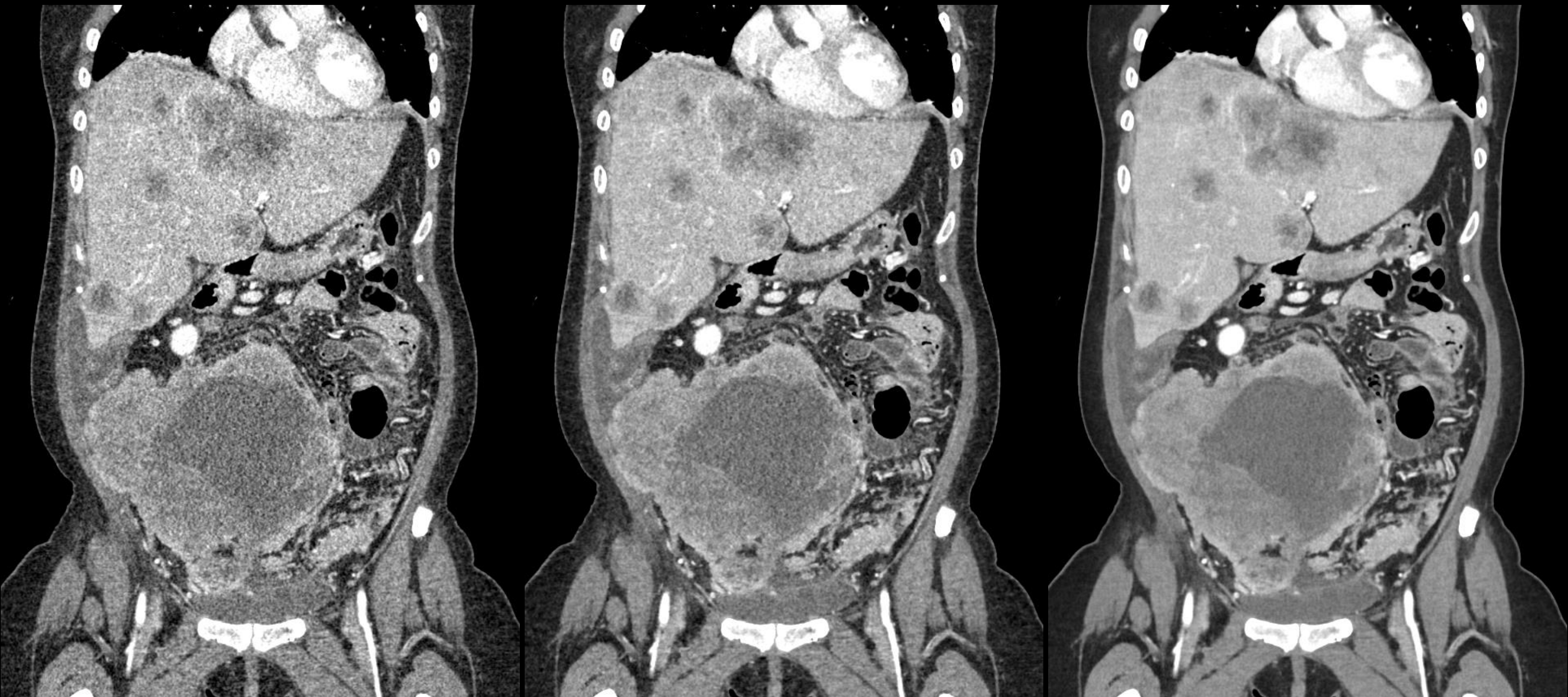
⋆ Electrical and Computer Engineering at Purdue University
† Electrical and Computer Engineering at Marquett University
‡ GE Healthcare
⊕ Electrical Engineering at University of Notre Dame

ABSTRACT

While Model Based Iterative Reconstruction (MBIR) of CT scans has been shown to have better image quality than Filtered Back Projection (FBP), its use has been limited by its high computational cost. More recently, deep convolutional neural networks (CNN) have shown great promise in both denoising and reconstruction applications. In this research, we propose a fast reconstruction algorithm, which we call Deep

streaking artifacts caused by sparse projection views in CT images [8]. More recently, Ye, et al. [9] developed method for incorporating CNN denoisers into MBIR reconstruction as advanced prior models using the Plug-and-Play framework [10, 11].

In this paper, we propose a fast reconstruction algorithm, which we call Deep Learning MBIR (DL-MBIR), for approximately achieving the improved quality of MBIR using a deep residual neural network. The DL-MBIR method is trained to



FBP | ASIR V 50% | True Fidelity

Courtesy of GE Healthcare

Summary on
CT Dose Reduction for Paediatric

- Tube voltage as low as possible:
  - 70 kV for some vendors today
  - 40, 50, 60 kV are most important to have (future)
- Dedicated paediatric scan protocols
- Scan with additional prefilter (e.g. 0.6 mm Sn)
- Adapt filter thickness to patient, not mAs (future)
- Automatic exposure control on
  - Tube current and kV selection
  - Tube current modulation
- Dedicated (narrow) bowtie for kids
- Very high pitch scan mode (no sedation, no motion)
- Iterative or deep learning reconstruction
- Take topogram dose into account

Thank You!

This presentation is available at www.dkfz.de/ct.

Job opportunities through DKFZ's international PhD or Postdoctoral Fellowship programs (marc.kachelriess@dkfz.de).