Patient-Specific Prefilters and Tube Current Modulation

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Prefilters that can be inserted depending on the patient size and imaging task

PATIENT-SPECIFIC PREFILTERS (PSP)

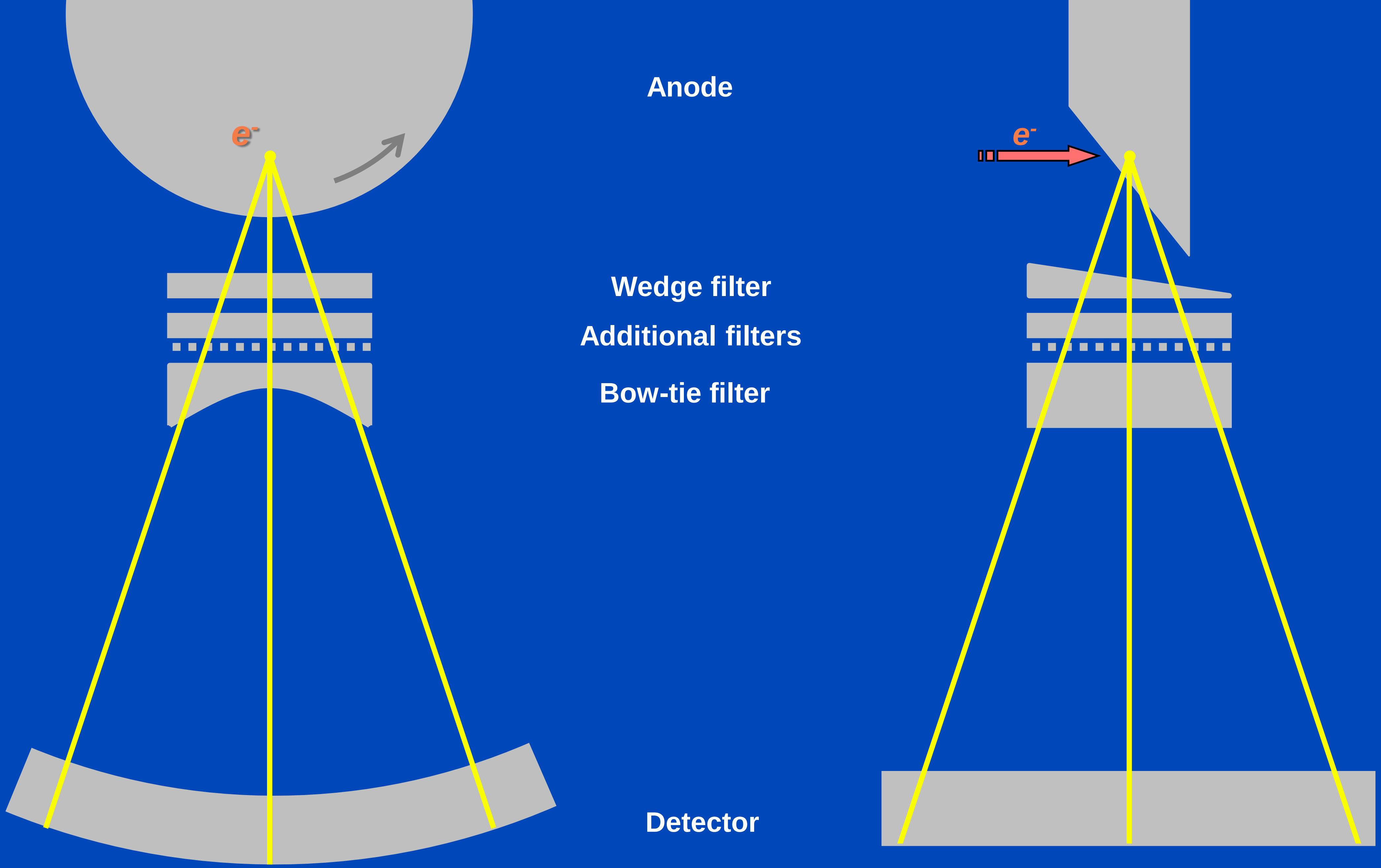
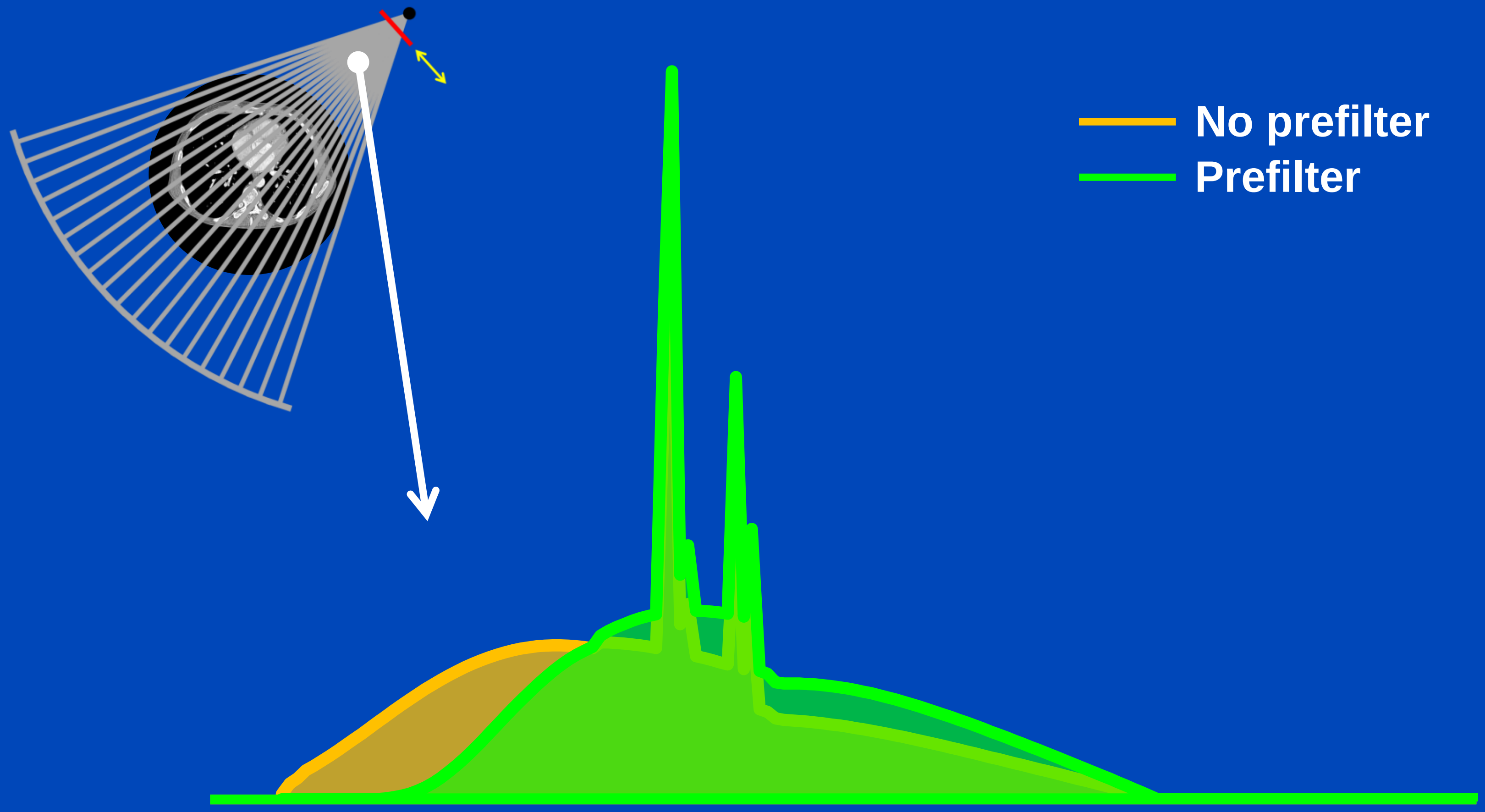
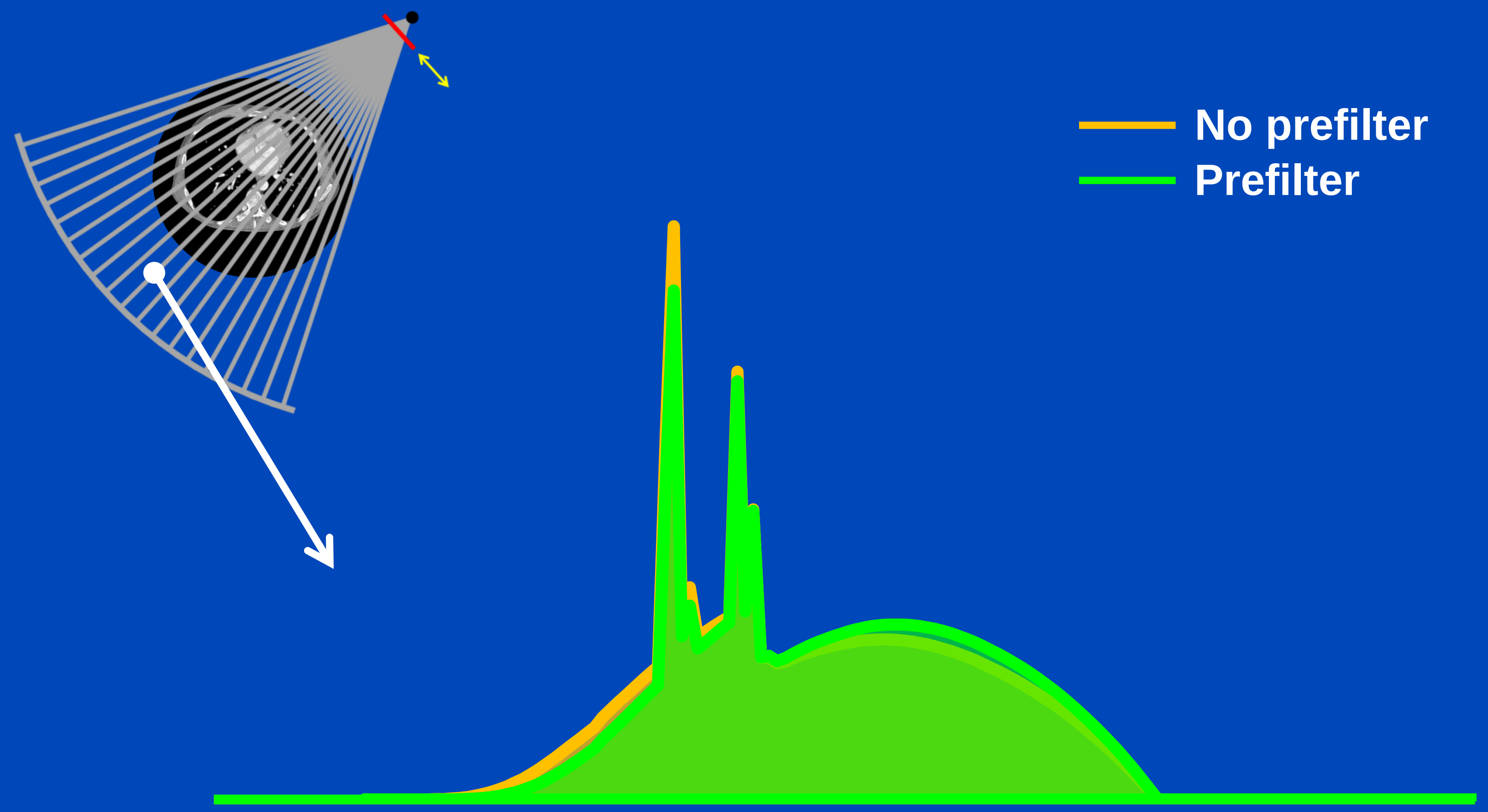


Figure not drawn to scale. Type and order of prefiltration may differ from scanner to scanner.
Depending on the selected protocol filters are changed automatically (e.g. small bowtie for pediatric scans).

120 kV + 0 mm water with and without prefilter



120 kV + 320 mm water with and without prefilter

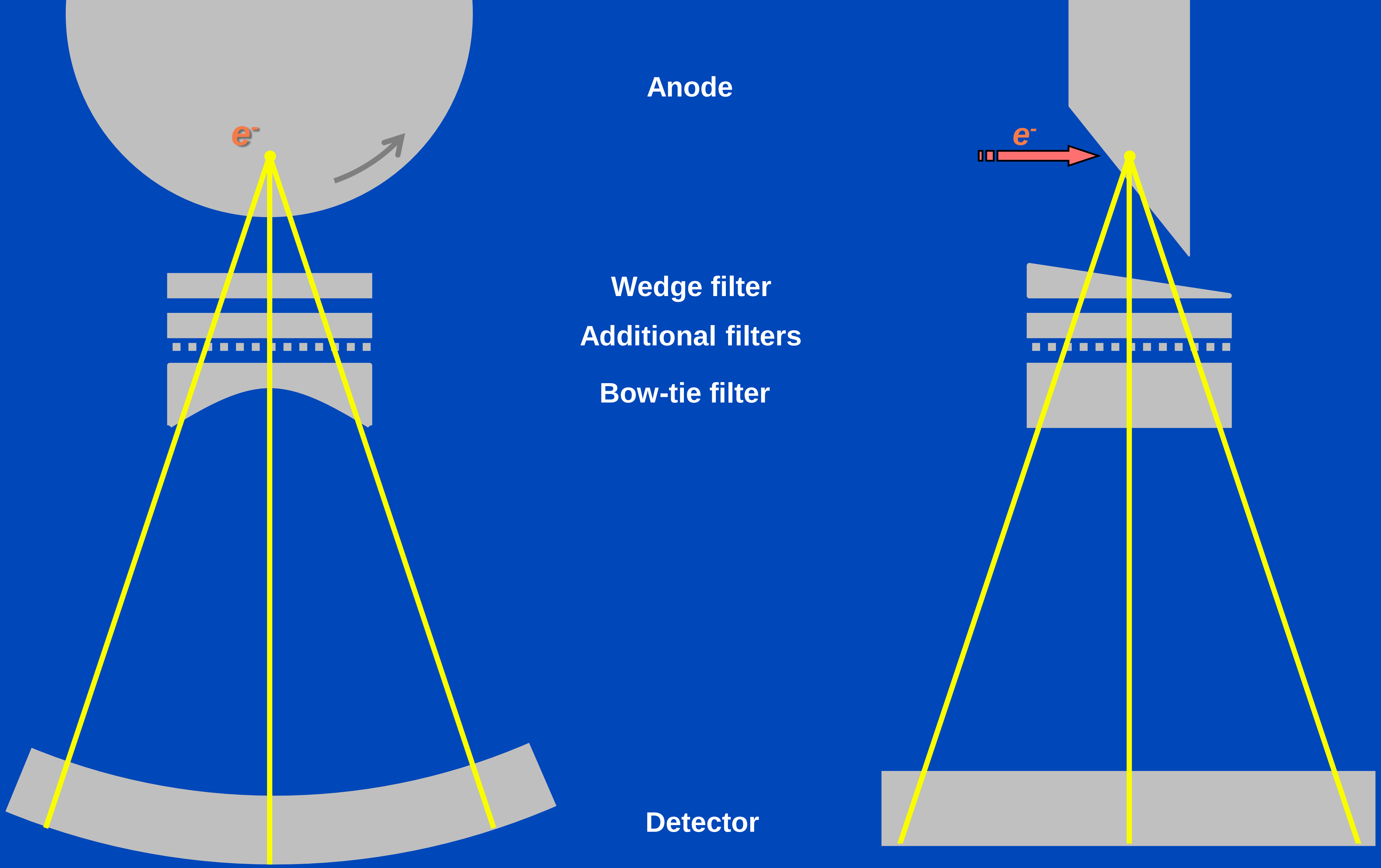


Task- and Patient-Specific (i.e. Removable) Prefilters in Use Today

- 0.4 mm Sn for Siemens‘ Naeotom Alpha
- 0.6 mm Sn for Siemens‘ Somatom Force, Edge Plus, go.Top and Definition Edge
- 0.4 mm Sn for Siemens‘ Somatom Flash, Drive, go.Now, go.Up, go.all, and pro.Pulse
- 0.4 mm and 0.7 mm Sn for Siemens‘ Somatom X.cite
- ≈ 0.5 mm Au for Canon‘s Aquilion ONE Prism Edition
- ≈ 1 mm Cu “for scout scans” in GE‘s Revolution Apex systems

In the energy range of clinical CT and with objects similar to patients we find that 0.5 mm Ag ≈ 0.6 mm Sn ≈ 2.0 mm Cu.

Cu: $Z = 29$, $\rho = 8.92$ g/cm^3, $E_K = 8.98$ keV. **Ag:** $Z = 47$, $\rho = 10.49$ g/cm^3, $E_K = 25.5$ keV. **Sn:** $Z = 50$, $\rho = 7.31$ g/cm^3 , $E_K = 29.2$ keV.



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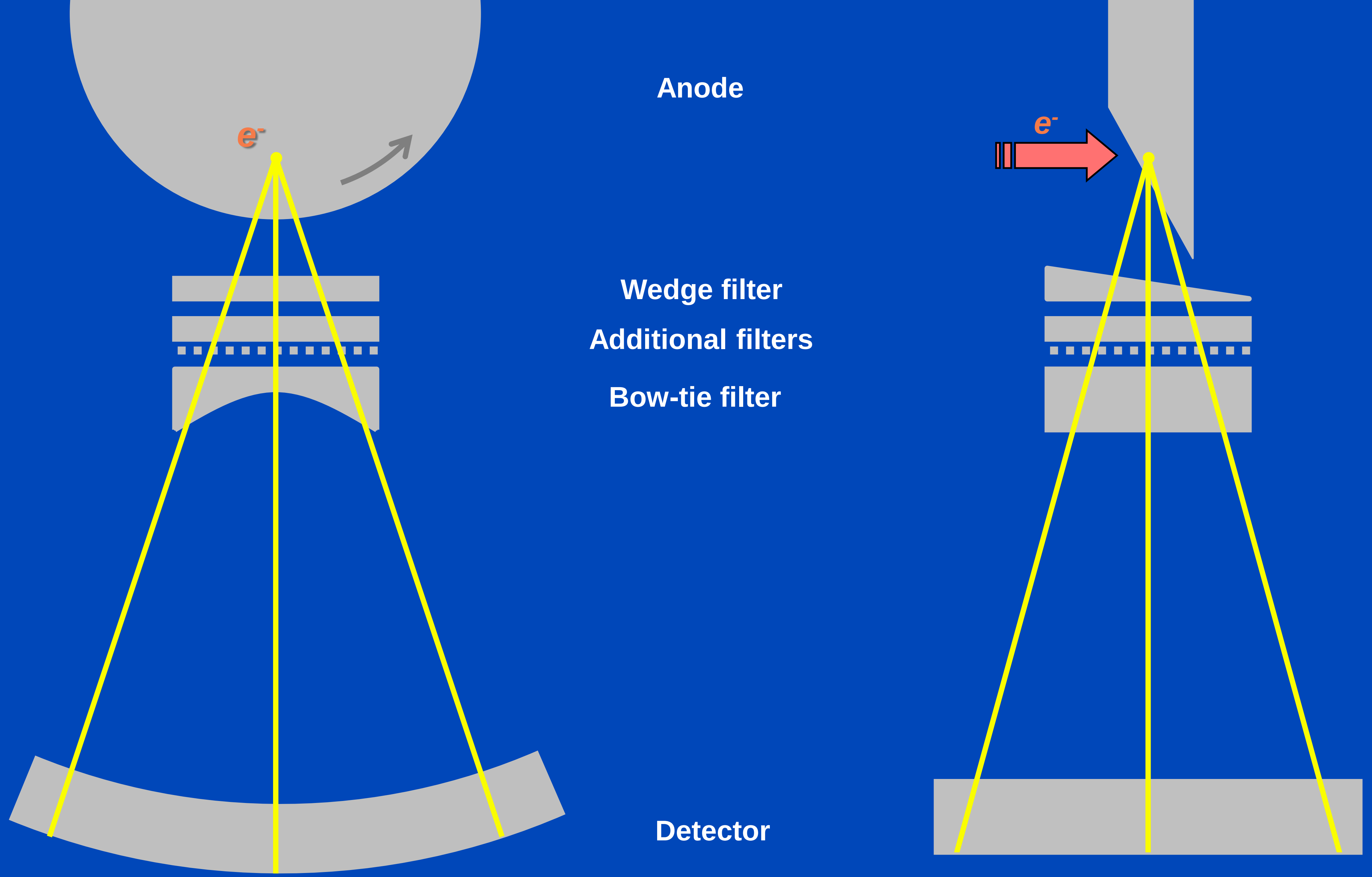
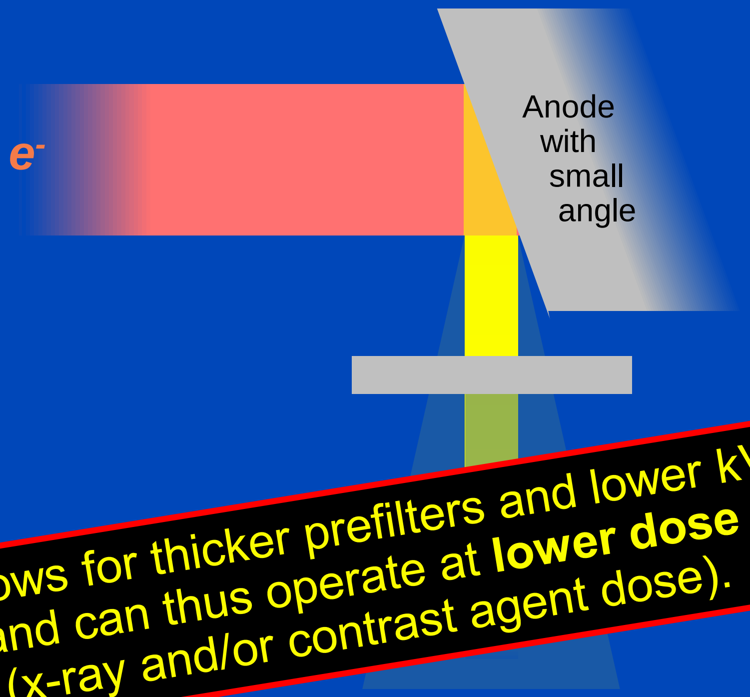


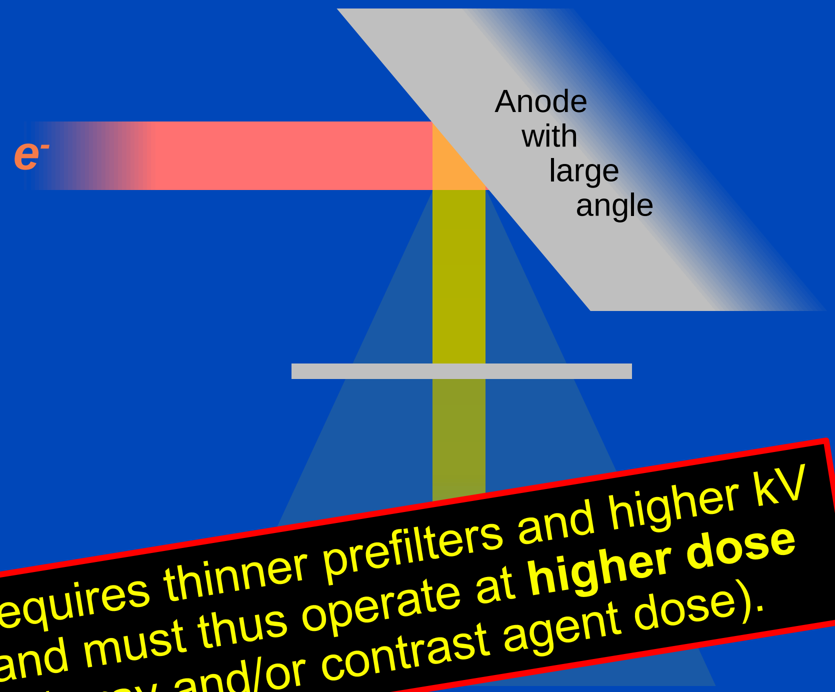
Figure not drawn to scale. Type and order of prefiltration may differ from scanner to scanner.
Depending on the selected protocol filters are changed automatically (e.g. small bowtie for pediatric scans).

Narrow Cone = High Tube Power

Wide Cone = Low Tube Power



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



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

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

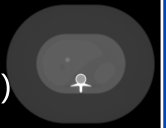
Dose Reduction due to Tin Prefiltration

Reference	Topic	Dose Reduction	Assessment	Recon
Agostini et al., 2021	chest, DECT, COVID-19	89%	subjective, different pitch values	iterative
Apfaltrer et al., 2018	coronary artery calcium scoring	73%	subjective	FBP
Axer et al., 2022	urolithiasis	20%	subjective	iterative
Dewes et al., 2016	abdomen, urinary stones	22%	subjective	iterative
Gordic et al., 2014	chest, pulmonary nodules, phantom	95%	subjective	iterative
Grunz et al., 2022	urinary stone	18% - 38%	subjective, objective	iterative
Hasegawa et al., 2022	chest, detectability index, phantom	22% - 25%	objective	FBP
Jeon et al., 2019	DECT, gout diagnosis	65%	subjective, different scanners	iterative
Kimura et al., 2022	colorectal cancer	89%	subjective	iterative, FBP
Kunz et al., 2022	urinary tract	62%	frequency of calculi detection	iterative
Leyendecker et al., 2019	abdomen	81%	subjective, objective	iterative
Martini et al., 2016	chest, pulmonary nodules	97%	subjective	iterative
Rajendran et al., 2020	sinus, temporal bone	67% - 85%	objective, EICT and PCCT	FBP
Saltybaeva et al., 2019	topogram	80%	effect on TCM	-
Schabel et al., 2018	thoracic aorta calcification	92%	subjective	iterative
Schüle et al., 2022	pelvis	90%	subjective, objective	iterative, FBP
Takemitsu et al., 2022	topogram	80%	effect on TCM	-
Weis et al., 2017	chest, pediatric	77%	subjective, objective	iterative
Wuest et al., 2016	paranasal sinus	73%	subjective, different scanners	FBP
Zhang et al., 2022	guided lung biopsy	73%	subjective	iterative

Dose Reduction due to Tin Prefiltration

1. Agostini, Andrea, et al. "Third-generation iterative reconstruction on a dual-source, high-pitch, low-dose chest CT protocol with tin filter for spectral shaping at 100 kV: a study on a small series of COVID-19 patients." *La radiologia medica* 126:388–398, 2021.
2. Apfaltrer, Georg, et al. "High-pitch low-voltage CT coronary artery calcium scoring with tin filtration: accuracy and radiation dose reduction." *European Radiology* 28(7):3097-3104, 2018.
3. Axer, Benedikt, et al. "Comparative evaluation of diagnostic quality in native low-dose CT without and with spectral shaping employing a tin filter in urolithiasis with implanted ureteral stent." *RöFo-Fortschritte auf dem Gebiet der Röntgenstrahlen und der bildgebenden Verfahren* 194(12):1358-1366, 2022.
4. Dewes, Patricia, et al. "Low-dose abdominal computed tomography for detection of urinary stone disease - Impact of additional spectral shaping of the x-ray beam on image quality and dose parameters." *European Journal of Radiology* 85(6):1058-1062, 2016.
5. Gordic, Sonja, et al. "Ultralow-dose chest computed tomography for pulmonary nodule detection: First performance evaluation of single energy scanning with spectral shaping." *Investigative Radiology* 49(7):465-473, 2014.
6. Grunz, Jan-Peter, et al. "Thermoluminescence dosimetry in abdominal CT for urinary stone detection: Effective radiation dose reduction with tin prefiltration at 100 kVp." *Investigative Radiology* 58(3):231-238, 2023.
7. Hasegawa, Akira, et al. "A tin filter's dose reduction effect revisited: Using the detectability index in low-dose computed tomography for the chest." *Physica Medica* 99:61-67, 2022.
8. Jeon, Ji Young, et al. "The effect of tube voltage combination on image artefact and radiation dose in dual-source dual-energy CT: Comparison between conventional 80/140 kV and 80/150 kV plus tin filter for gout protocol." *European Radiology* 29(3):1248-1257, 2019.
9. Kimura, Koichiro, et al. "Dose reduction and diagnostic performance of tin filter-based spectral shaping CT in patients with colorectal cancer." *Tomography* 8(2):1079-1089, 2022.
10. Kunz, Andreas Steven, et al. "Tin-filtered 100 kV ultra-low-dose abdominal CT for calculi detection in the urinary tract: A comparative study of 510 cases." *Academic Radiology*, 2022.
11. Leyendecker, Pierre, et al. "Prospective evaluation of ultra-low-dose contrast-enhanced 100-kV abdominal computed tomography with tin filter: effect on radiation dose reduction and image quality with a third-generation dual-source CT system." *European Radiology* 29(4):2107-2116, 2019.
12. Martini, Katharina, et al. "Evaluation of pulmonary nodules and infection on chest CT with radiation dose equivalent to chest radiography: Prospective intra-individual comparison study to standard dose CT." *European Journal of Radiology* 85(2):360-365, 2016.
13. Rajendran, Kishore, et al. "Dose reduction for sinus and temporal bone imaging using photon-counting detector CT with an additional tin filter." *Investigative Radiology* 55(2):91-100, 2020.
14. Saltybaeva, Natalia, et al. "Radiation dose reduction from computed tomography localizer radiographs using a tin spectral shaping filter." *Medical Physics* 46(2):544-549, 2019.
15. Schabel, Christoph, et al. "Tin-filtered low-dose chest CT to quantify macroscopic calcification burden of the thoracic aorta." *European Radiology* 28:1818-1825, 2018.
16. Schüle, Simone, et al. "Low-dose CT imaging of the pelvis in follow-up examinations-significant dose reduction and impact of tin filtration: Evaluation by phantom studies and first systematic retrospective patient analyses." *Investigative Radiology* 57(12):789-801, 2022.
17. Takemitsu, Masaki, et al. "Patient dose reduction for a localizer radiograph with an additional tin filter in chest-abdomen-pelvis, spine, and head computed tomography examinations." Radiological Physics and Technology, 2023.
18. Weis, Meike, et al. "Radiation dose comparison between 70 kvp and 100 kVp with spectral beam shaping for non-contrast-enhanced pediatric chest computed tomography: a prospective randomized controlled study." Investigative Radiology 52(3):155-162, 2017.
19. Wuest, Wolfgang, et al. "Low-dose CT of the paranasal sinuses: minimizing x-ray exposure with spectral shaping." European Radiology 26(11):4155-4161, 2016.
20. Zhang, Jing, et al. "Low-dose CT with tin filter combined with iterative metal artefact reduction for guiding lung biopsy." Quantitative Imaging in Medicine and Surgery 12(2):1359, 2022.
21. … and many more …

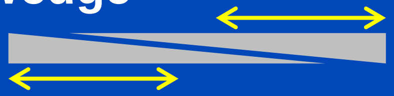
Dose Reduction by Patient-Specific Tin or Copper Prefilters 1000 mAs Limit, 50-150 kV in 5 kV Steps

	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, 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%

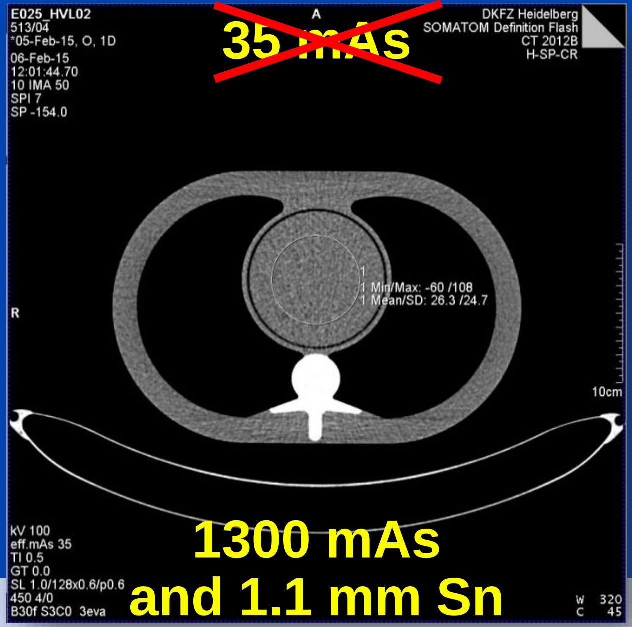
Steidel, Maier, Sawall, Kachelrieß. Dose reduction potential in diagnostic single energy CT through patient-specific prefilters and a wider range of tube voltages. Med. Phys. 49(1):93-106, 2022.

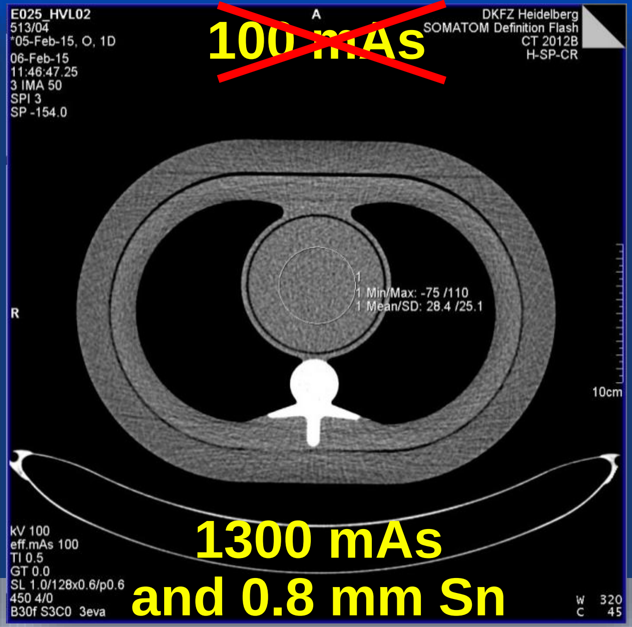
Prefilters

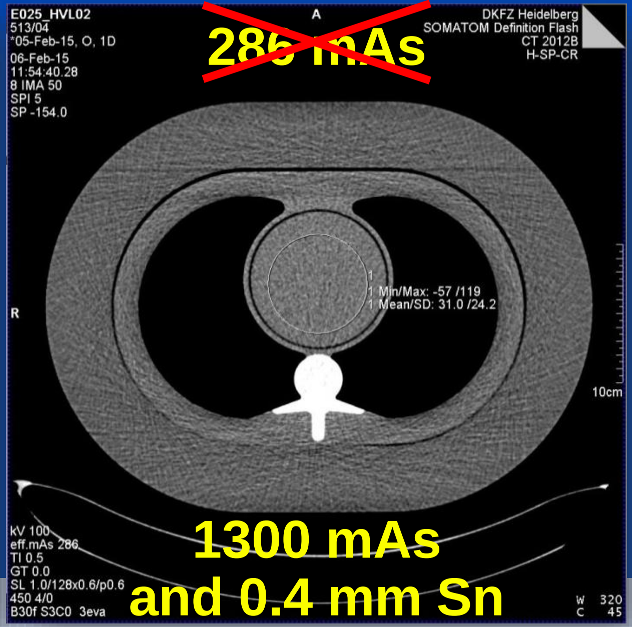
- **We want**
  - a filter changer with, say, 10 different filters, or a sliding double wedge
  - tubes with much higher power and lower kV
  - to always operate the tube close to its power limit
  - to adjust the filter thickness and kV to the patient
  - copper instead of tin



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







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 **(0.4 mm)**	120	100Sn **(0.6 mm)**
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

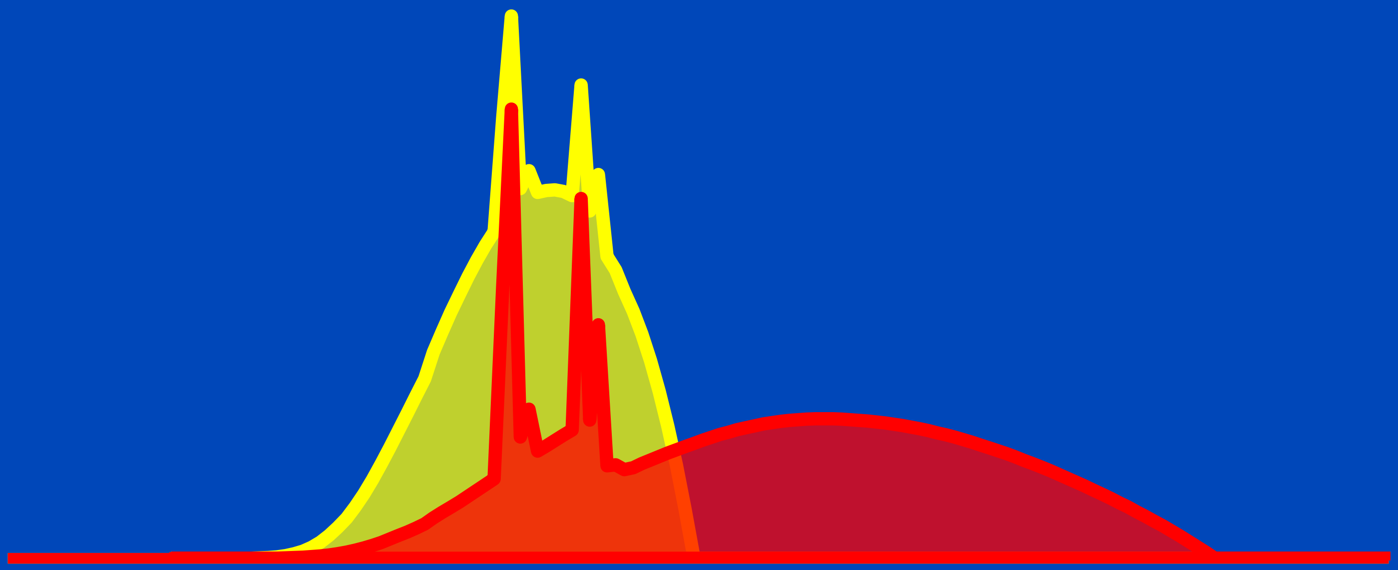
RECON 1

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

→ thicker prefilter means less dose

80 kV / 140 kV

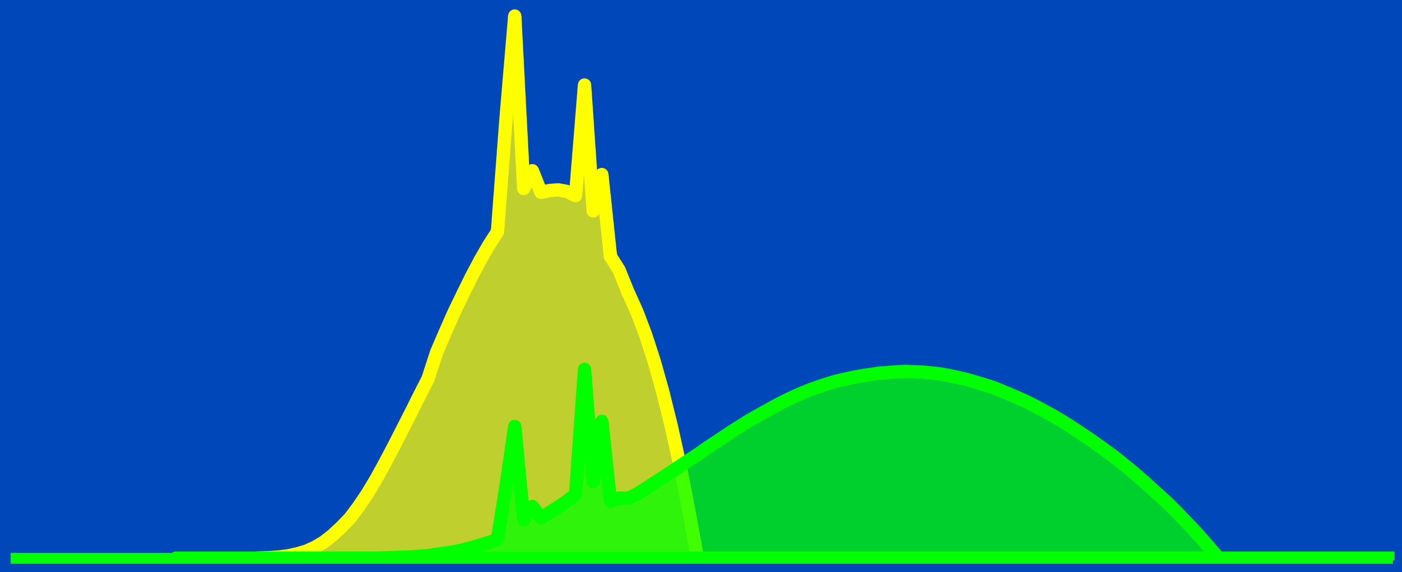
Used in
- **Siemens‘ 1st generation DSCT**



Spectra as seen after having passed a 32 cm water layer.

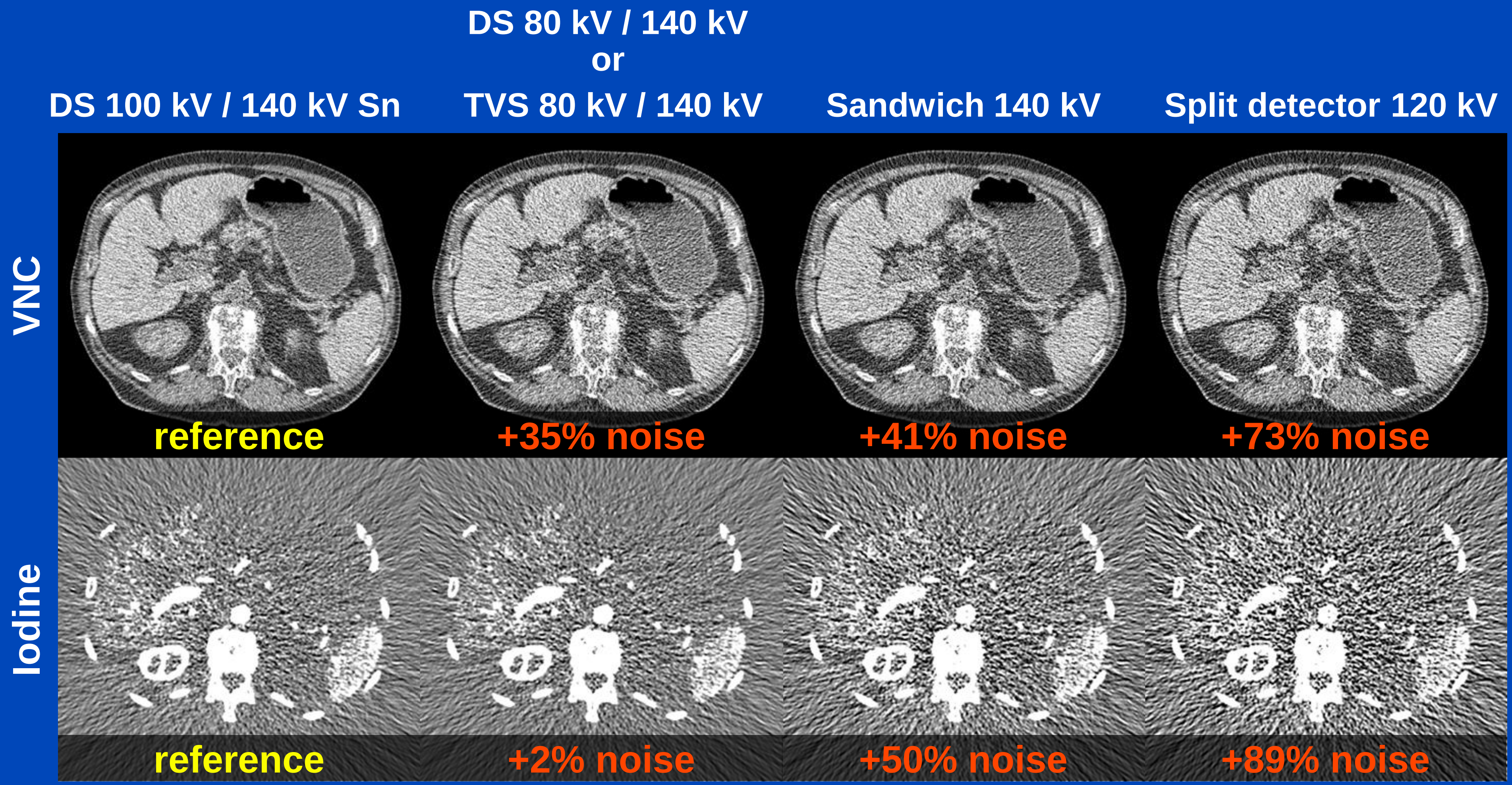
80 kV / 140 kV $Sn_{0.4\ mm}$

Used in
- Siemens‘ 2nd generation DSCT



Spectra as seen after having passed a 32 cm water layer.

Results – Different DECT Techniques



Faby and Kachelrieß, MedPhys 42(7):4349-4366, July 2015.

Water: *C* = 0 HU / *W* = 400 HU
Iodine: *C* = 0 mg/mL / *W* = 6 mg/mL

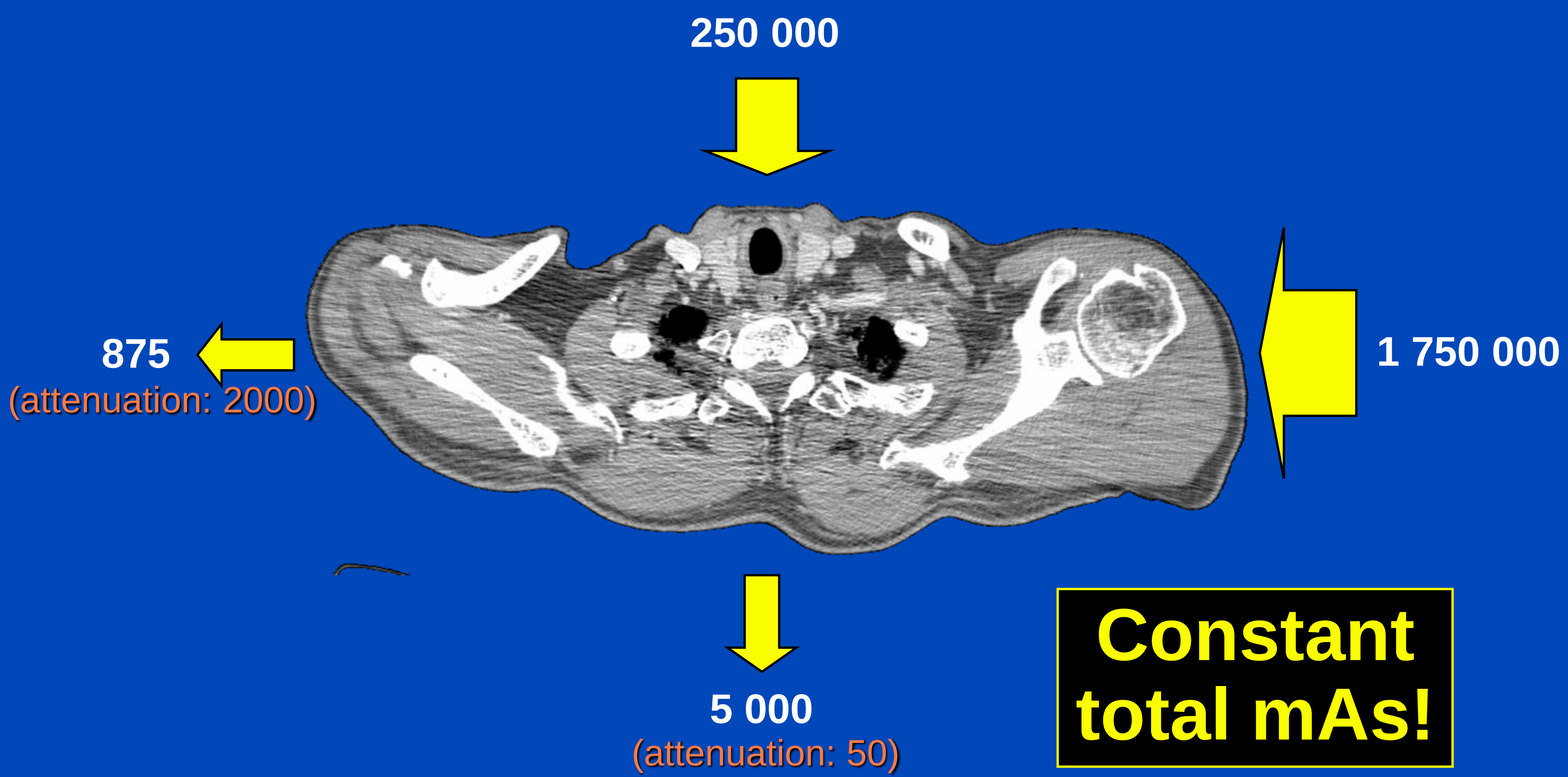
Conclusions on Patient-Specific Prefilters

- PSPs are filters that can be inserted or removed, depending on the patient size and imaging task.
- PSPs in single energy CT
  - Spectrum becomes more monochromatic
  - Low energy photons are kept from reaching the patient
  - Substantial dose savings can be obtained
  - X-ray tubes need to be as powerful as possible
  - The thinner the patient, the thicker the prefilter should be
  - Today‘s CTs offer at most two settings: no filter or the installed filter thickness
- PSPs in dual energy CT
  - Applied today only in dual source CT on the high kV tube
  - Maximizes the spectral separation between the low and the high kV spectrum
  - Substantial dose savings can be obtained

Adaptation of the tube current to the patient anatomy

TUBE CURRENT MODULATION (TCM)

Tube Current Modulation (mAsTCM)



Constant total mAs!

Modulated tube current: Low, homogeneous noise.

Theory of mAsTCM

$$\int d\alpha \left(\underbrace{I(\alpha)} + \lambda \underbrace{\mathrm{Var}\, p(\alpha)} \right) = \min$$

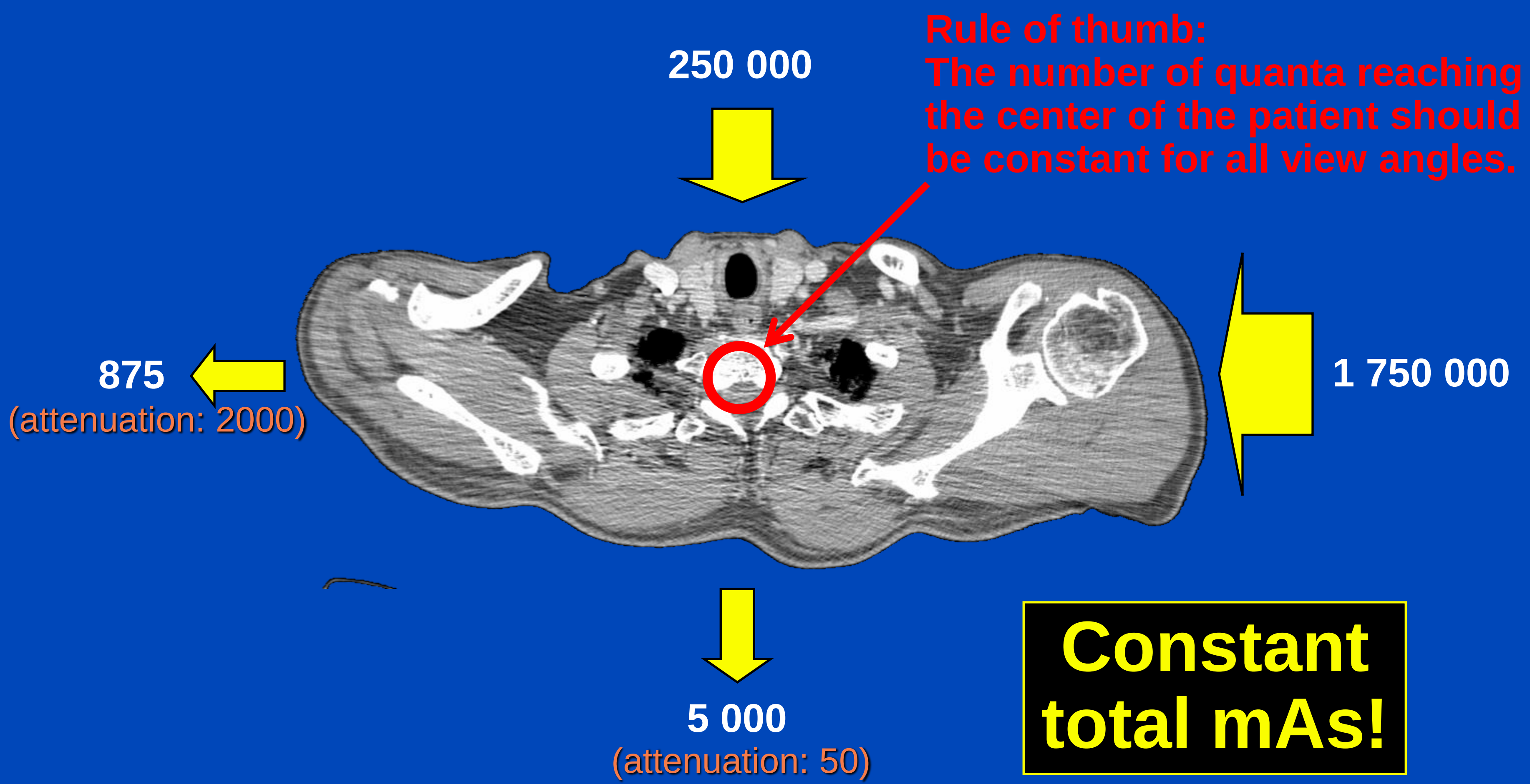
minimize mAs | keep noise constant

$$\boxed{I^2(\alpha) \propto \left(\frac{\partial p}{\partial q}\right)^2 \gamma\, e^q}$$

$$p = p(q)$$

$$\mathrm{Var}\, q = \gamma \frac{e^q}{I}$$

Tube Current Modulation (mAsTCM)



Constant total mAs!

Modulated tube current: Low, homogeneous noise.

Dose Reduction by Tube Current Modulation

Conventional scan: 327 mAs

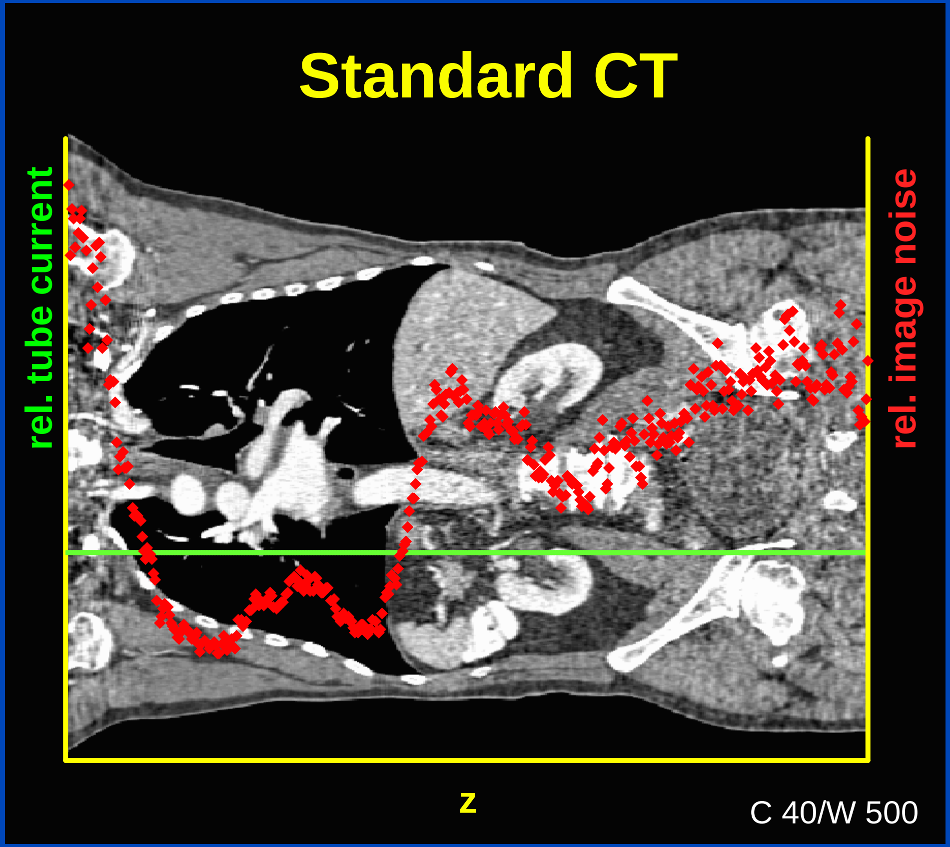
Online current modulation: 166 mAs

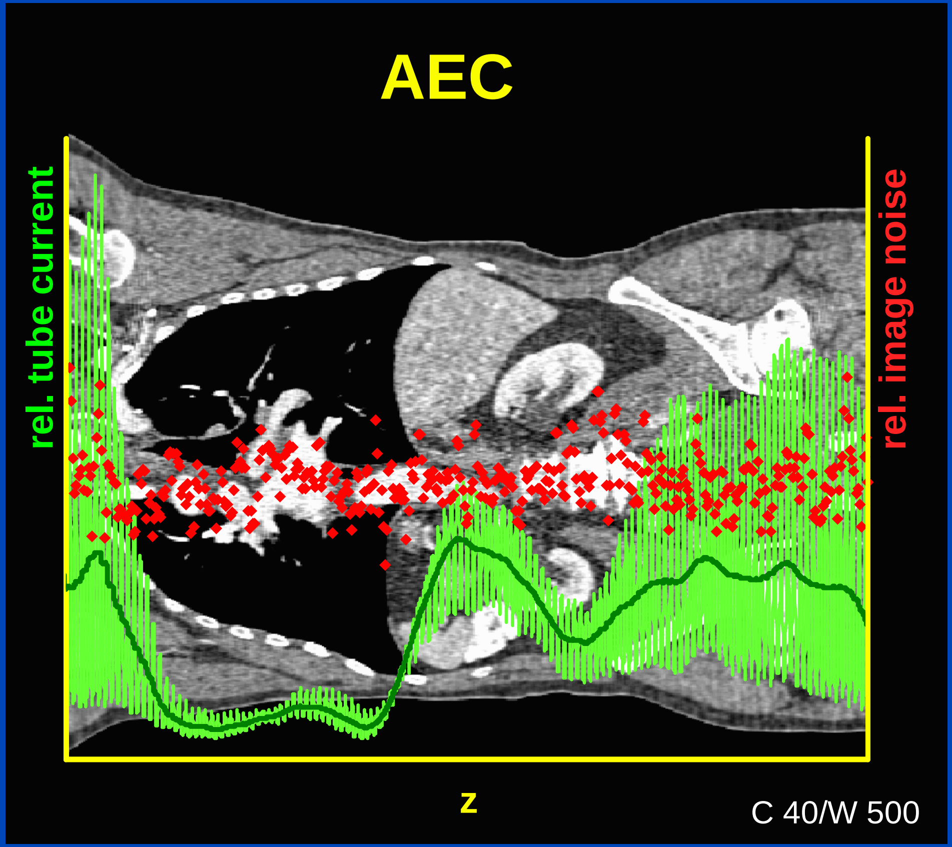
53% dose reduction on average for the shoulder region
49% dose reduction in this case

Kalender WA et al. Med Phys 1999; 26(11):2248-2253

Automatic Exposure Control (AEC)

(z-dependent + angular dependent tube current modulation)





34% mAs reduction with AEC at constant image quality for that specific case

Vendor Realizations: Image Quality Metrics

- The user has to specify a certain image quality in terms of quality metrics parameters:
  - Canon: The desired standard deviation in soft tissue is being preset.
  - GE: A so-called “noise index” and a minimum and maximum mA value are chosen. Images reconstructed with a standard kernel will then show the specified noise in soft tissue regions.
  - Philips: A “baseline mAs” is chosen. The system will calculate tube current modulation curves, so that the resulting images will best correspond to “reference images”.
  - Siemens: The “IQ level”, that replaces the former “reference mAs value”, is chosen. It corresponds to a standard patient (75 kg adult) at 120 kV and scales across tube voltages and scanners, i.e. it is kV and scanner independent. Modulation strength can be set (very weak, weak, average, strong, very strong).

Features of AEC Systems

	Canon SUREExposure 3D	GE AutomA 3D[1]	Philips DoseRight ACS	Siemens CARE Dose 4D
mA adaptation for patient size	SUREExposure	AutomA	automatic current selection (ACS)	yes
mA adaption for z-dimension	SUREExposure	AutomA	Z-DOM, DOM	yes
mA adaption for α-angle	SUREExposure 3D	SmartmA	D-DOM	yes
Simultaneous application	xy-AEC can be chosen separately	AutomA + SmartmA = AutomA 3D	ACS+Z-DOM or ACS+D-DOM, but not ACS+Z-DOM+D-DOM	always on
Method to determine the exposure level	standard deviation	noise index	reference image	reference mAs (old) IQ-level (new, 2021)
Basis for AEC for z-position / α-angle	a.p. and lateral topogram / sinusoidal modulation	single topogram / sinusoidal modulation	a.p. and lateral topogram / previously acquired 180° data	a.p. and lateral topogram / previously acquired 180° data

DOM = dose modulation = TCM = tube current modulation

[1]Feature is disabled when in fast tube voltage switching DECT mode

dkfz

More Features of AEC Systems

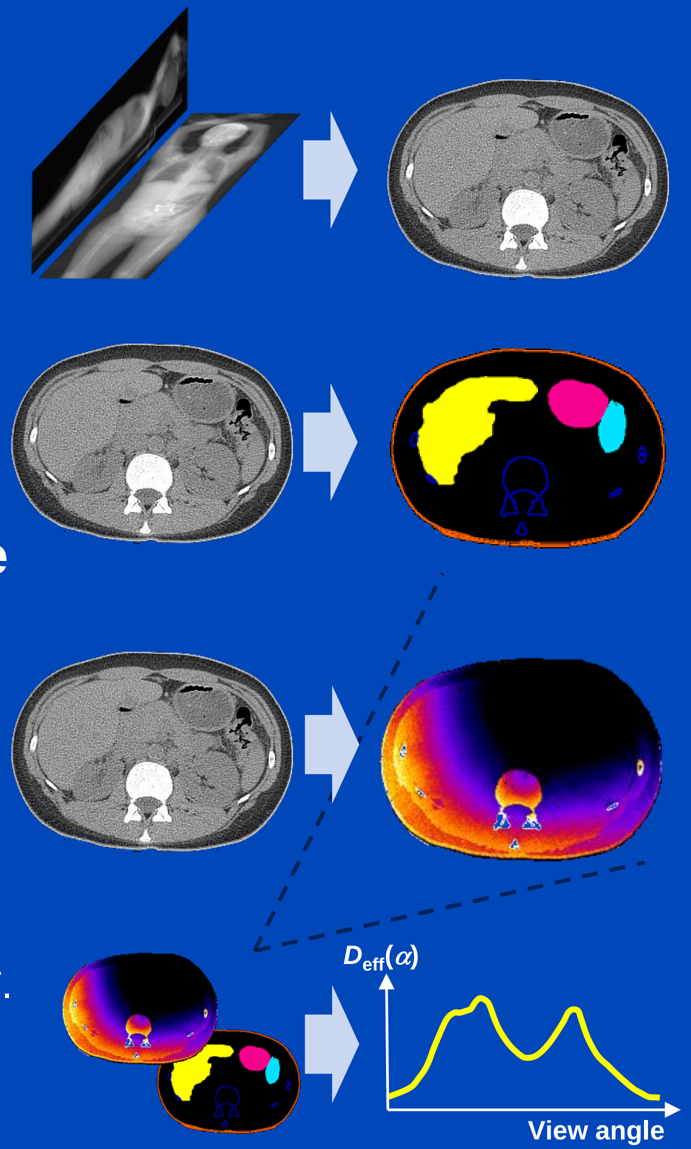
	Canon SURE Exposure 3D	GE AutomA 3D	Philips DoseRight ACS	Siemens CARE Dose 4D
Automatic tube voltage selection	Sure kV	kV Assist	-	CARE kV
Modulation for cardiac CT - retrospective	"ECG Modulation"	"ECG Modulated mA"	DoseRight Cardiac "Step and Shoot"	"Adaptive ECG-Pulsing"
Modulation for cardiac CT - prospective	"SURE Cardio Prospective"	"Prospective Gating"	DoseRight Cardiac ECG triggered dose modulation	Prospective sequ-ence = "Adaptive Cardio" + "Pulsing", prospective spiral = "Flash mode"
Variable spiral pitch for cardiac	Variable helical pitch (vHP)	-	-	-
Organ-Specific AEC/TCM	OEM, Decrease anterior tube current	ODM, Decrease anterior tube current	Liver DRI, Different image quality settings for the liver	X Care Decrease anterior, increase posterior tube current
Perfusion special	"time sequence" (mAs reduction after baseline scan)	-	-	-

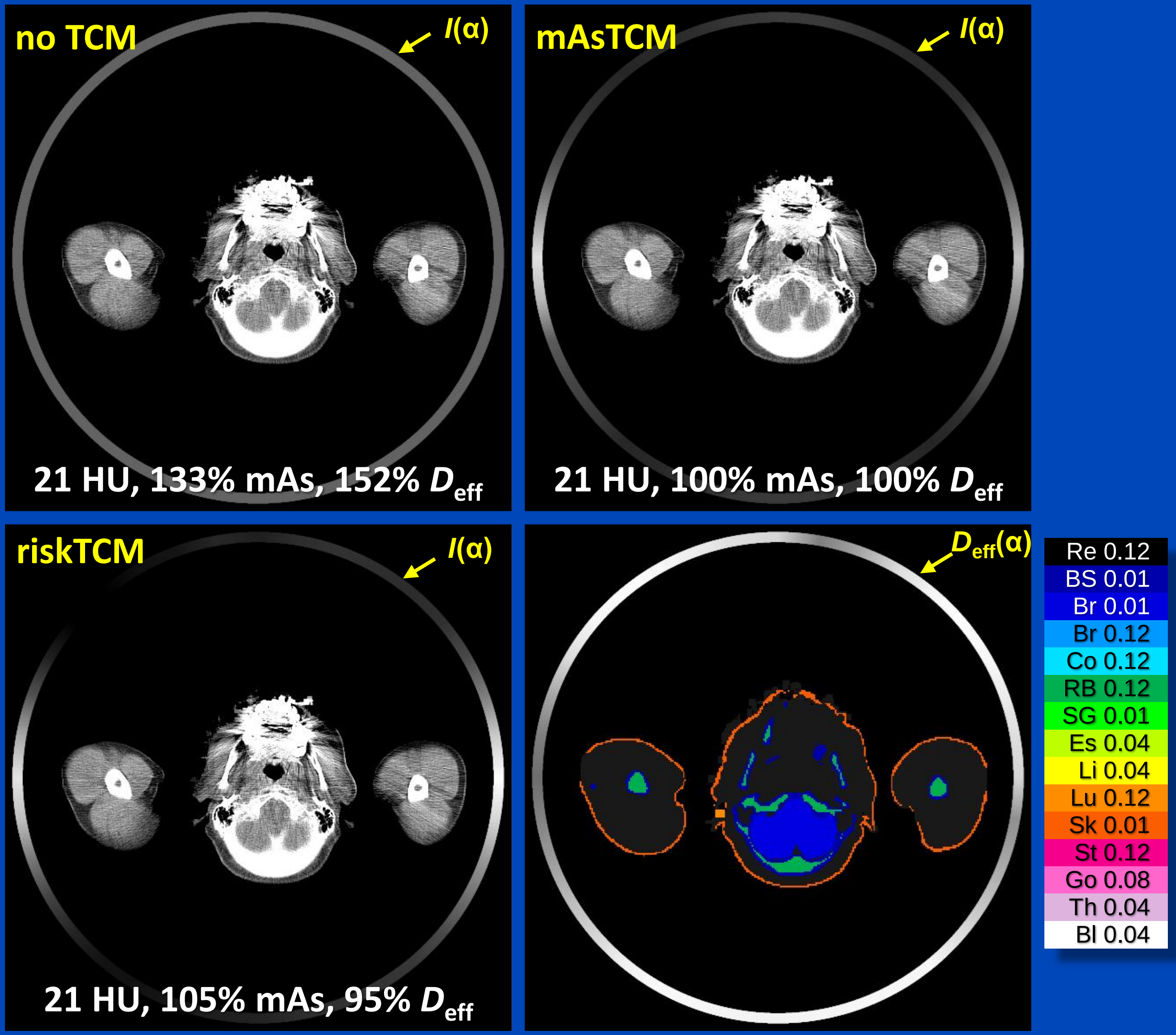
Conclusions on mAsTCM

- Routinely used today
- Allows for more homogeneous image noise
- Achieves substantial dose reduction (although mAs is minimized)

Patient Risk-Minimizing Tube Current Modulation (riskTCM)

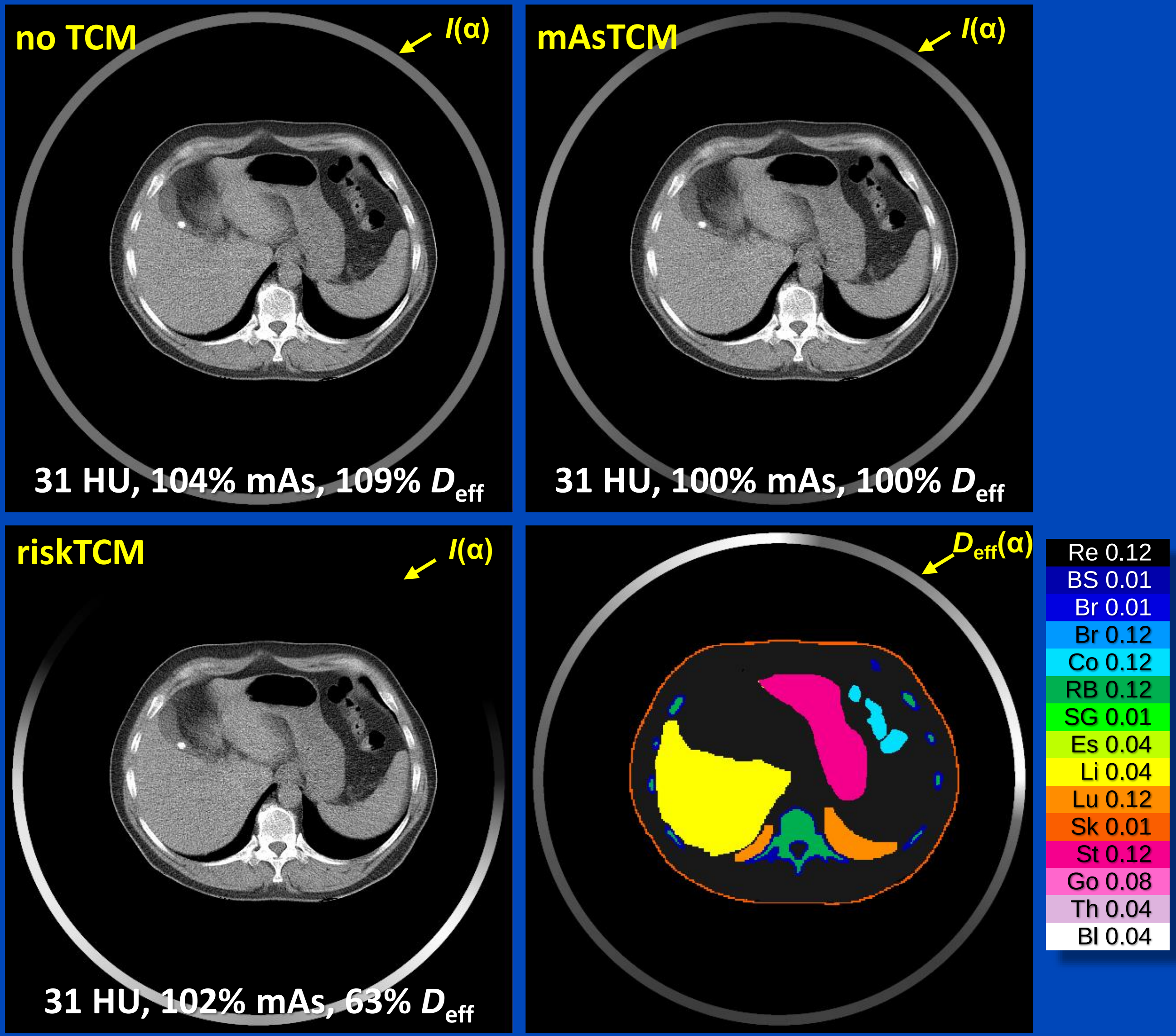
1. **Coarse reconstruction from two scout views**
   – E.g. X. Ying, et al. X2CT-GAN: Reconstructing CT from biplanar x-rays with generative adversarial networks.
   CVPR 2019.
2. **Segmentation of radiation-sensitive organs**
   – E.g. S. Chen, M. Kachelrieß et al., Automatic multi-organ segmentation in dual-energy CT (DECT) with dedicated 3D fully convolutional DECT networks. Med. Phys. 2019.
3. **Calculation of the effective dose per view using the deep dose estimation (DDE)**
   – J. Maier, E. Eulig, S. Dorn, S. Sawall and M. Kachelrieß. Real-time patient-specific CT dose estimation using a deep convolutional neural network. IEEE Medical Imaging Conference Record, M-03-178: 3 pages, Nov. 2018.
4. **Determination of the tube current modulation curve that minimizes the radiation risk**
   – L. Klein, C. Liu, J. Steidel, L. Enzmann, M. Knaup, S. Sawall, A. Maier, M. Lell, J. Maier, and M. Kachelrieß. Patient-specific radiation risk-based tube current modulation for diagnostic CT. Med. Phys. 49(7):4391-4403, July 2022.





C = 25 HU, *W* = 400 HU

L. Klein, C. Liu, J. Steidel, L. Enzmann, M. Knaup, S. Sawall, A. Maier, M. Lell, J. Maier, and M. Kachelrieß. Patient-specific radiation risk-based tube current modulation for diagnostic CT. Med. Phys. 49(7):4391-4403, July 2022. *This paper received the Sylvia&Moses Greenfield Award for the best scientific paper on imaging in Medical Physics in 2022.*



C = 25 HU, *W* = 400 HU

L. Klein, C. Liu, J. Steidel, L. Enzmann, M. Knaup, S. Sawall, A. Maier, M. Lell, J. Maier, and M. Kachelrieß. Patient-specific radiation risk-based tube current modulation for diagnostic CT. Med. Phys. 49(7):4391-4403, July 2022. *This paper received the Sylvia&Moses Greenfield Award for the best scientific paper on imaging in Medical Physics in 2022.*

Effective Dose Values Relative to mAsTCM

Average over all patients and across all tube voltages (70 to 150 kV)

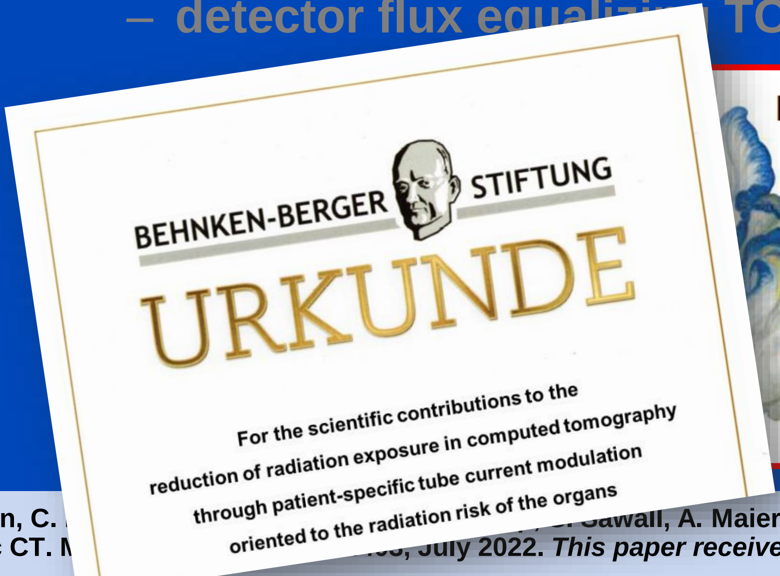
	noTCM	mAsTCM	riskTCM
Head	110%	100%	92%
Head+Arms	162%	100%	88%
Neck	223%	100%	76%
Thorax	113%	100%	81%
Abdomen	114%	100%	71%
Pelvis	152%	100%	79%

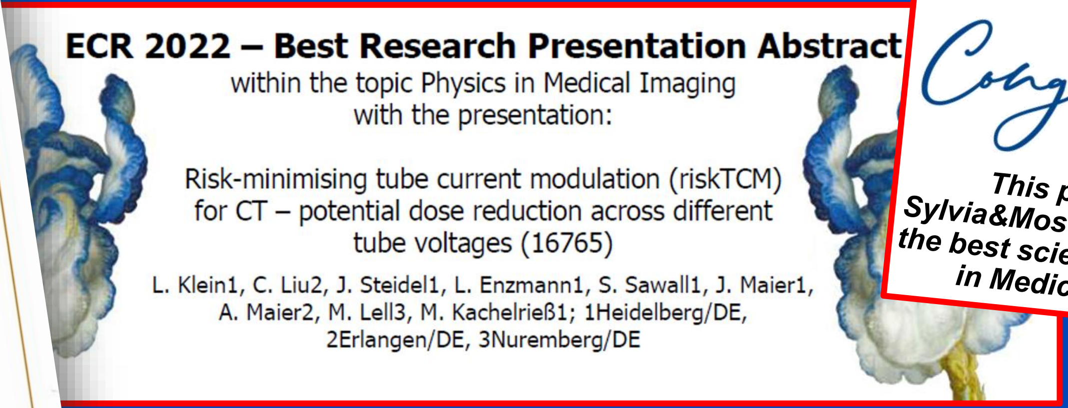
L. Klein, C. Liu, J. Steidel, L. Enzmann, M. Knaup, S. Sawall, A. Maier, M. Lell, J. Maier, and M. Kachelrieß. Patient-specific radiation risk-based tube current modulation for diagnostic CT. Med. Phys. 49(7):4391-4403, July 2022. *This paper received the Sylvia&Moses Greenfield Award for the best scientific paper on imaging in Medical Physics in 2022.*

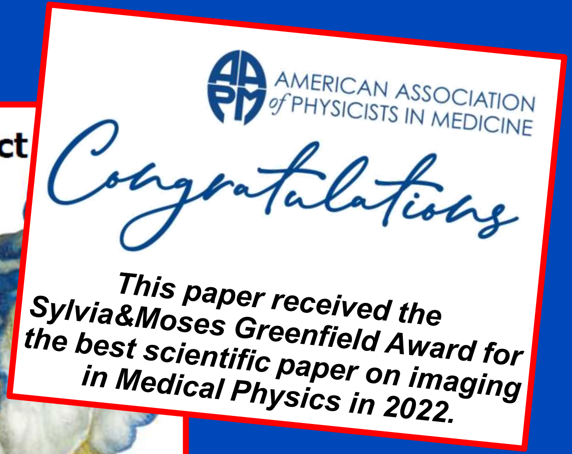
Conclusions on riskTCM

- Risk-specific TCM minimizes the patient risk.
- With D_{eff} as a risk model riskTCM can reduce risk b[...] to 30%, compared with the gold standar[...]
- Other risk m[...] weight- and sex-specific models, car[...] with riskTCM as well.
- Note:
  - mAsTCM = good for the x-ray tube
  - riskTCM = good for the patient
  - detector flux equalizi[...] TCM = good for the detector

It is up to the vendors to take action!







L. Klein, C. [...] S. Sawall, A. Maier, M. Lell, J. Maier, and M. Kachelrieß. Patient-specific radiation risk-based tube current modulation for diagnostic CT. M[...]05, July 2022. *This paper received the Sylvia&Moses Greenfield Award for the best scientific paper on imaging in Medical Physics in 2022.*

Thank You!

- This presentation will soon be available at www.dkfz.de/ct.
- Job opportunities through DKFZ's international PhD or Postdoctoral Fellowship programs (marc.kachelriess@dkfz.de).
- Parts of the reconstruction software were provided by RayConStruct® GmbH, Nürnberg, Germany.