A Novel CT Tube Current Modulation Technique That Minimizes Patient Risk (riskTCM)

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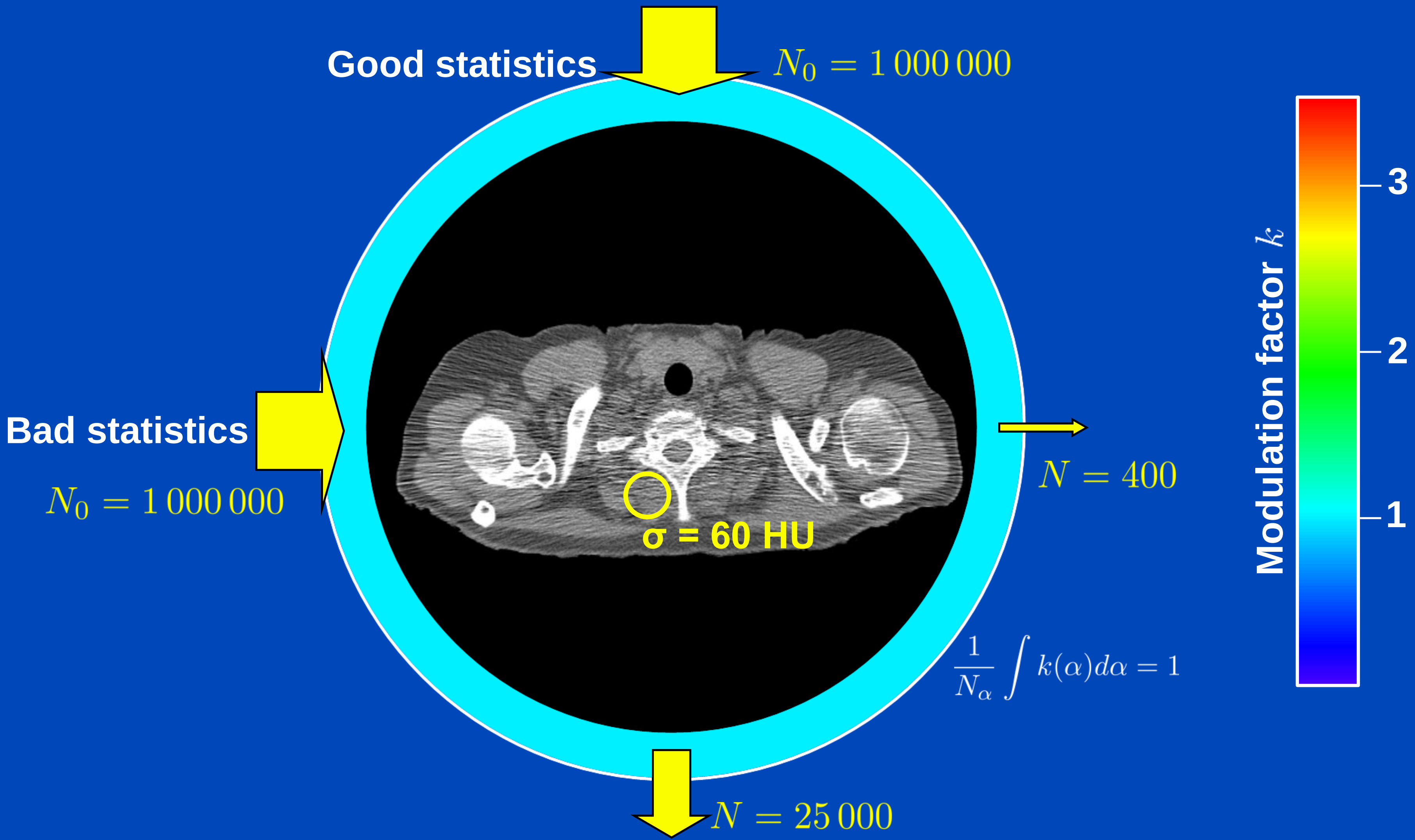
Aim

Design a tube current modulation (TCM) that minimizes the radiation risk by taking into account varying radiation sensitivities of different organs, e.g. by minimizing the effective dose (riskTCM).

And to compare riskTCM to state-of-the-art TCM (mAsTCM) and a constant tube current (noTCM).

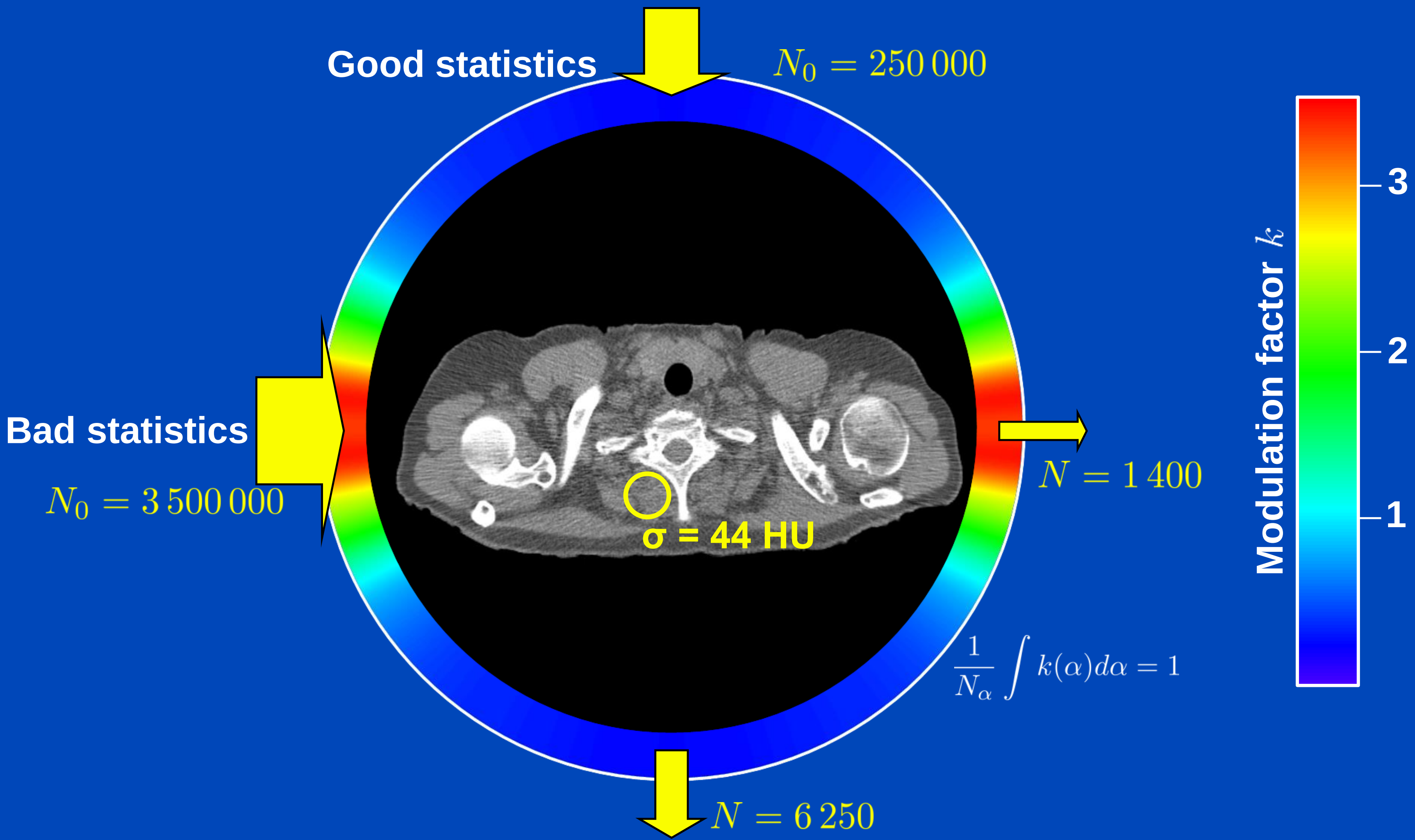
Tube Current Modulation



Constant tube current: High, inhomogeneous noise.

M. Gies, W. A. Kalender, H. Wolf, C. Suess, M. T. Madsen, “Dose reduction in CT by anatomically adapted tube current modulation. I. Simulation studies”, Medical Physics 26 (11): 2235–2247 (1999).

Tube Current Modulation



Modulated tube current: Lower, more homogeneous noise.

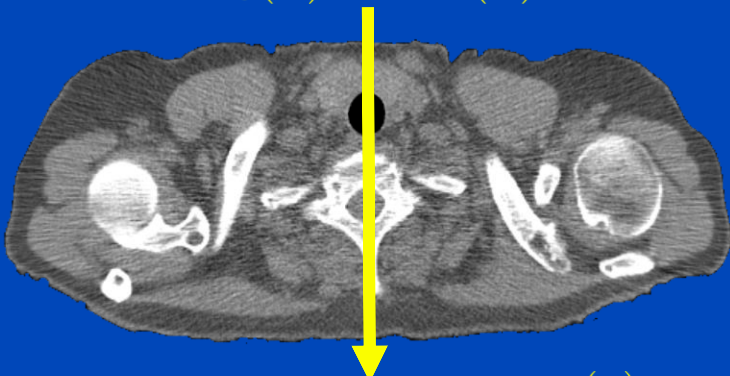
M. Gies, W. A. Kalender, H. Wolf, C. Suess, M. T. Madsen, "Dose reduction in CT by anatomically adapted tube current modulation. I. Simulation studies", Medical Physics 26 (11): 2235–2247 (1999).

Tube Current Modulation

From a mathematical perspective

- **The tube current modulation curve $I(\alpha)$ is chosen such that the variance in the CT reconstruction is minimal**

$$N_0(\alpha) = c \cdot I(\alpha)$$



$$N(\alpha) = c \cdot I(\alpha) \cdot e^{-p(\alpha)}$$

  - **X-rays reaching the detector follow Poisson statistics:** $\sigma^2_{N(\alpha)} = N(\alpha) = c \cdot I(\alpha) \cdot e^{-p(\alpha)}$
  - **Variance propagation to projection domain yields:** $\sigma^2_{p(\alpha)} = \dfrac{1}{c \cdot I(\alpha) \cdot e^{-p(\alpha)}}$
  - **Variance propagation to image domain yields:**

$$\sigma^2_f = \sum_\alpha \frac{1}{c \cdot I(\alpha) \cdot e^{-p(\alpha)}}$$

- **Cost function:**

$$C = \sum_\alpha \frac{1}{c \cdot I(\alpha) \cdot e^{-p(\alpha)}} + \boxed{\lambda \left(\sum_\alpha I(\alpha) - \mathrm{const} \right)}$$

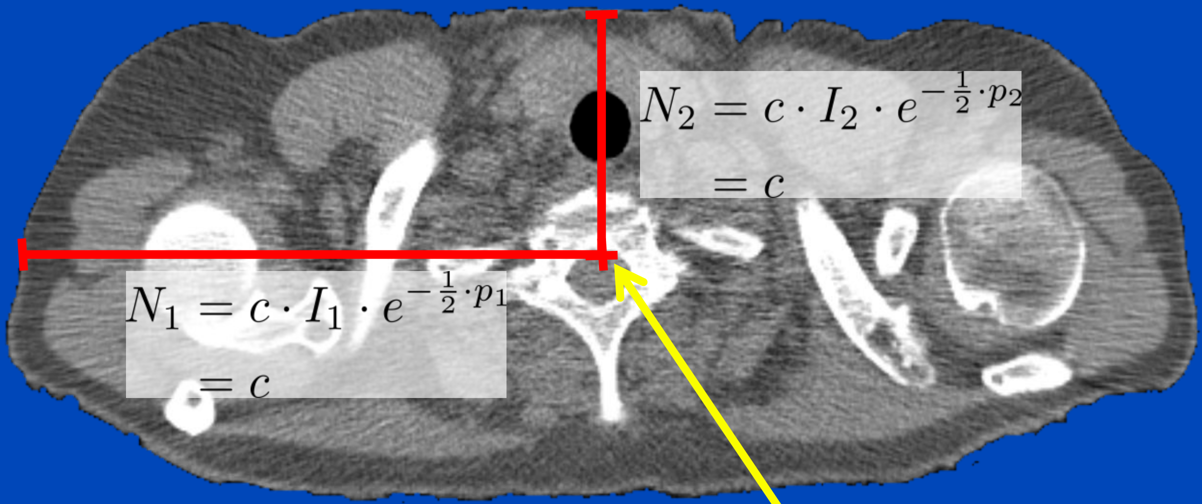
For riskTCM, we also account for the effective dose $D_{\mathrm{eff}}(\alpha)$ here, as you will see later.

- **Minimization yields:** $I(\alpha) \propto e^{\frac{1}{2} \cdot p(\alpha)}$

Tube Current Modulation

Interpretation

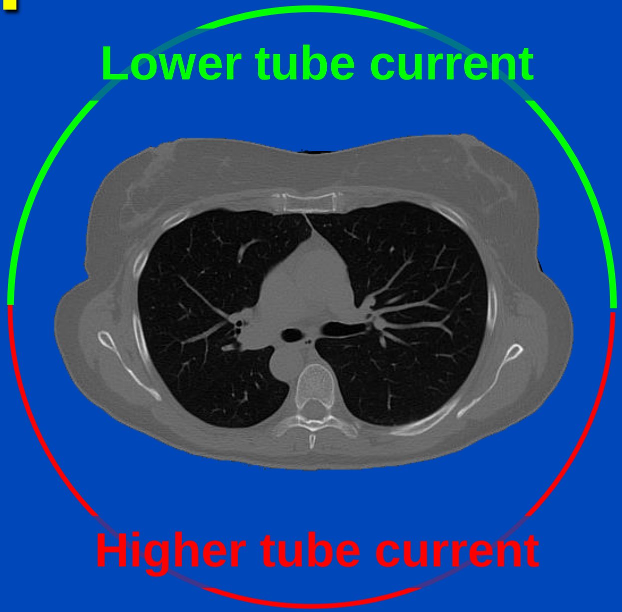
- **Tube current:** $I(\alpha) \propto e^{\frac{1}{2}\cdot p(\alpha)}$
- **Photon numbers:** $N(\alpha) = c \cdot I(\alpha) \cdot e^{-p(\alpha)}$



Rule of thumb:
The number of quanta reaching the center of the patient should be constant for all view angles.

Organ-Specific Tube Current Modulation

- Limit the radiation exposure of sensitive organs at the anterior body surface (breast, thyroid glands, eyes).
- Tube current is lowered in a 120° to 180° interval in front of the organ.
- Tube current may be increased for posterior-anterior views to maintain image quality.

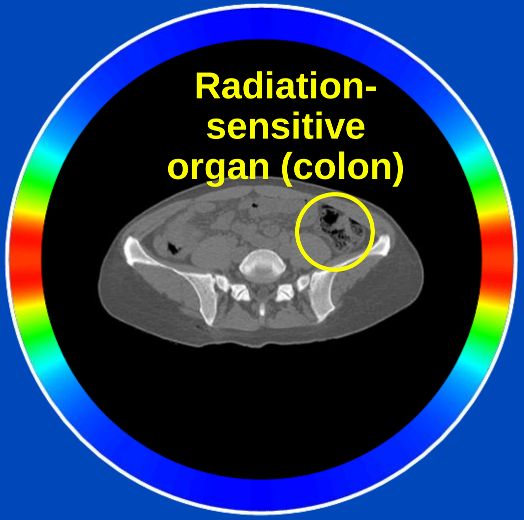


	Canon	GE	Philips	Siemens
TCM	**SUREExposure 3D**	**SmartmA**	**DoseRight ACS**	**CARE Dose 4D**
Organ-Specific AEC/TCM	OEM, Decrease anterior tube current	ODM, Decrease anterior tube current	Liver DRI, Different image quality setting for the liver	XCare, Decrease anterior tube current, increase posterior tube current

dkfz.

TCM Minimizing the Radiation Risk
Motivation

- Conventional tube current modulation approaches can only account for a few organs.
- Conventional tube current modulation approaches do not have access to the actual dose distribution, but are based on minimizing the mAs product.



➡ Additional prior knowledge may enable more sophisticated approaches.

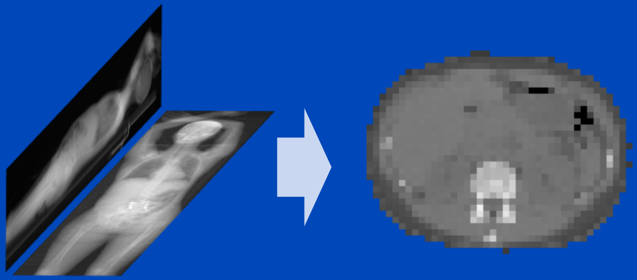
- Here: Use deep learning-based prior knowledge to perform a tube current modulation that minimizes the radiation risk, e.g. the effective dose.

TCM Minimizing the Radiation Risk

Basic workflow

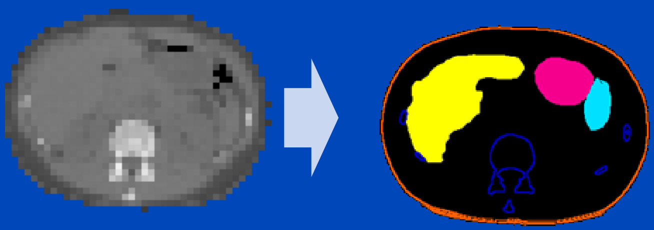
1. **Coarse reconstruction from two scout views**

   X. Ying, et al., "X2CT-GAN: Reconstructing CT From Biplanar X-Rays With Generative Adversarial Networks," *CVPR 2019*



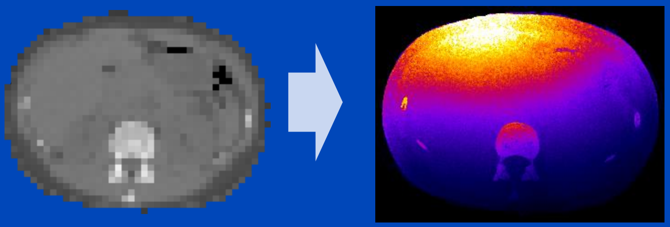
2. **Segmentation of radiation-sensitive organs**

   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

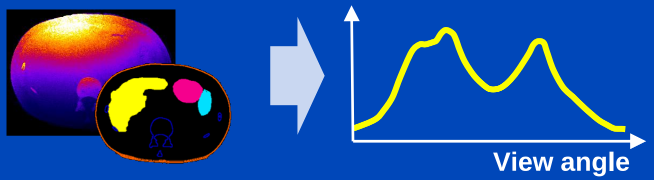


3. **Calculation of the effective dose per view using the deep dose estimation (DDE)**

   J. Maier, M. Kachelrieß et al., " Real–Time Estimation of Patient Dose Distributions and Organ Dose Values for Medical CT using the Deep Dose Estimation." Med. Phys. 2021, currently under review.



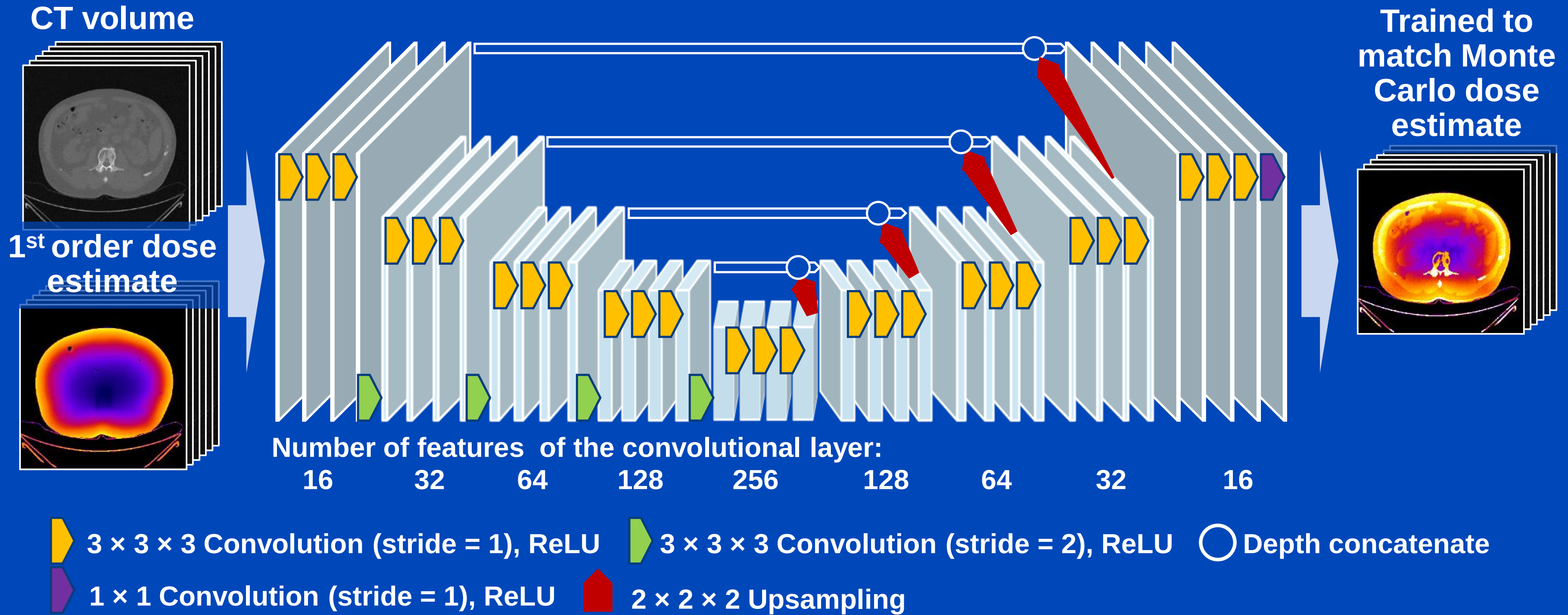
4. **Determination of the tube current modulation curve that minimizes the radiation risk (riskTCM)**



Deep Dose Estimation (DDE)

Basic principle

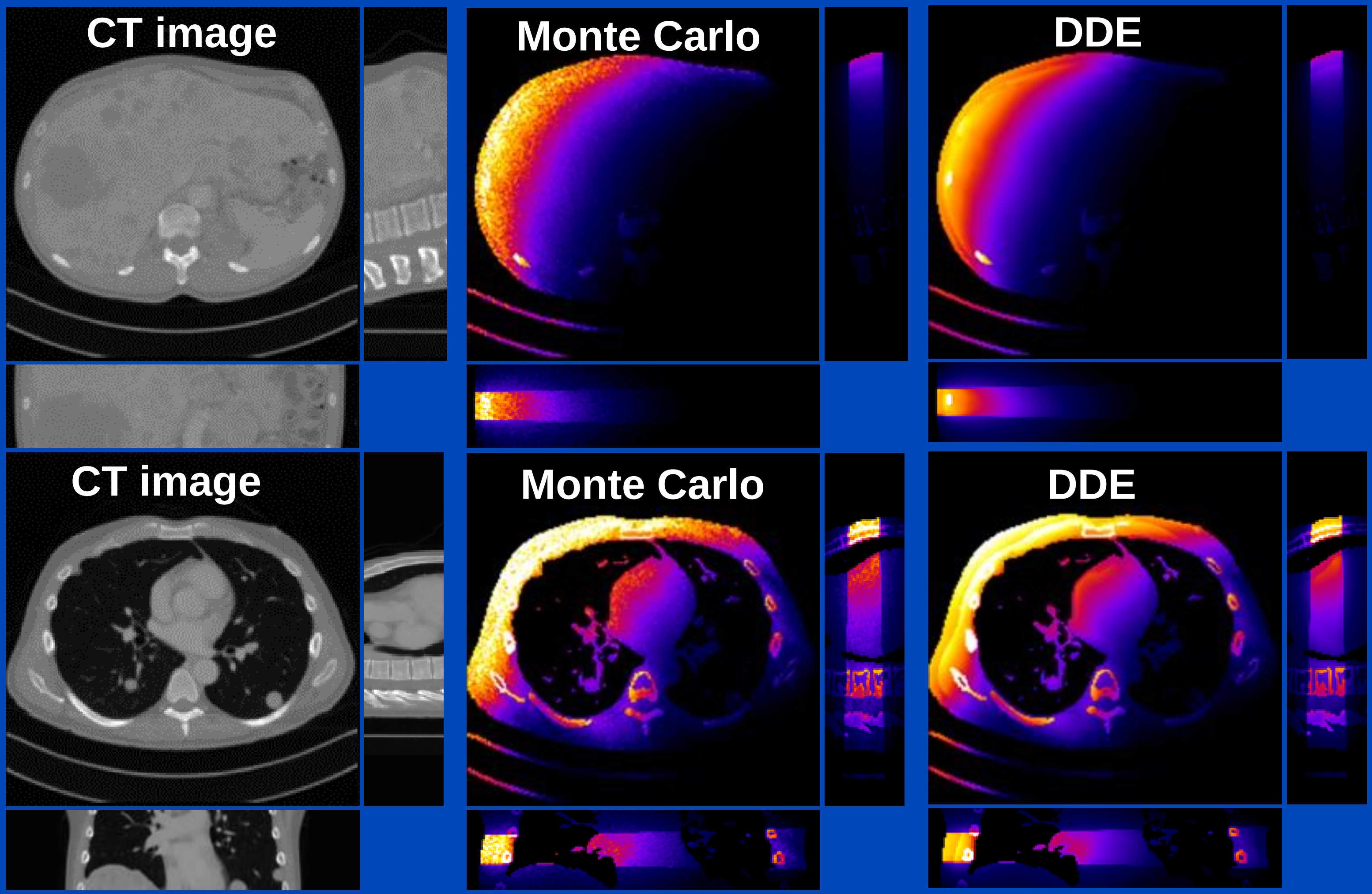
- Monte Carlo (MC) simulation is the gold standard for patient-specific dose estimation, but too slow to be applied routinely.
- ⇨ Training of a deep convolution to reproduce MC simulations given only the CT image and a 1st order dose estimate as input.



J. Maier, E. Eulig, S. Dorn, S. Sawall, M. Kachelrieß, in *Proceedings of the IEEE Nuclear Science Symposium and Medical Imaging Conference* (2018).
J. Maier, M. Kachelrieß et al., " Real–Time Estimation of Patient Dose Distributions and Organ Dose Values for Medical CT using the Deep Dose Estimation." Med. Phys. 2021, currently under review.

Deep Dose Estimation (DDE)

Dose predictions for a single view



Mean relative error on the testing data set: 5%

TCM Minimizing the Radiation Risk

Determination of the modulation curve

- Calculation of dose estimates for each view using the deep dose estimation
- Calculation of the effective dose according to the ICRP weighting factors for each view α:

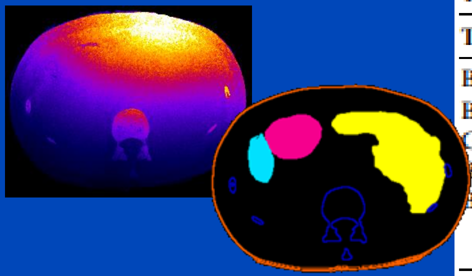


Table 3. Recommended tissue weighting factors.

Tissue	w_T	$\sum w_T$
Bone-marrow (red), Colon, Lung, Stomach, Breast, Remainder tissues*	0.12	0.72
Gonads	0.08	0.08
Bladder, Oesophagus, Liver, Thyroid	0.04	0.16
Bone surface, Brain, Salivary glands, Skin	0.01	0.04
	Total	1.00

$$D_{\mathrm{eff}}(\alpha) = \sum_T w_T \cdot D_T(\alpha)$$

- Minimization of the novel cost function to obtain the final riskTCM curve.

Cost Function

- **For mAsTCM, the cost function is**

$$C = \underbrace{\sum_\alpha \frac{1}{c \cdot I(\alpha) \cdot e^{-p(\alpha)}}}_{\text{Image variance}} + \lambda \left(\sum_\alpha I(\alpha) - \text{const} \right)$$

- **For riskTCM, the equation is of the form**

$$C = \sum_\alpha \text{Image variance}(\alpha) + \lambda \left(\sum_\alpha I(\alpha) \cdot D_{\text{eff}}(\alpha) - \text{const} \right)$$

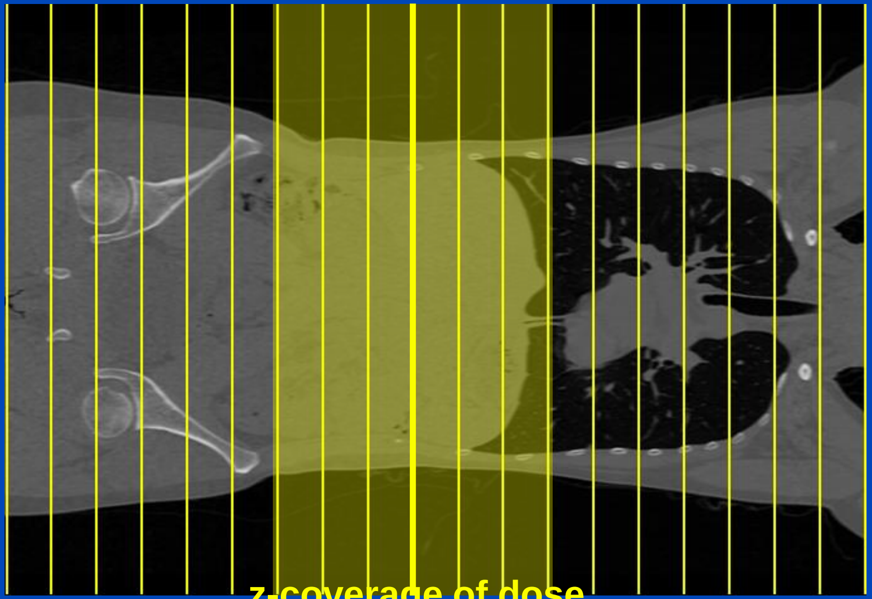
- **The cost function for riskTCM also takes into account that the effective dose is dependent on the direction and is therefore not the same for two complementary (180°) rays, i.e.** $D_{\text{eff}}(\alpha_{\text{D}}) \neq D_{\text{eff}}(\alpha_{\text{C}})$**.**

Retrospective Study

- Simulation of CT scans covering different anatomies at 70 kV, 120 kV, and 150 kV (6 mm Al prefiltration).
- Simulation of consecutive circle scans (38.4 mm apart), each with a z-collimation of 38.4 mm.

Axial view

Coronal view



Effective Dose at Same Image Noise for 70 kV

Average over all patients

Anatomical region	noTCM	mAsTCM	riskTCM
Head+Arms	151%	100%	88%
Neck+Arms	222%	100%	71%
Thorax	112%	100%	76%
Abdomen	111%	100%	67%
Pelvis	149%	100%	73%

Effective Dose at Same Image Noise for 120 kV and 150 kV

Average over all patients

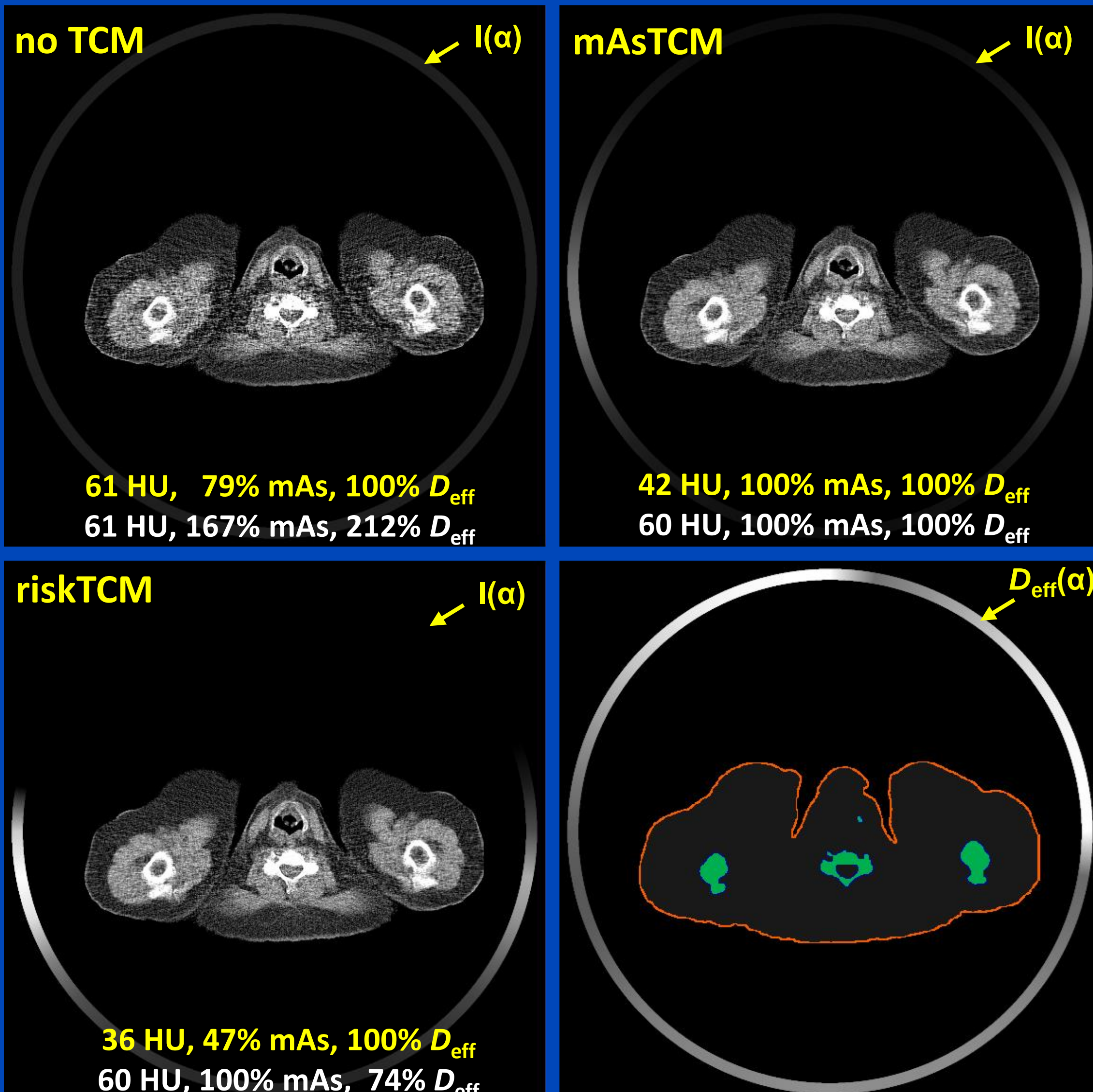
120 kV

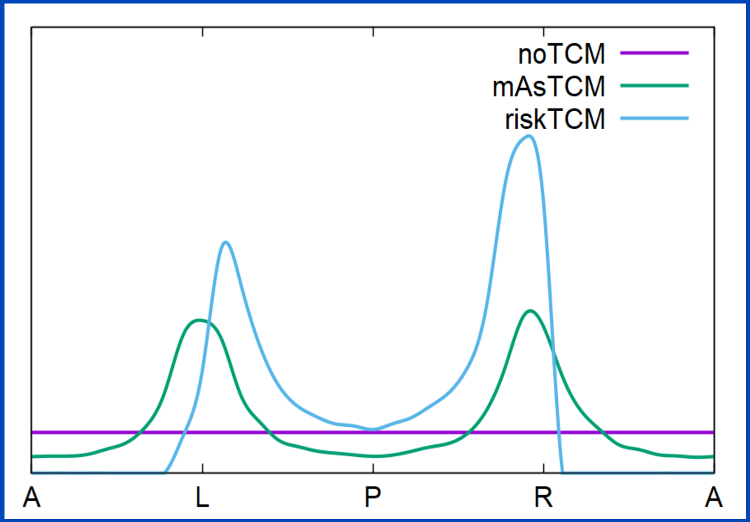
Anatomical region	noTCM	mAsTCM	riskTCM
Head+Arms	156%	100%	91%
Neck+Arms	208%	100%	77%
Thorax	112%	100%	82%
Abdomen	112%	100%	71%
Pelvis	149%	100%	76%

150 kV

Anatomical region	noTCM	mAsTCM	riskTCM
Head+Arms	156%	100%	89%
Neck+Arms	213%	100%	77%
Thorax	114%	100%	83%
Abdomen	112%	100%	72%
Pelvis	149%	100%	81%

Modulation Curves for 70 kV





Left: noTCM, mAsTCM, riskTCM images and the organ segmentation of a neck examination. The circular density plots circumscribing the 50 cm FOM indicate the tube current curves $I(\alpha)$ for the CT images and the effective dose curve $D_{eff}(\alpha)$ for the organ segmentation image. The CT images are shown at constant D_{eff}.

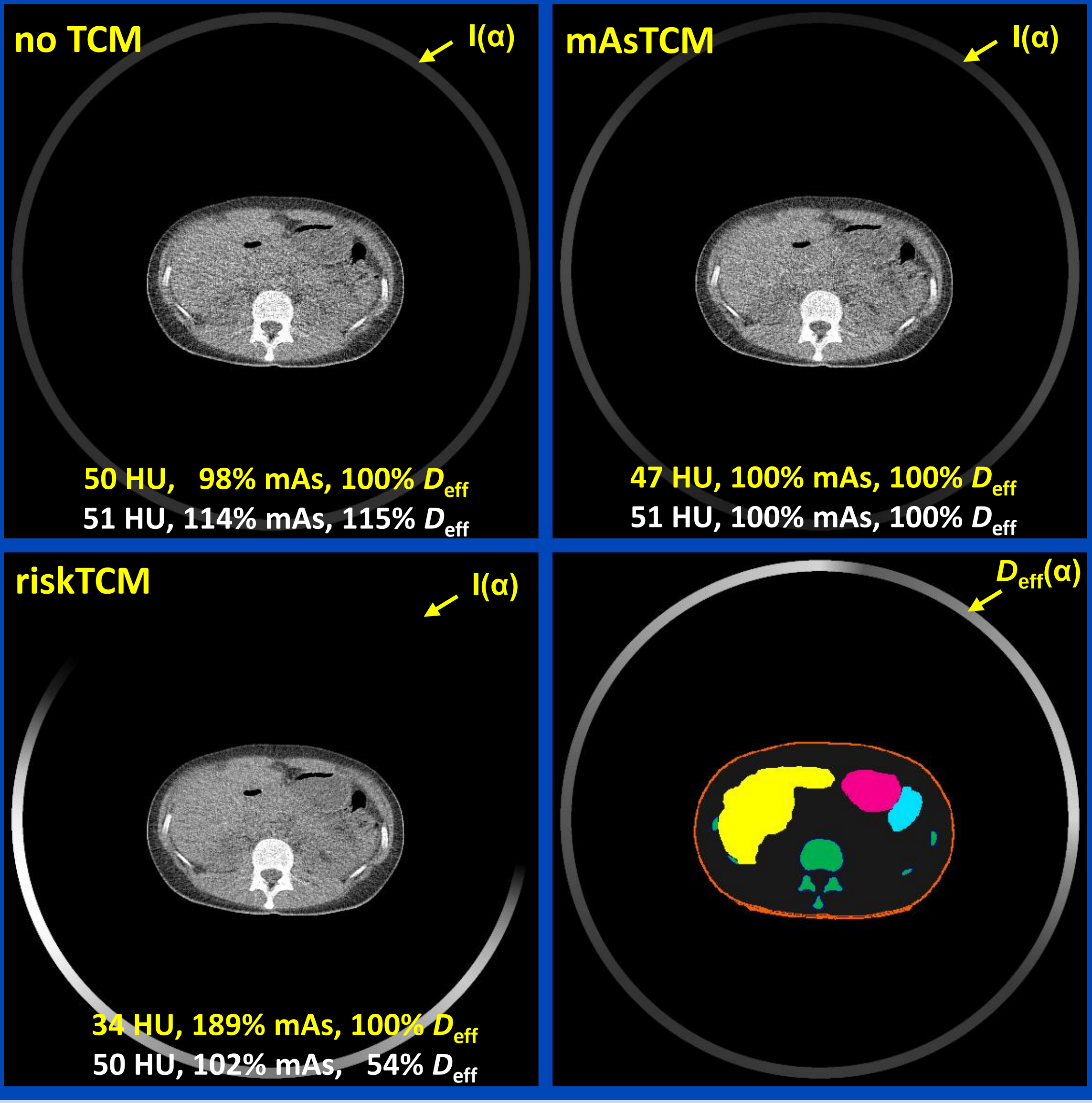
Quantitative values:

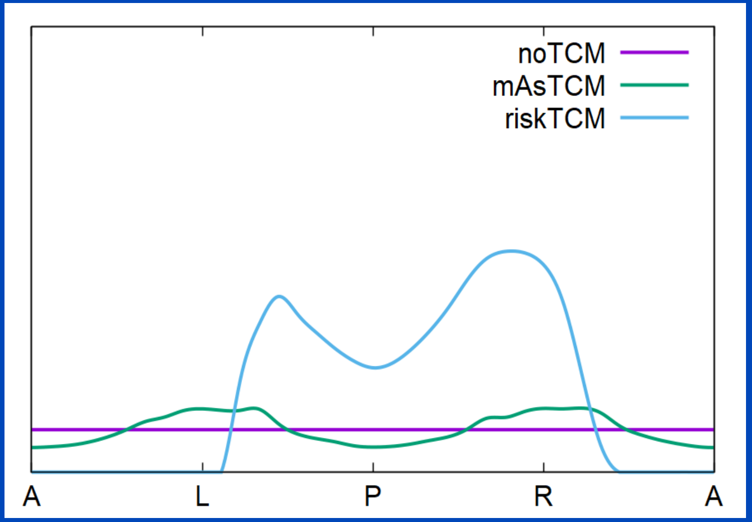
- **Yellow:** Image noise, mAs integrals and D_{eff} for constant D_{eff}.
- **White:** Image noise, mAs integrals and D_{eff} for constant image noise.

Right: Resulting TCM curves I(α). The ticks indicate the source positions anterior, right, posterior, left, anterior.

C = 25 HU, *W* = 400 HU

Modulation Curves for 70 kV





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Conclusions

- All anatomical regions benefit from riskTCM.
- The highest potential D_{eff} reduction is seen for the abdomen, i.e. about 33% compared to mAsTCM, on average, for 70 kV.
- In case of pelvis, thorax and neck examinations, the proposed method achieves a D_{eff} reduction of about 24% to 30% compared to mAsTCM, for 70 kV.
- The proposed riskTCM method can be easily adapted to risk measures other than D_{eff}.

Thank You!

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

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