Potential CT Radiation Dose Reduction to the Female Breast by a Novel Risk-Minimizing Tube Current Modulation

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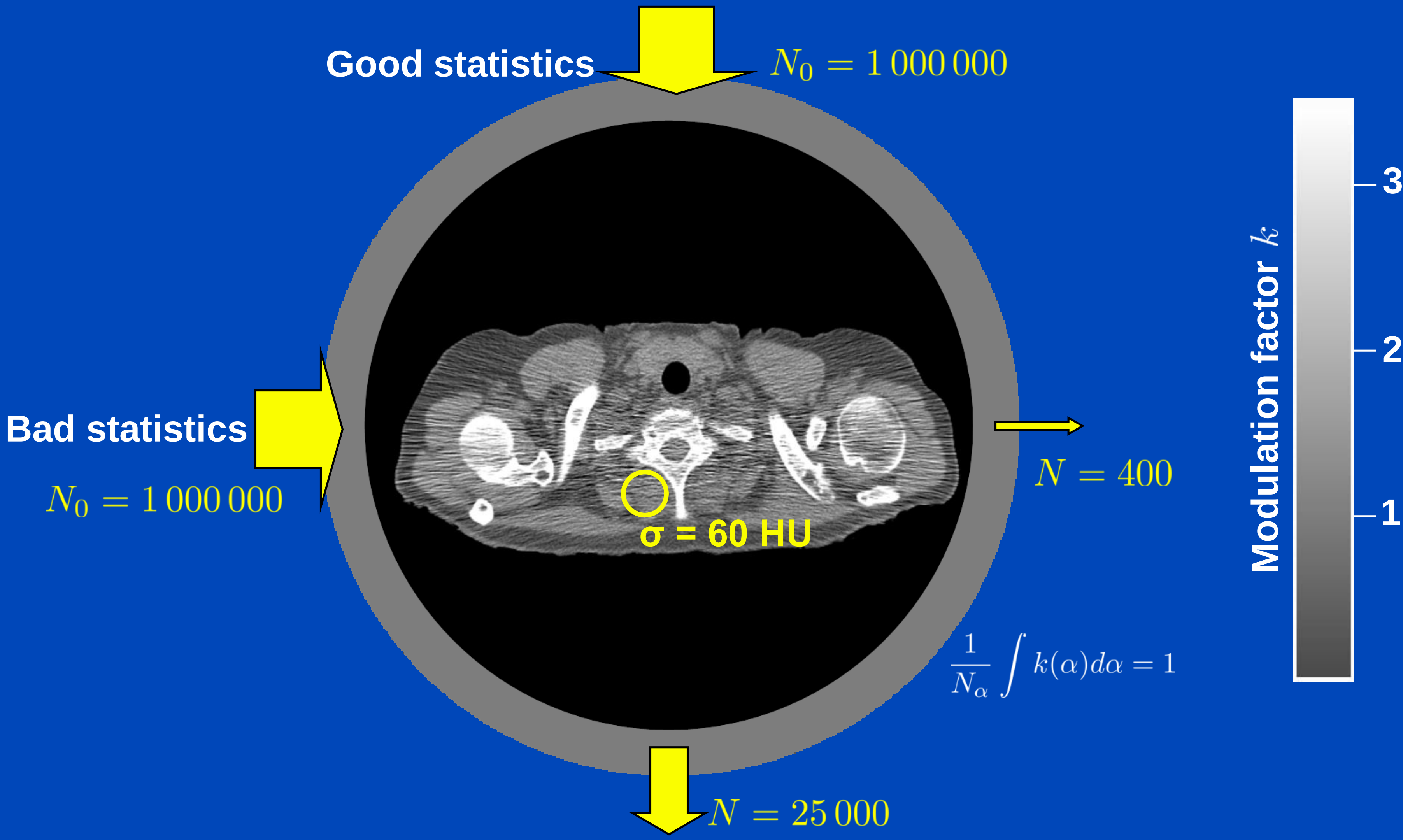
Aim

To evaluate 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 this riskTCM method to the state-of-the-art TCM (mAsTCM) and an established organ-specific TCM (osTCM) with special focus on the female breast.

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).

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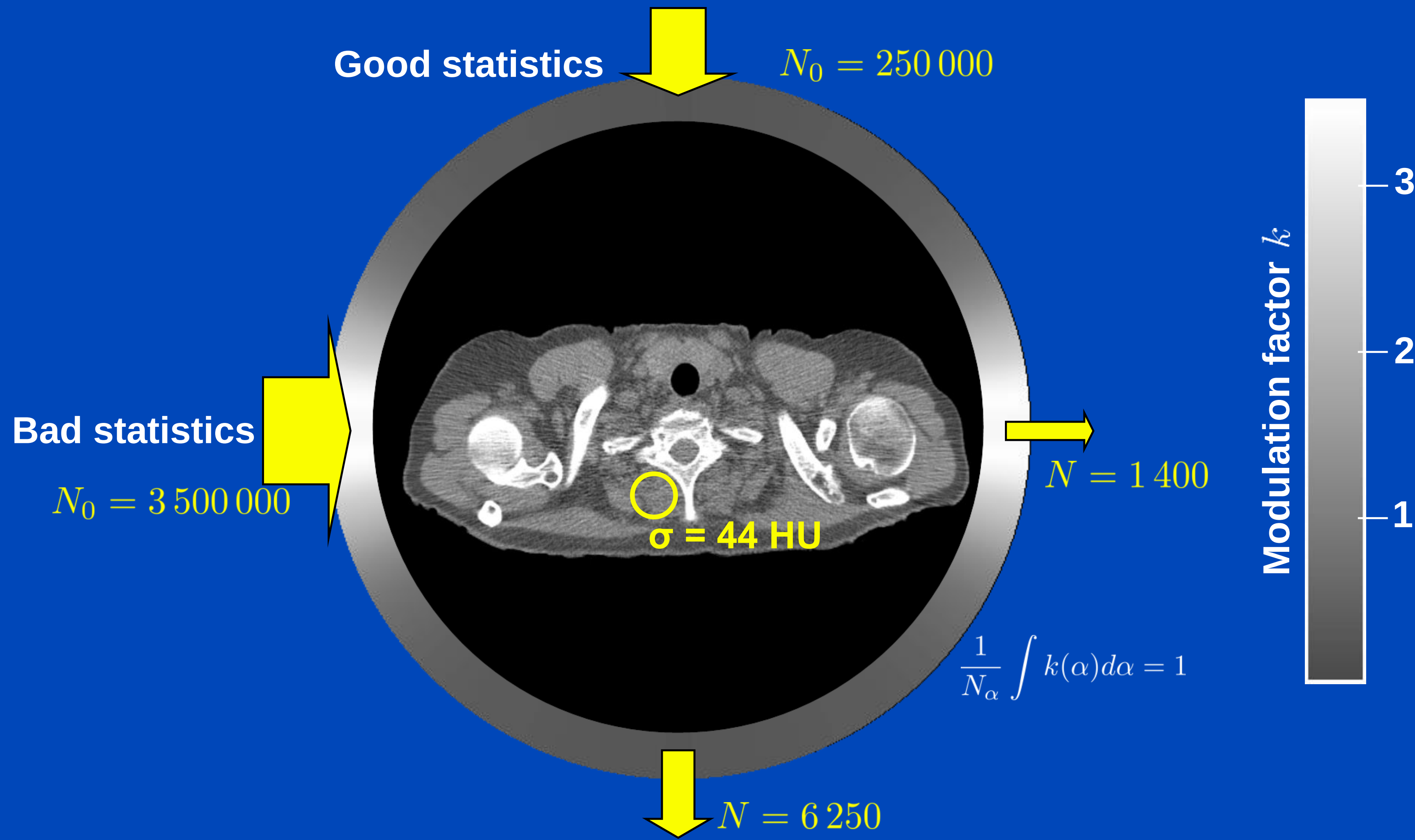
Tube Current Modulation



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).

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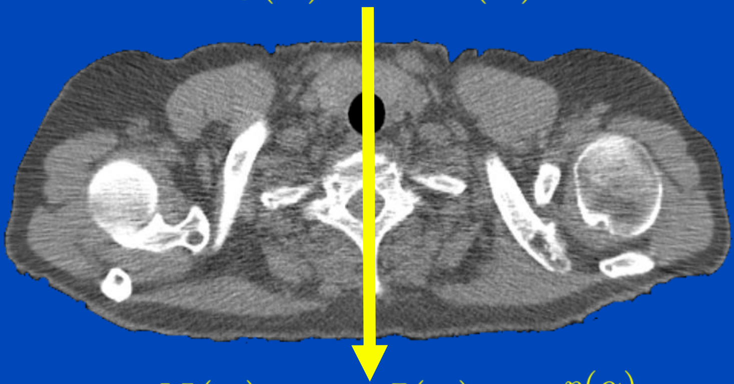
Tube Current Modulation

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:** $$\sigma^2_{p(\alpha)} = \frac{1}{c \cdot I(\alpha) \cdot e^{-p(\alpha)}}$$
- **Variance propagation to image domain yields:** $$\sigma^2_f = \sum_\alpha \frac{1}{c \cdot I(\alpha) \cdot e^{-p(\alpha)}}$$

- **Cost function:**

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

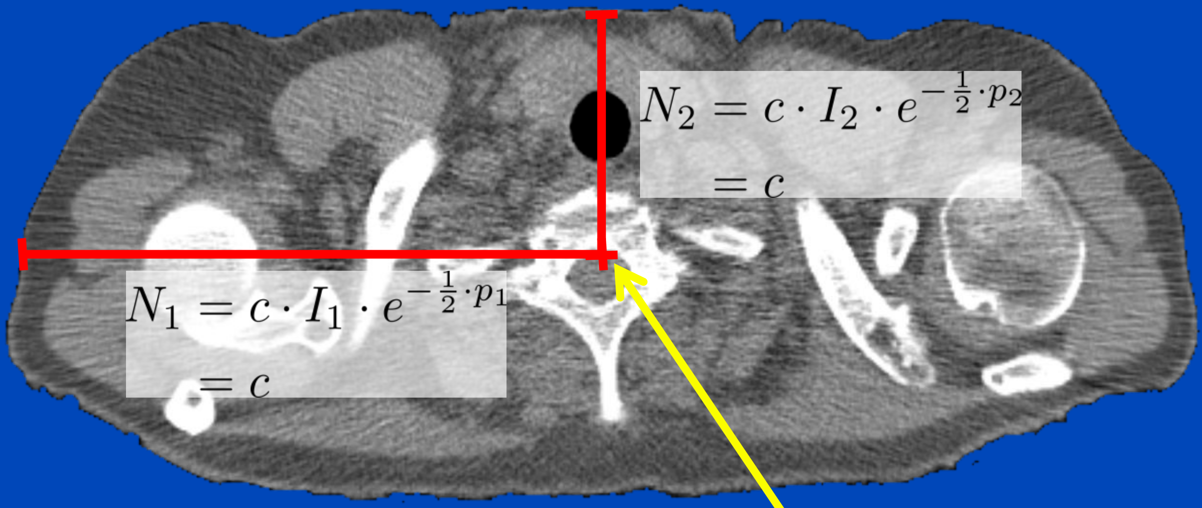
For riskTCM, we also account for the effective dose $D_{\text{eff}}(\alpha)$ here, as you will see later.

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

Tube Current Modulation

Interpretation

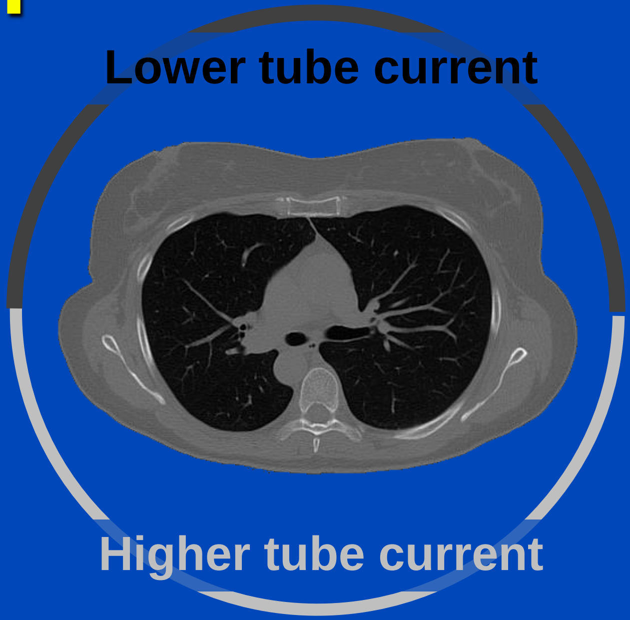
- **Tube current:** $I(\alpha) \propto e^{\frac{1}{2} \cdot p(\alpha)}$
- **Photon numbers:** $N(\alpha) = c \cdot I(\alpha) \cdot e^{-p(\alpha)}$



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

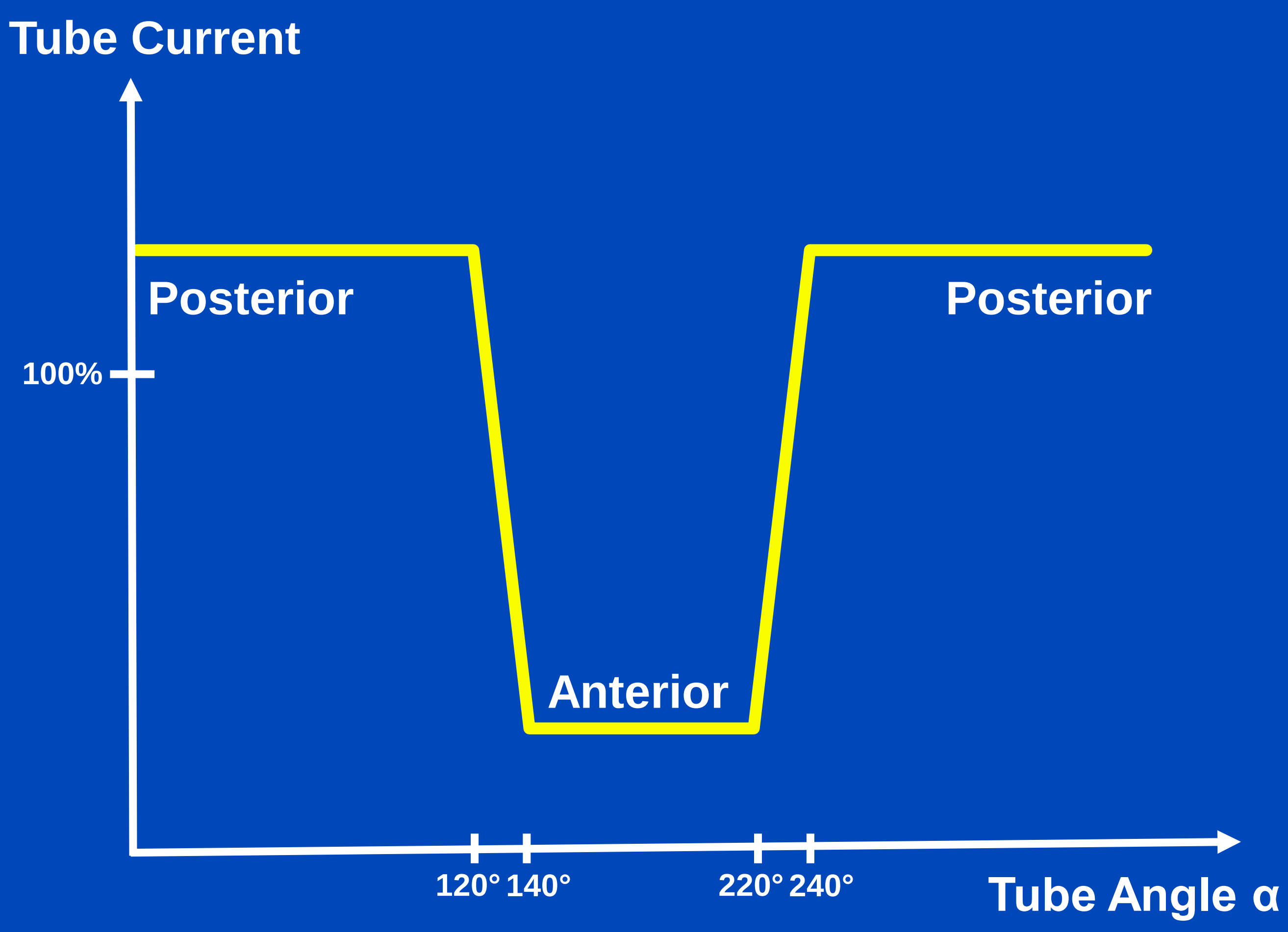
Organ-Specific Tube Current Modulation

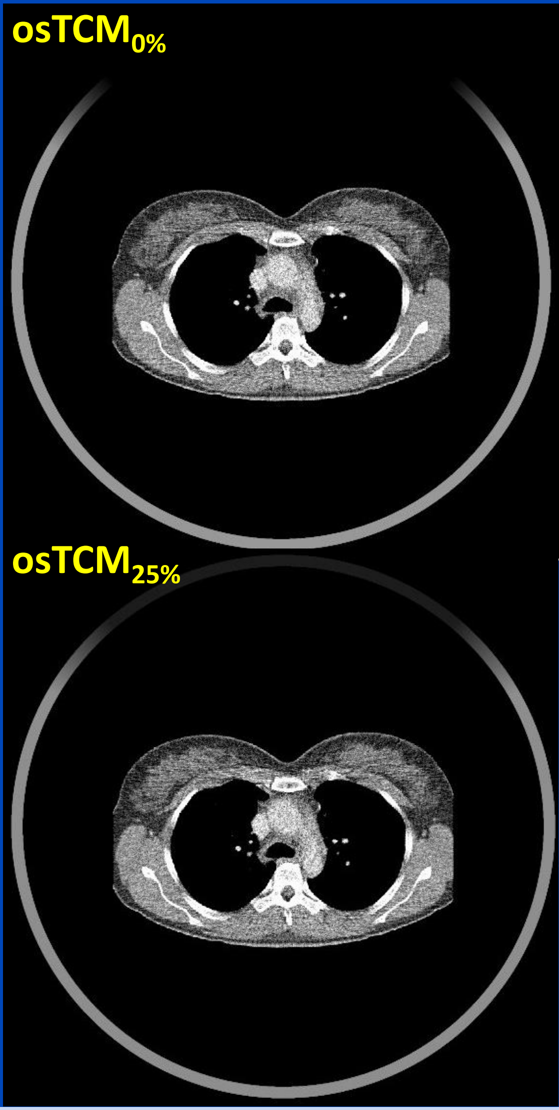
- **Limit the radiation exposure of sensitive organs at the anterior body surface (breast, thyroid glands, eyes).**
- **Tube current is lowered in a 120° to 180° interval in front of the organ.**
- **Tube current may be increased for posterior-anterior views to maintain image quality.**



	Canon	GE	Philips	Siemens
TCM	**^{SURE}Exposure 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

Organ-Specific Tube Current Modulation





D. Ketelsen et al. Automated computed tomography dose saving algorithm to protect radiosensitive tissues: estimation of radiation exposure and image quality considerations. Invest Radiol, 47(2):148–52, 2012

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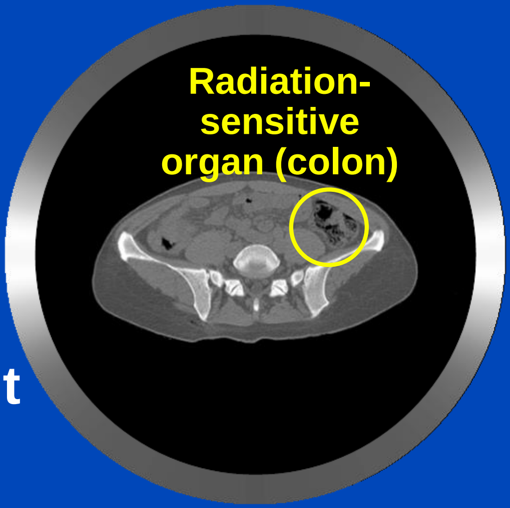
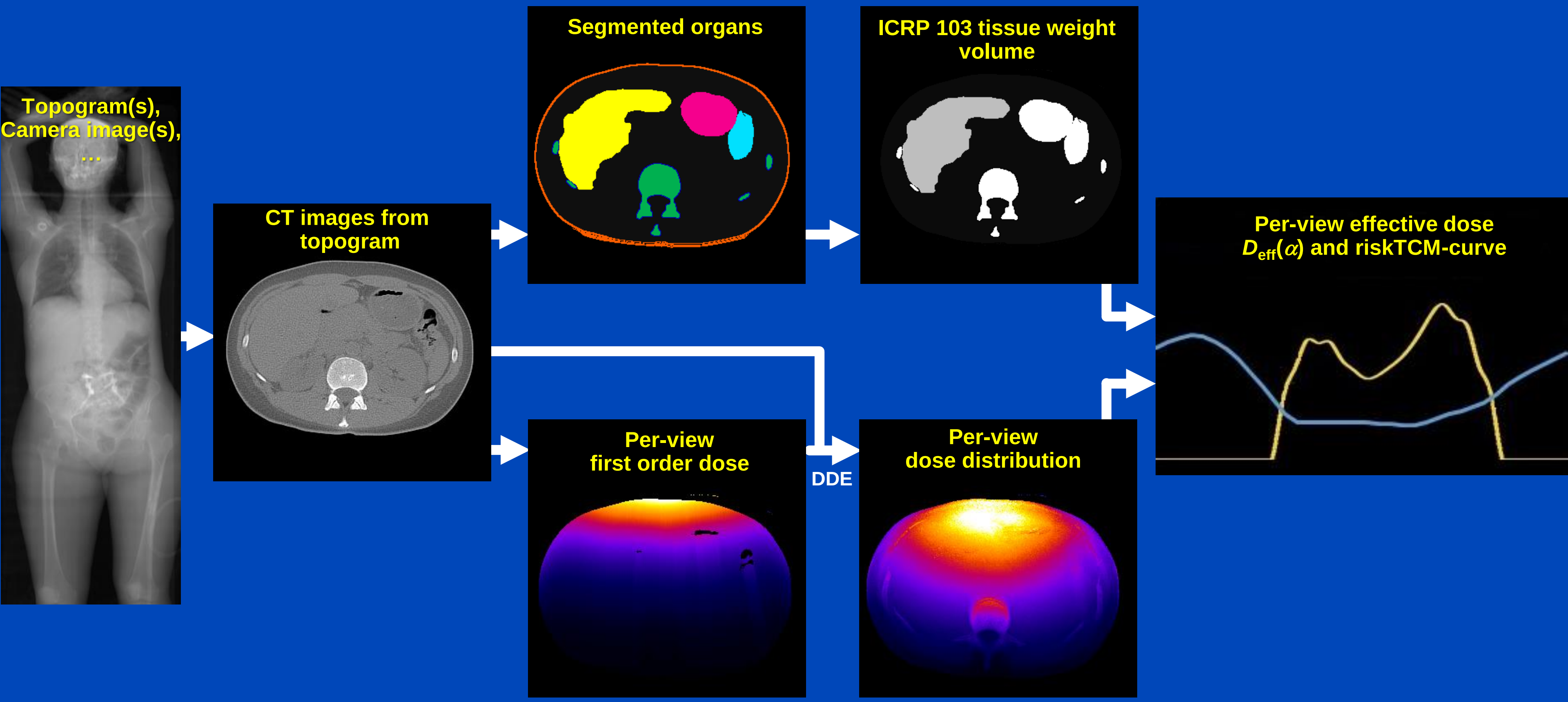
TCM Minimizing the Radiation Risk

Motivation

- Conventional tube current modulation approaches do not account for organs.
- Organ-specific TCM, as of today, is not patient-specific but rather a static tube current curve for all patients and only for a few organs.
- Conventional TCM approaches do not have access to the actual dose distribution and patient organ location, 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



L. Klein, C. Liu, J. Steidel, L. Enzmann, M. Knaup, S. Sawall, A. Maier, M. Lell, J. Maier, M. Kachelrieß. Patient-specific radiation risk-based tube current modulation for diagnostic CT. Med. Phys. 2022;49:4391-4403

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:**

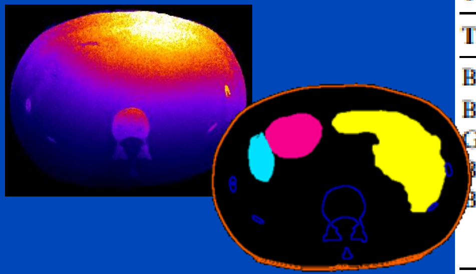


Table 3. Recommended tissue weighting factors.

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

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

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

Cost Function

- For mAsTCM, the cost function is

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

- For riskTCM, the equation is of the form

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

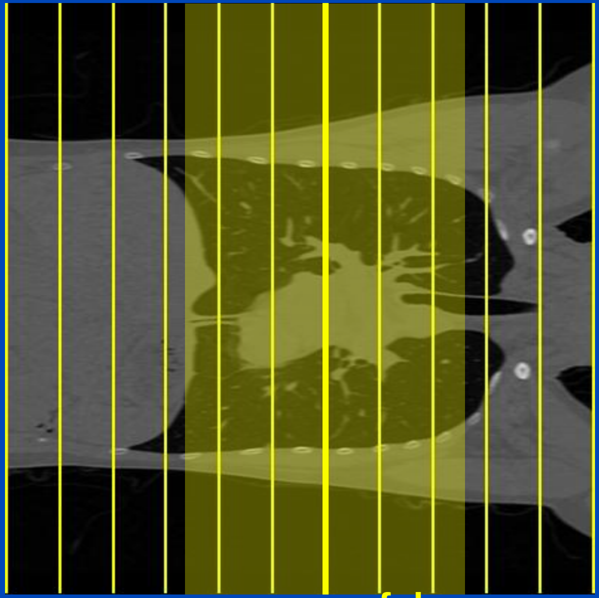
- The cost function for riskTCM also takes into account that the effective dose is dependent on the direction and is therefore not the same for two complementary (180°) rays, i.e. $D_{\text{eff}}(\alpha_{\text{D}}) \neq D_{\text{eff}}(\alpha_{\text{C}})$.

Retrospective Study

- Simulation of CT scans covering the chest at 70 kV (with 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

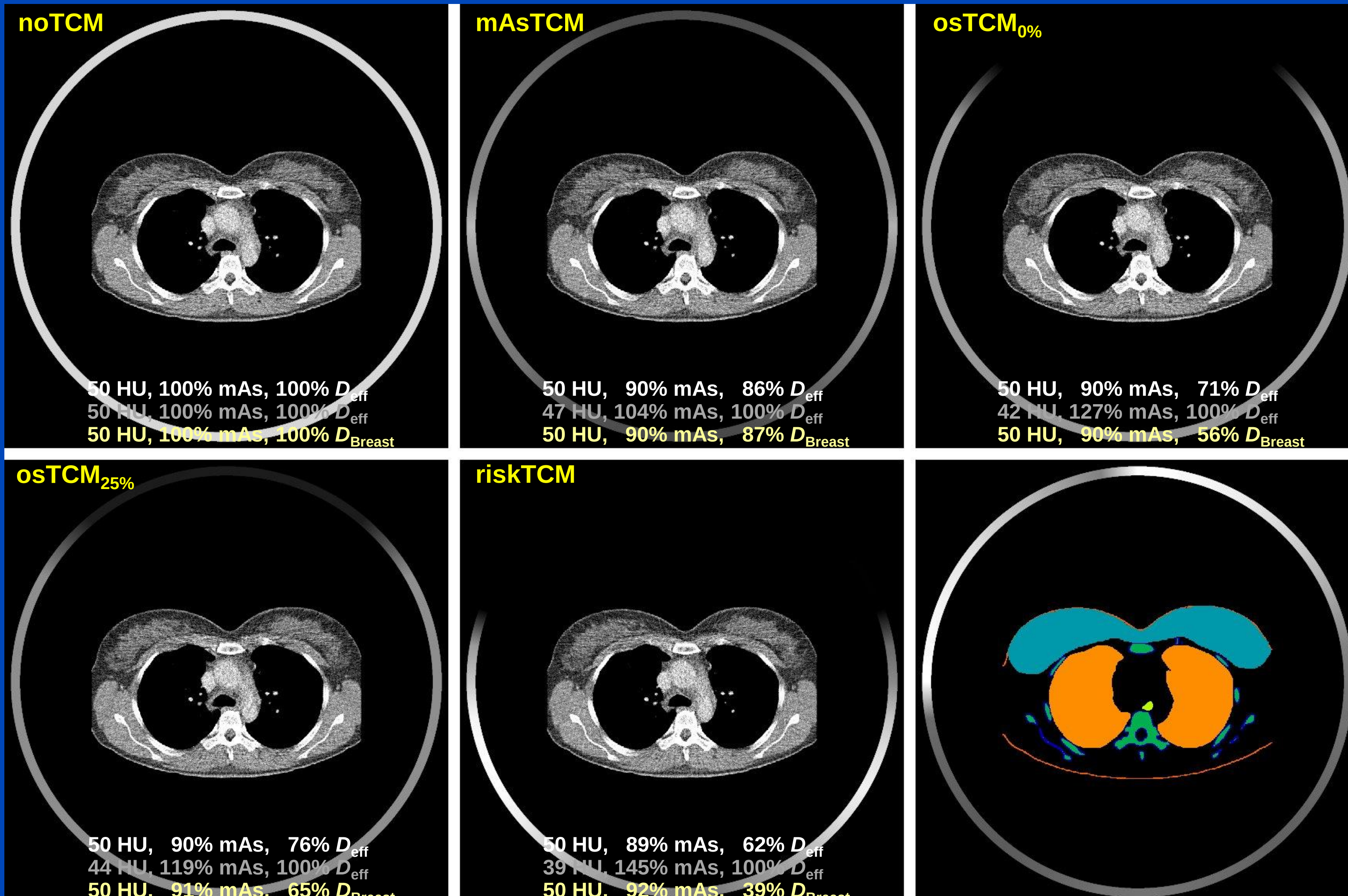


Dose Values at Same Image Noise for 70 kV

Average over all patients

TCM Method	Effective Dose D_{eff}	Dose to the Breast D_{Breast}
noTCM	100%	100%
mAsTCM	86%	93%
$osTCM_{25\%}$	82%	72%
$osTCM_{0\%}$	79%	64%
riskTCM	67%	45%

Results



Data courtesy of Prof. Lell, Nürnberg. *C* = 25 HU, *W* = 400 HU

Conclusions

- The proposed riskTCM method allows for the highest reduction of effective dose.
- Furthermore, the highest reduction of dose to the breast amongst all investigated TCMs was achieved by riskTCM.
- The riskTCM algorithm can easily be adapted to risk measures other than D_{eff}.

Thank You!

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

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