Tube Voltage Modulation for Contrast-Enhanced CT Scans

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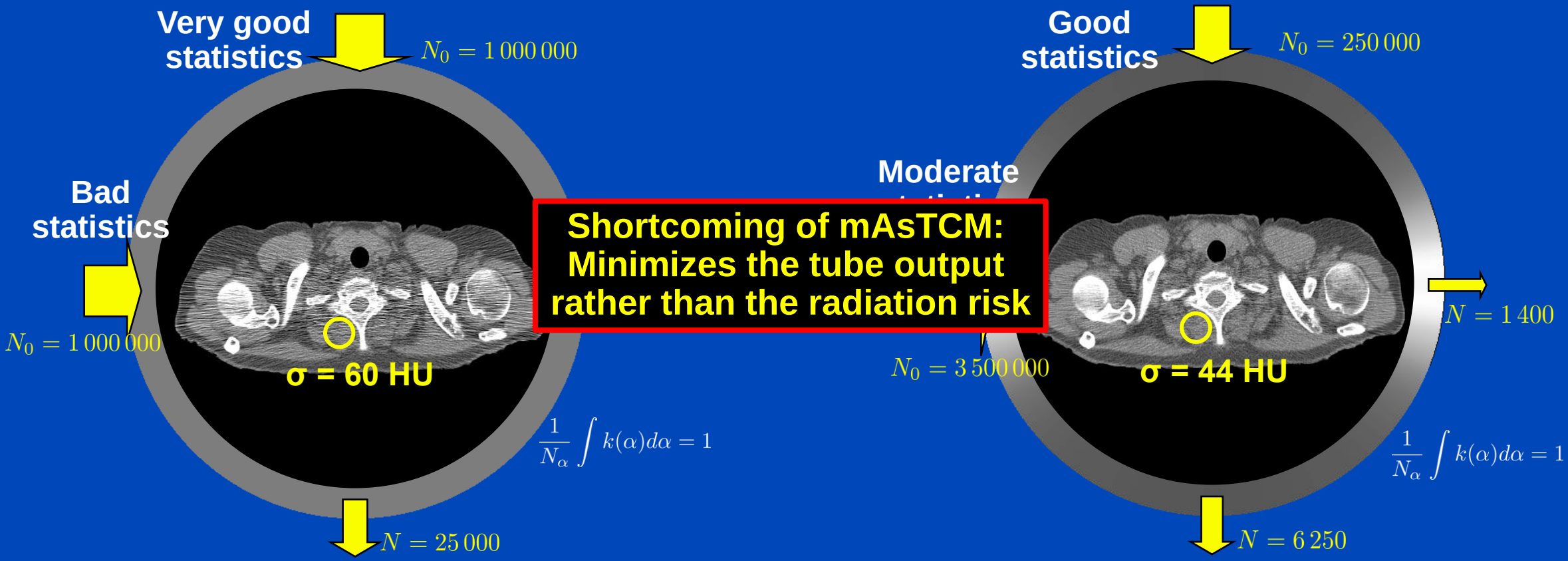
mAs-Minimizing Tube Current Modulation (mAsTCM)

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

Minimize

$$I(\alpha) \propto e^{\frac{1}{2} \cdot p(\alpha)}$$



Constant tube current:
High, inhomogeneous noise

Modulated tube current:
Lower, more homogeneous noise

M. Gies, W. A. Kalender, H. Wolf, C. Suess, and M. T. Madsen, Dose Reduction in CT by Anatomically Adapted Tube Current Modulation. I. Simulation Studies, Med. Phys. 26, 2235-2247 (1999).

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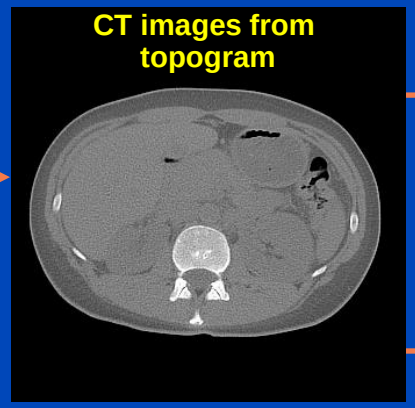
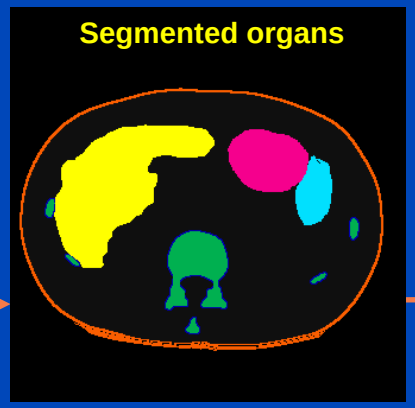
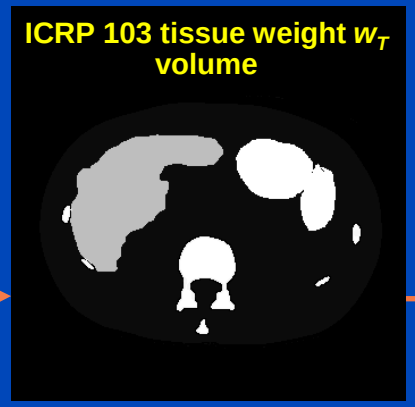
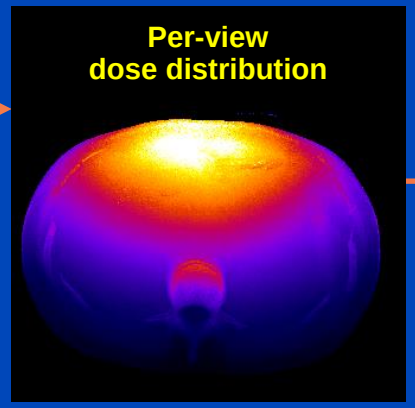
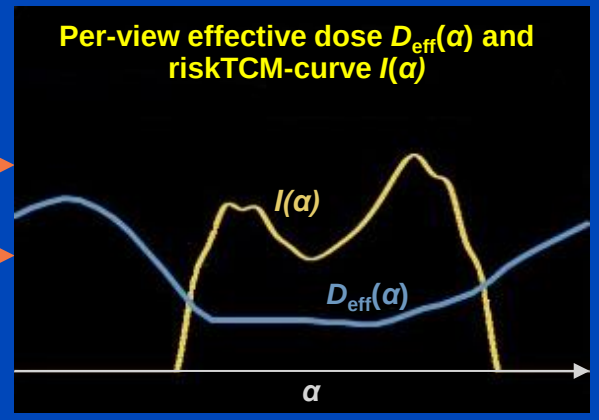
Risk-Minimizing Tube Current Modulation (riskTCM)











AMERICAN ASSOCIATION of PHYSICISTS IN MEDICINE

Congratulations

This paper received the Sylvia&Moses Greenfield Award for the best scientific paper on imaging in Medical Physics in 2022.

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

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

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.*

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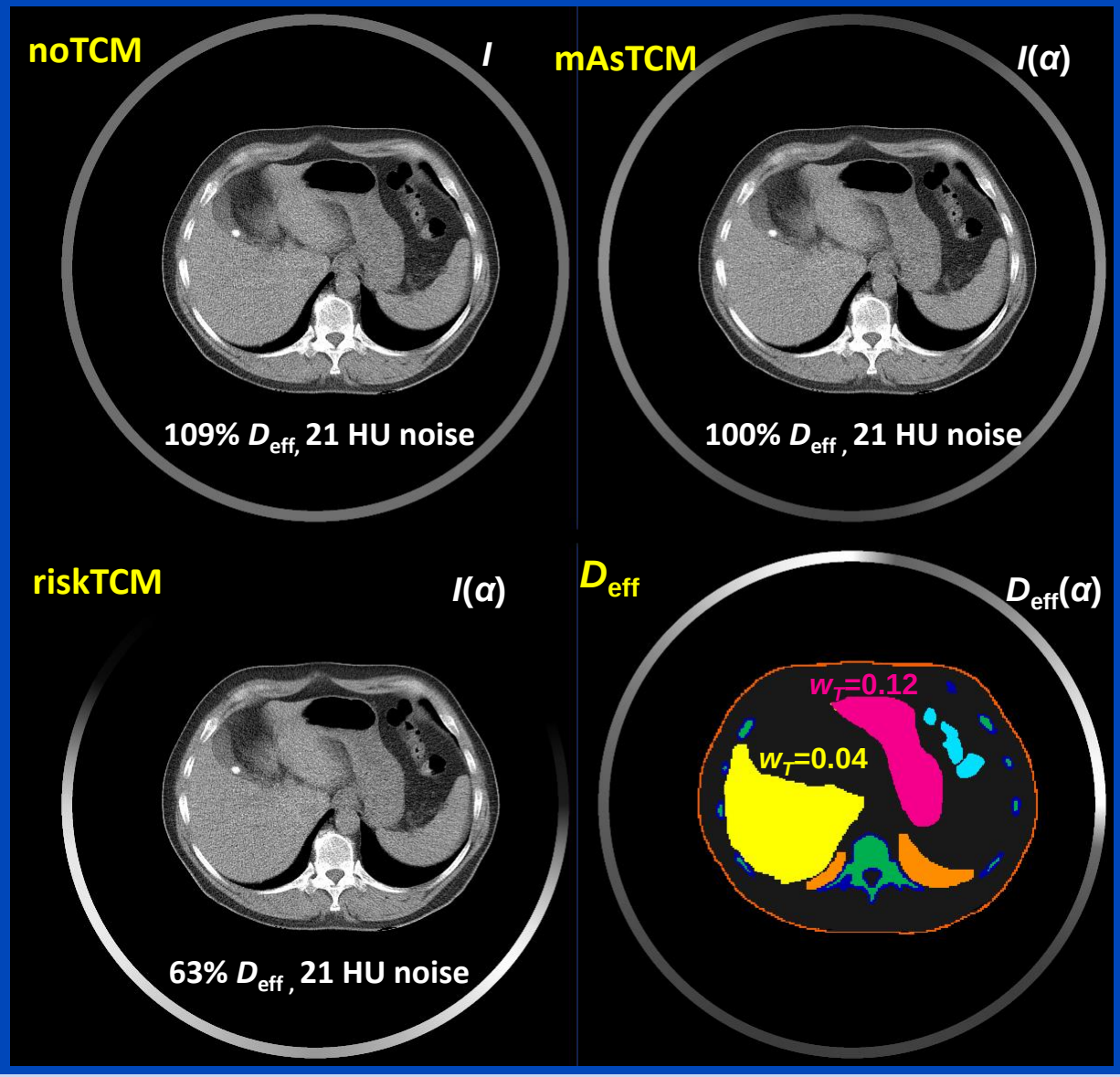
riskTCM Patient Example

At same image quality, i.e. same noise level and same spatial resolution, riskTCM reduces the effective dose between 10% and 30%, depending on the body region, compared to mAsTCM.

This work received the
Behnken-Berger Award
at the DGMP annual meeting 2023

BEHNKEN-BERGER STIFTUNG



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.*

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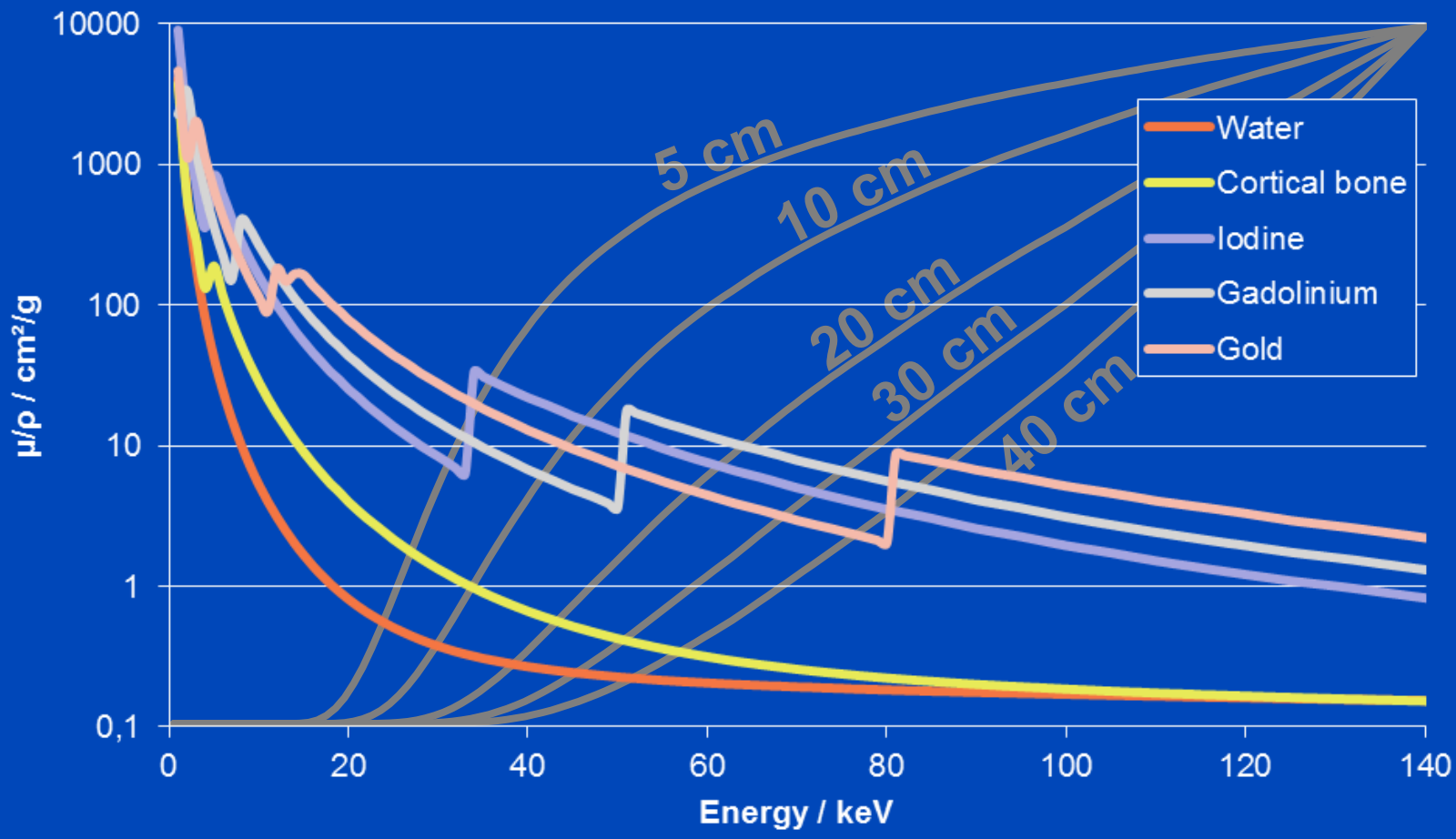
Tube Voltage Selection

- **Photon energy increases with tube voltage.**
- **Attenuation decreases with photon energy:**
  - **Increase tube voltage with patient diameter.**
- **Highest water-iodine contrast at 33 keV:**
  - **Decrease tube voltage for iodine contrast.**



Gray curves: 120 kV water transmission on a non-logarithmic ordinate individually normalized to 1 at 140 keV.

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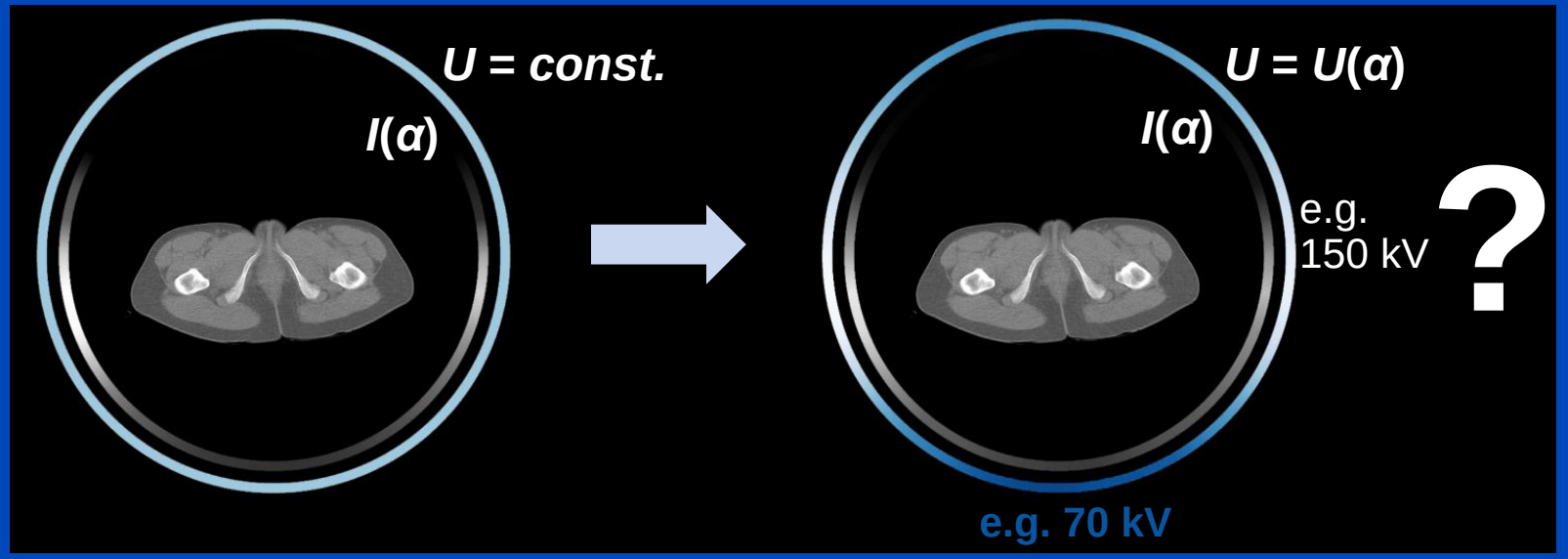
Tube Voltage Modulation?

- **Photon energy increases with tube voltage.**
- **Attenuation decreases with photon energy:**
  - **Increase tube voltage with patient diameter.**
- **Highest water-iodine contrast at 33 keV:**
  - **Decrease tube voltage for iodine contrast.**

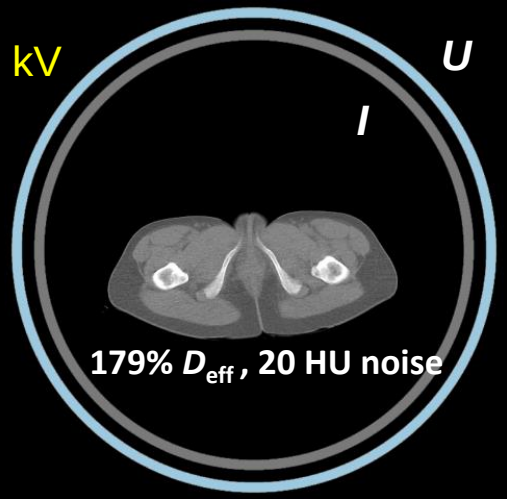


Patient attenuation is a function of longitudinal position and projection angle.

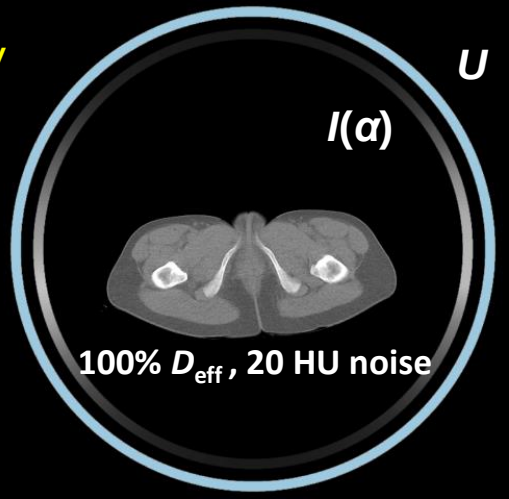
- **Should we modulate the tube voltage?**

Risk Minimizing Tube Current and Tube Voltage Modulation (riskTCTVM)

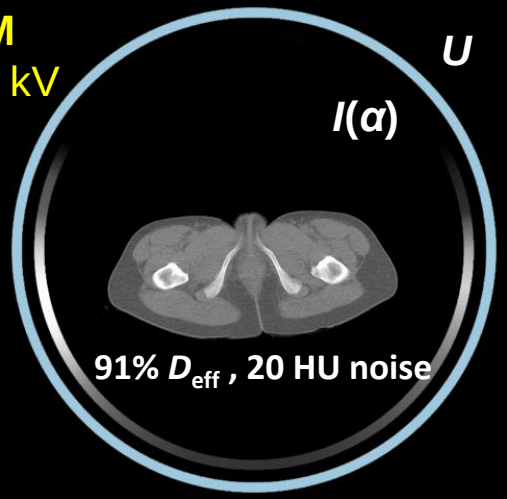
noTCM
U = 120 kV



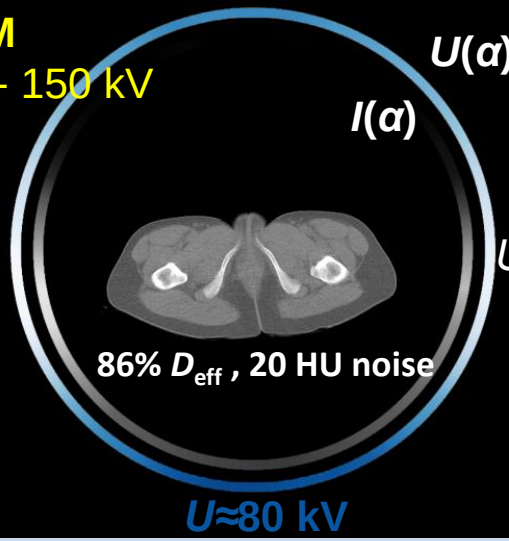
mAsTCM
U = 120 kV



riskTCM
U = 120 kV



riskTCTVM
U = 70 kV - 150 kV



E. Baader, L. Klein, S. Sawall, J. Maier, and M. Kachelrieß. CT tube current and tube voltage modulation to minimize the patient's radiation risk. Proceedings of the European Congress of Radiology (ECR), 2023.

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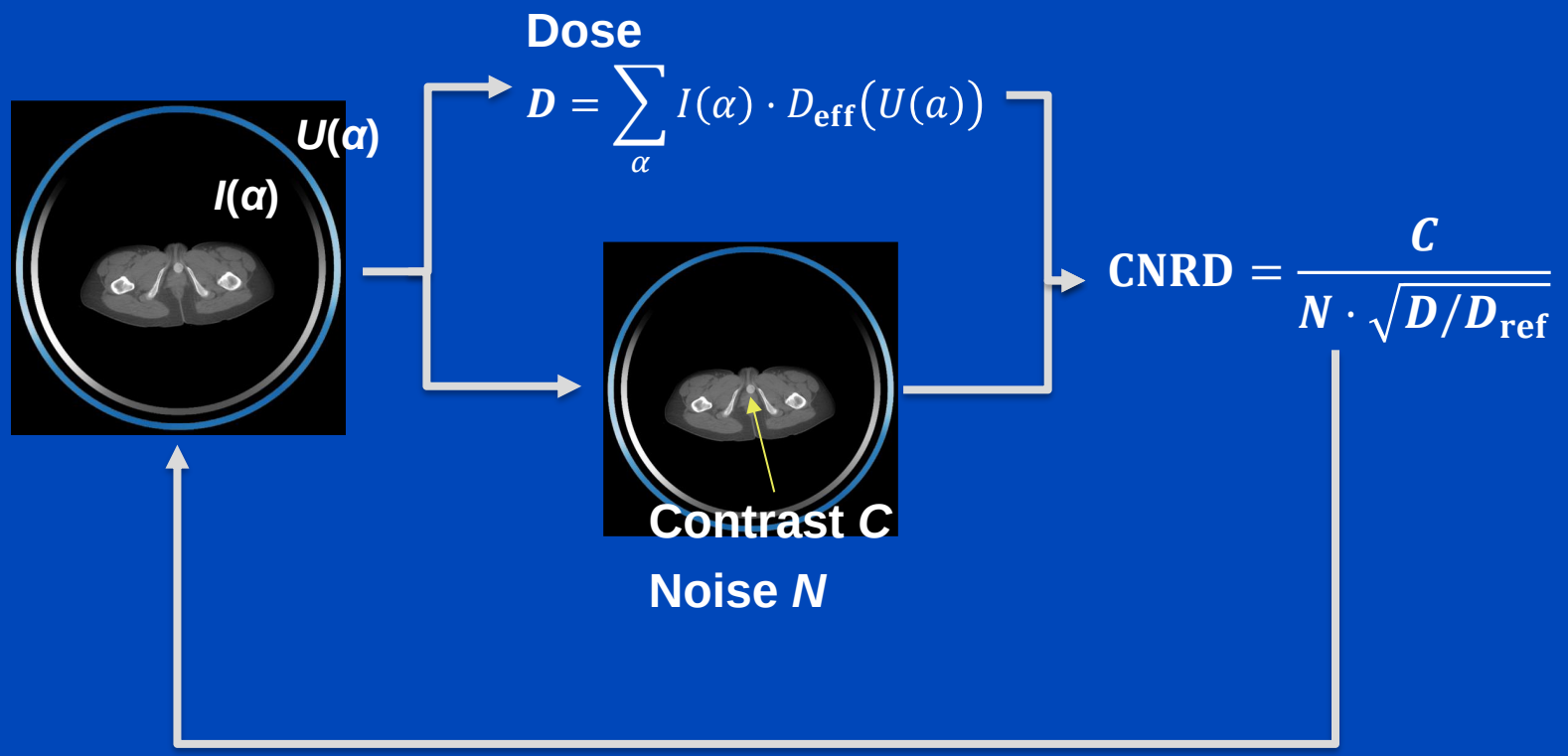
CNRD-Optimizing TCTVM

- Contrast: overlay of 2 cm iodine disk of density 4.93 mg/cm³ in isocenter (~ 250 HU at 70 kV)
- Contrast and noise estimation in center
- Relative dose = $\frac{\mathrm{CNRD}_{\mathrm{ref}}^2}{\mathrm{CNRD}^2}$ (at constant CNR)



[1]J. A. Nelder and R. Mead. A simplex method for function minimization. The computer journal, vol. 7, no. 4, pp. 308–313, 1965.

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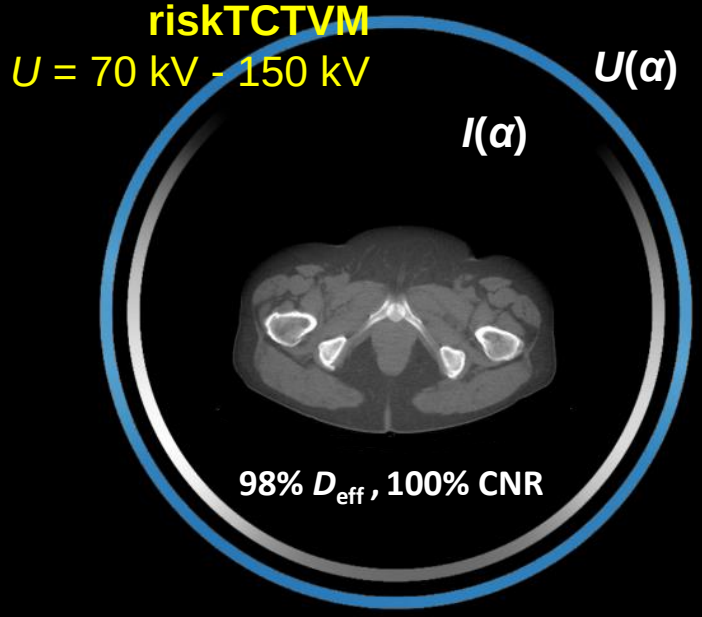
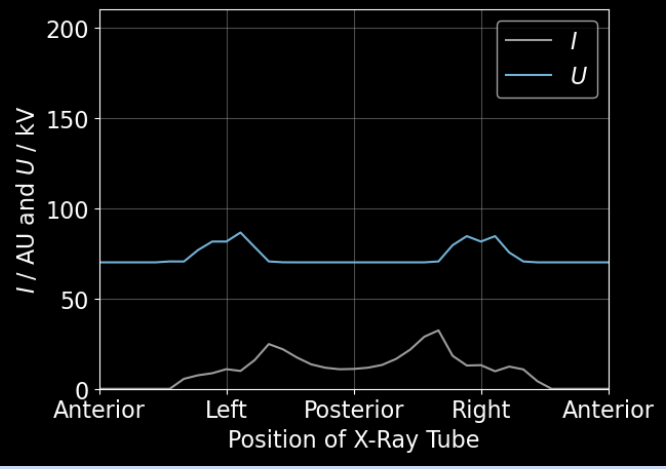
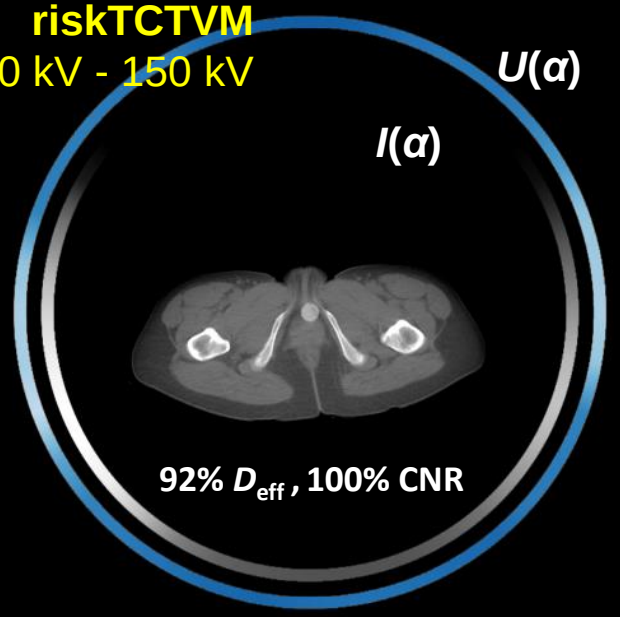
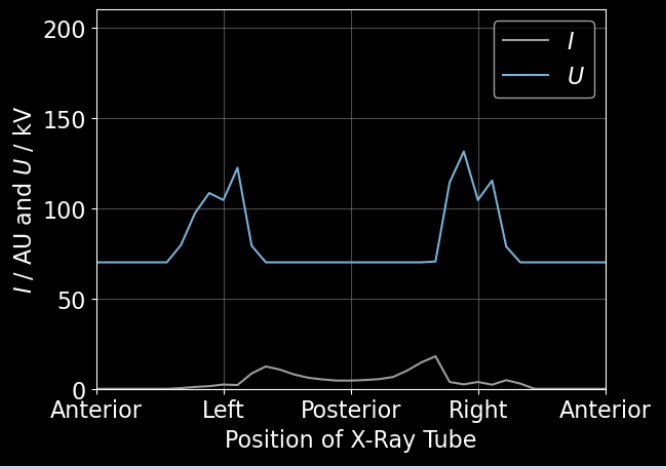
Results Pelvis

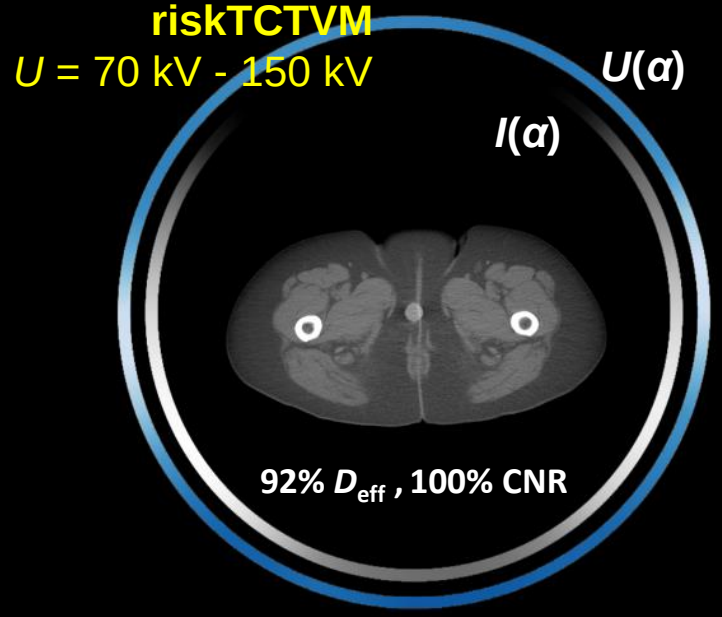
70 kV - 150 kV

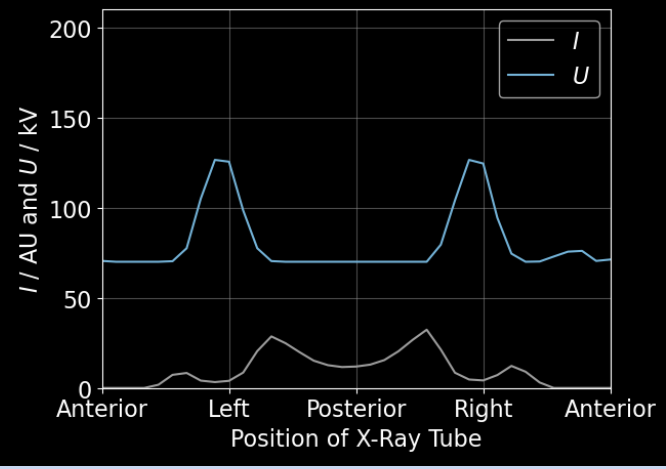








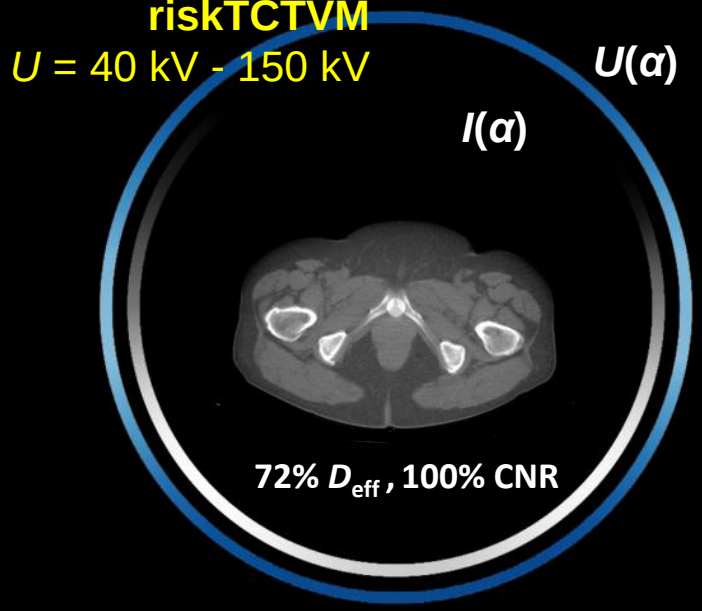


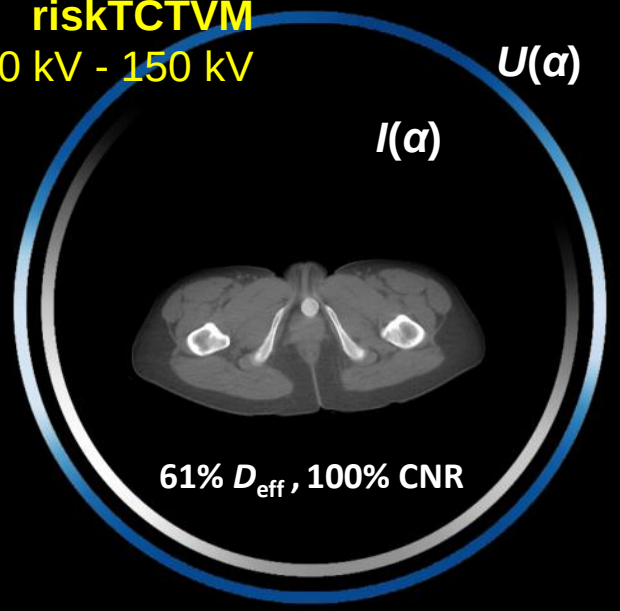


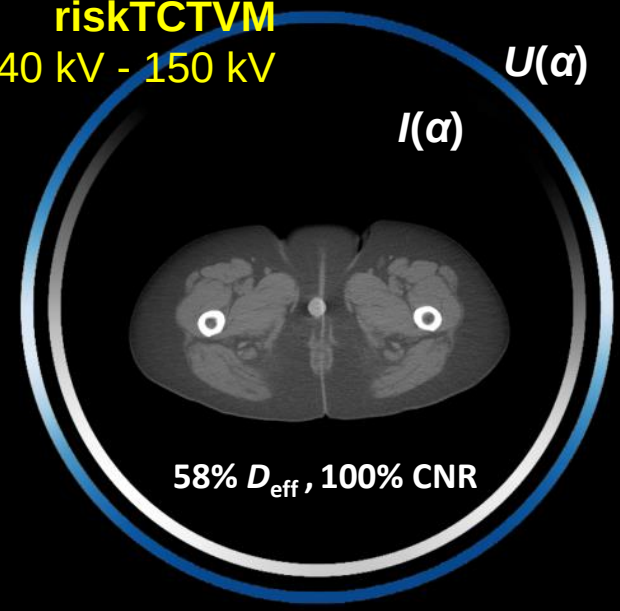
D_{eff} relative to riskTCM at 70 kV at same CNR (same image quality).

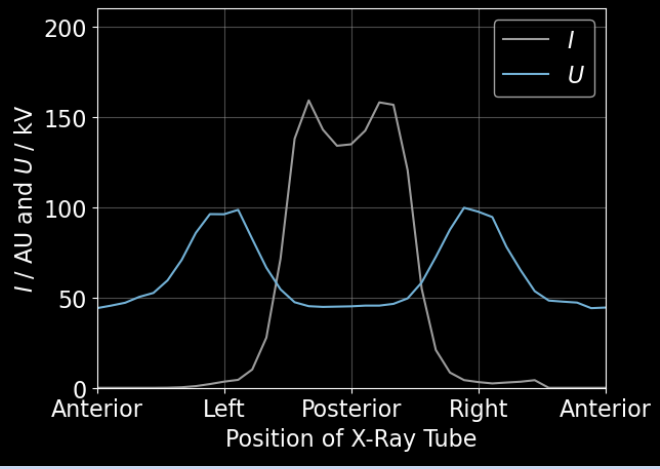
Results Pelvis

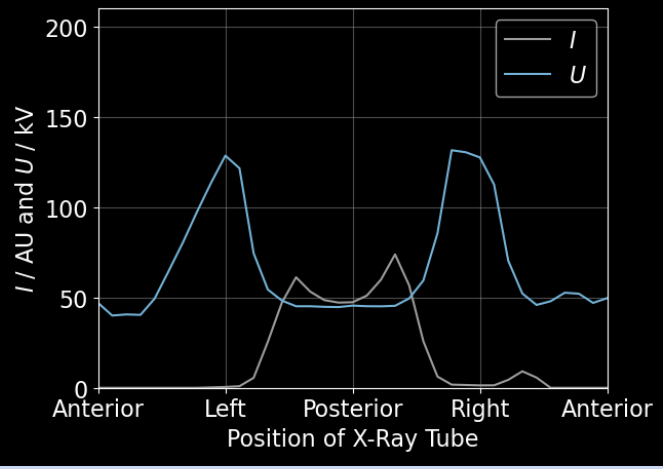
40 kV - 150 kV

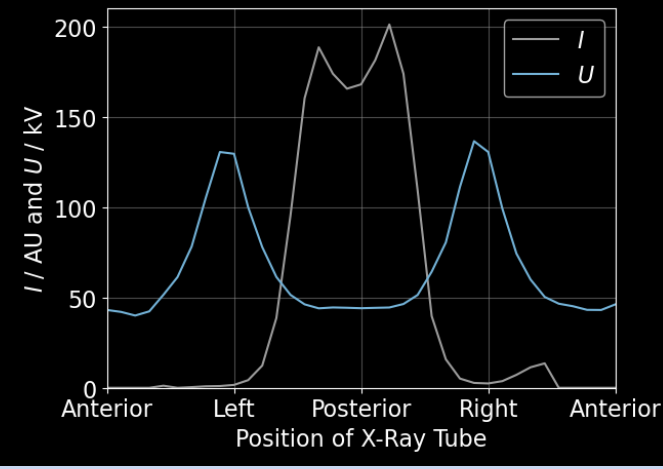












D_{eff} relative to riskTCM at 60 kV at same CNR (same image quality).

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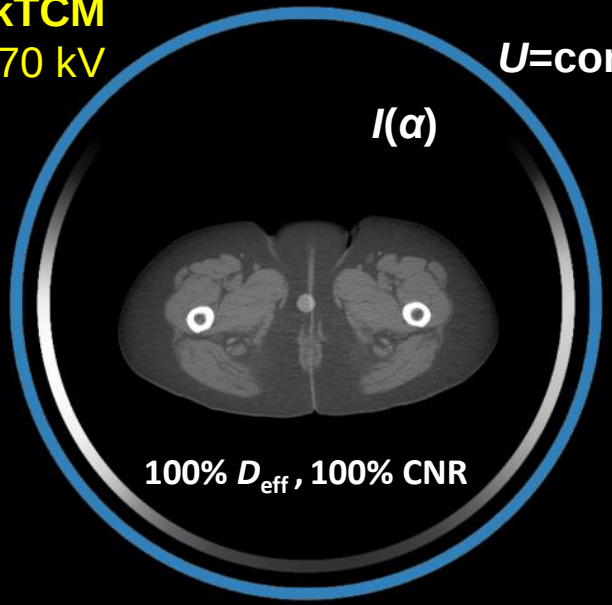
Comparison Maximum Tube Current

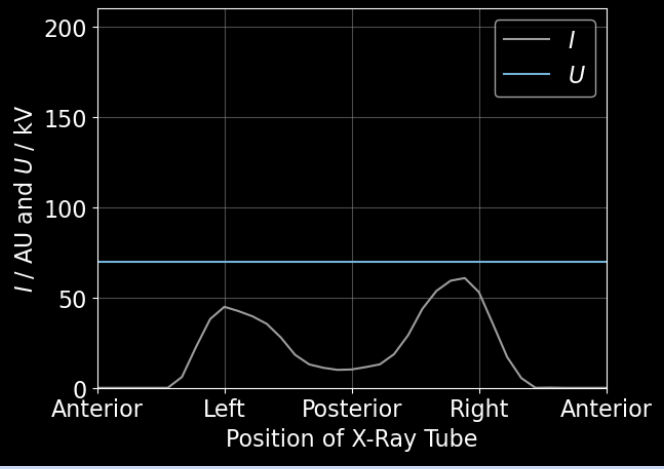
riskTCM
U = 70 kV

***U*=const.**

***I*(α)**



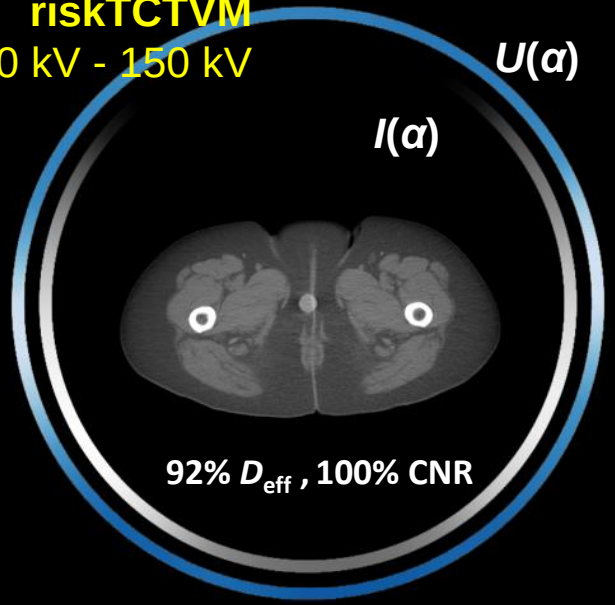
100% D_{eff}, 100% CNR



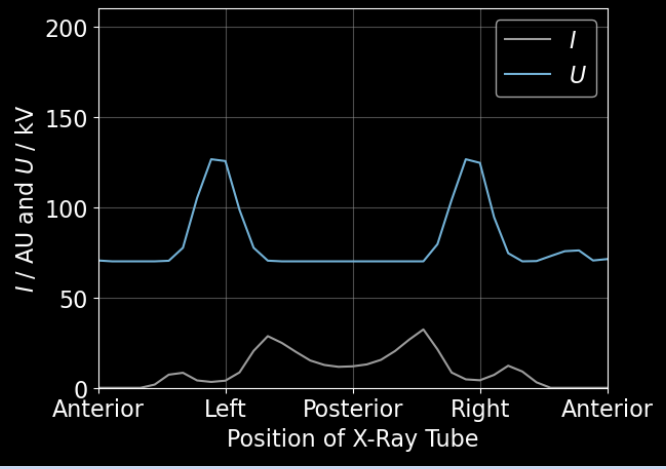
riskTCTVM
U = 70 kV - 150 kV

***U*(α)**

***I*(α)**



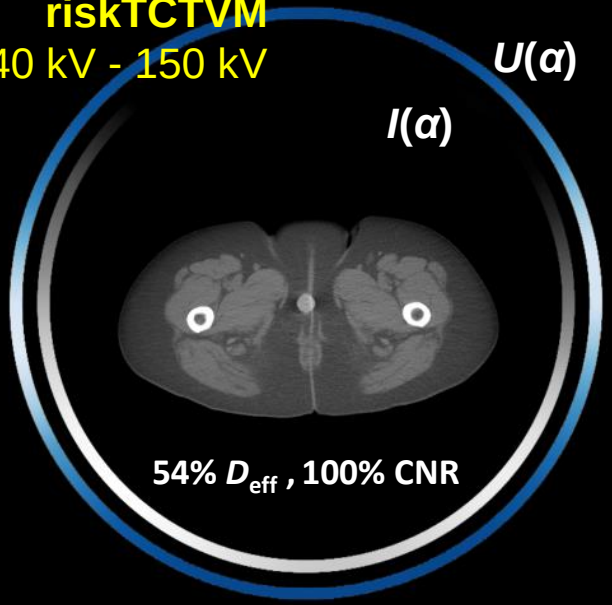
92% D_{eff}, 100% CNR



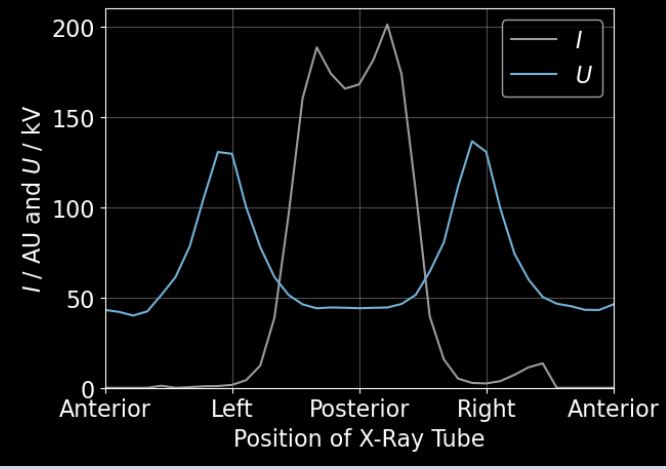
riskTCTVM
U = 40 kV - 150 kV

***U*(α)**

***I*(α)**



54% D_{eff}, 100% CNR



D_{eff} relative to riskTCM at 70 kV at same CNR (same image quality).

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Conclusions on riskTCTVM for Contrast-Enhanced Scans

- Benefit depends on the anatomical region.
- For the pelvis, we found:
  - Up to 8% less dose than riskTCM (at 70 kV) for a voltage range of 70 kV to 150 kV.
  - Up to 40% less dose than riskTCM (at 60 kV) if voltages down to 40 kV were available.
- A voltage modulation of 70 kV to 150 kV
  - Reduces the tube current requirements compared to constant 70 kV.
  - This could be beneficial for normal weight and obese patients.
- Instead of reducing the radiation dose, the amount of contrast media could be reduced or the image quality increased.

Thank You!

- This presentation will soon be available at www.dkfz.de/ct.
- This study was supported in part by a DKFZ International PhD Program Fellowship.
- 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.