Incorporating CT Tube Current Latency in Risk-Based Tube Current Modulation

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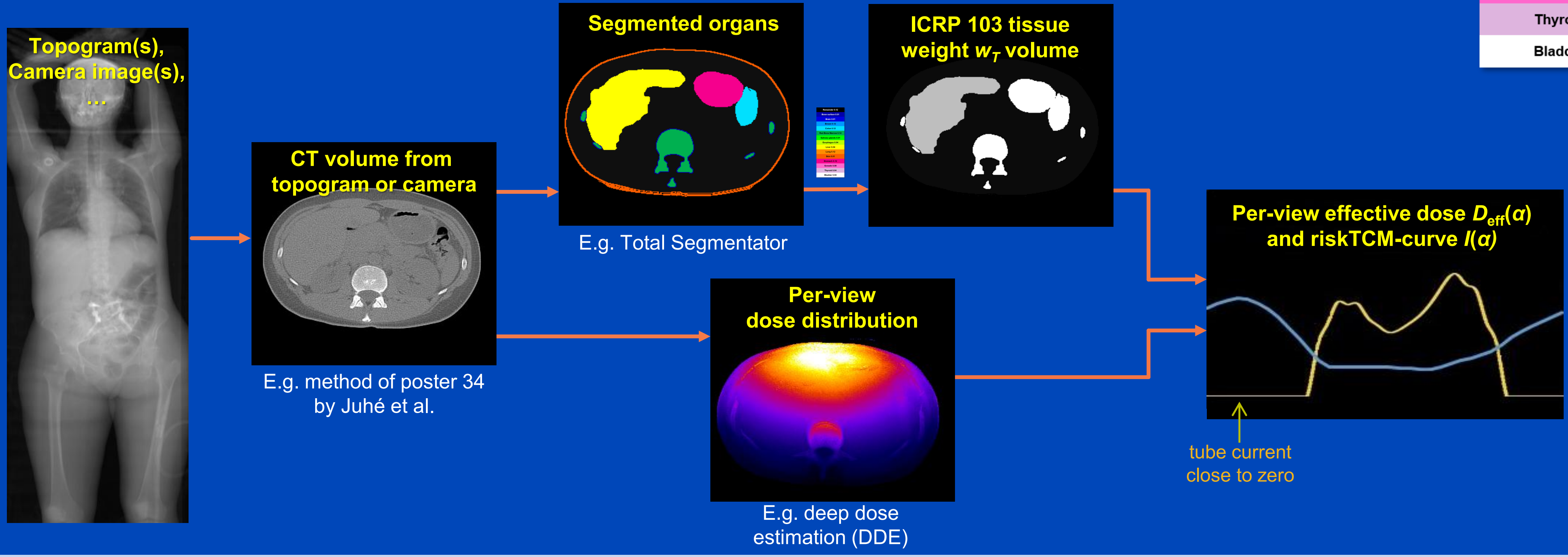
BACKGROUND

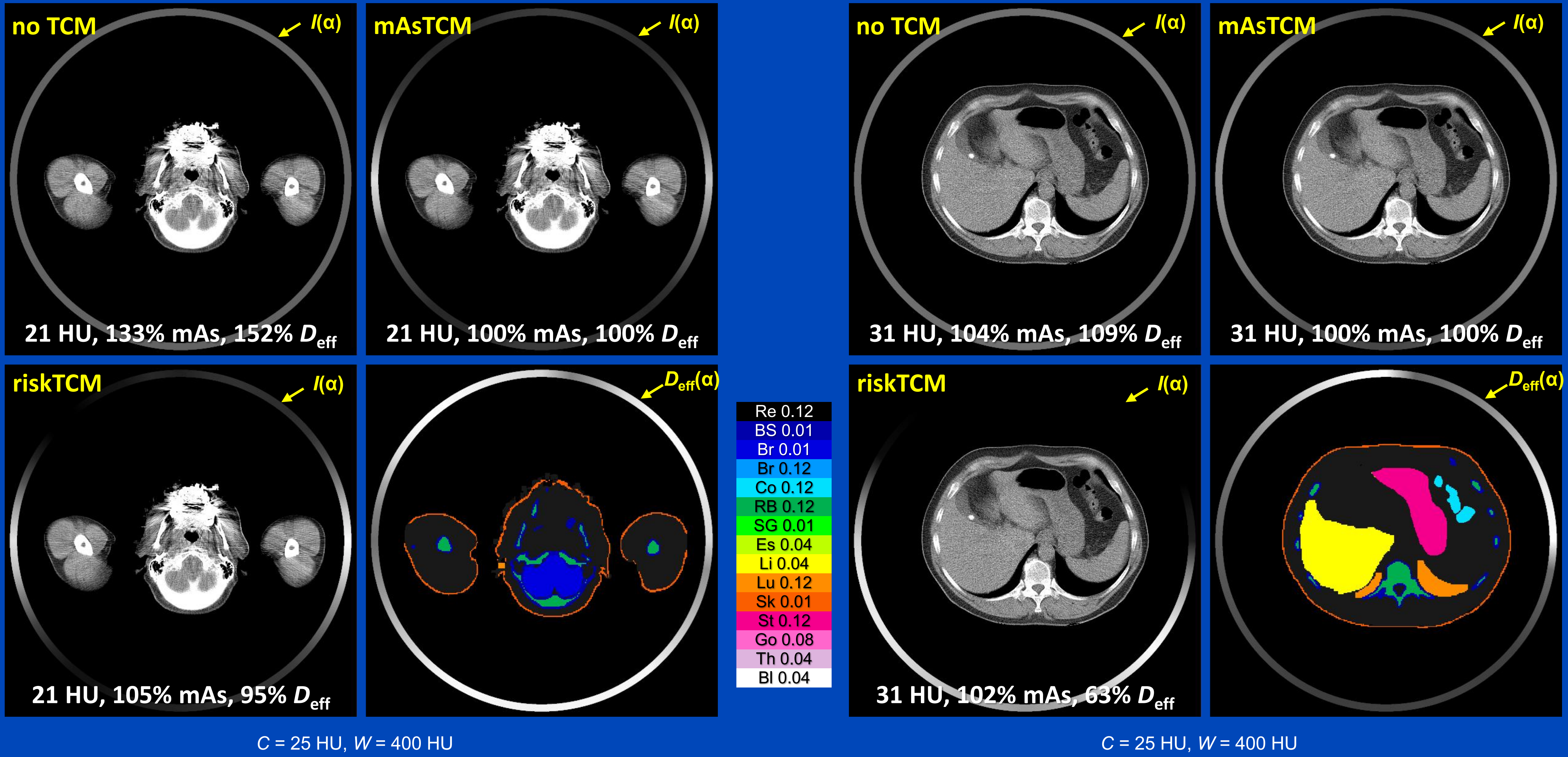
RiskTCM

- Risk-minimizing tube current modulation
- Weights the dose according to organ sensitivity.
- Finds $I(\alpha)$ that minimizes D_{eff} while keeping image noise constant.

Remainder	0.12
Bone surface	0.01
Brain	0.01
Breast	0.12
Colon	0.12
Red Bone Marrow	0.12
Salivary glands	0.01
Esophagus	0.04
Liver	0.04
Lung	0.12
Skin	0.01
Stomach	0.12
Gonads	0.08
Thyroid	0.04
Bladder	0.04



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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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%

- **Nearly up to 30% dose reduction is possible with riskTCM.**
- **This is due to significantly reducing or even zeroing the tube current for selected complementary projections.**

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Theory of TCM

$$\int d\alpha \, \underbrace{\left(D(\alpha)I(\alpha)\right.}_{\text{minimize dose}} + \underbrace{\left.\lambda \frac{e^{p(\alpha)}}{I(\alpha)}\right)}_{\text{keep noise constant}} = \min$$

$$\operatorname{Var} p \propto \frac{e^p}{I}$$

projection noise

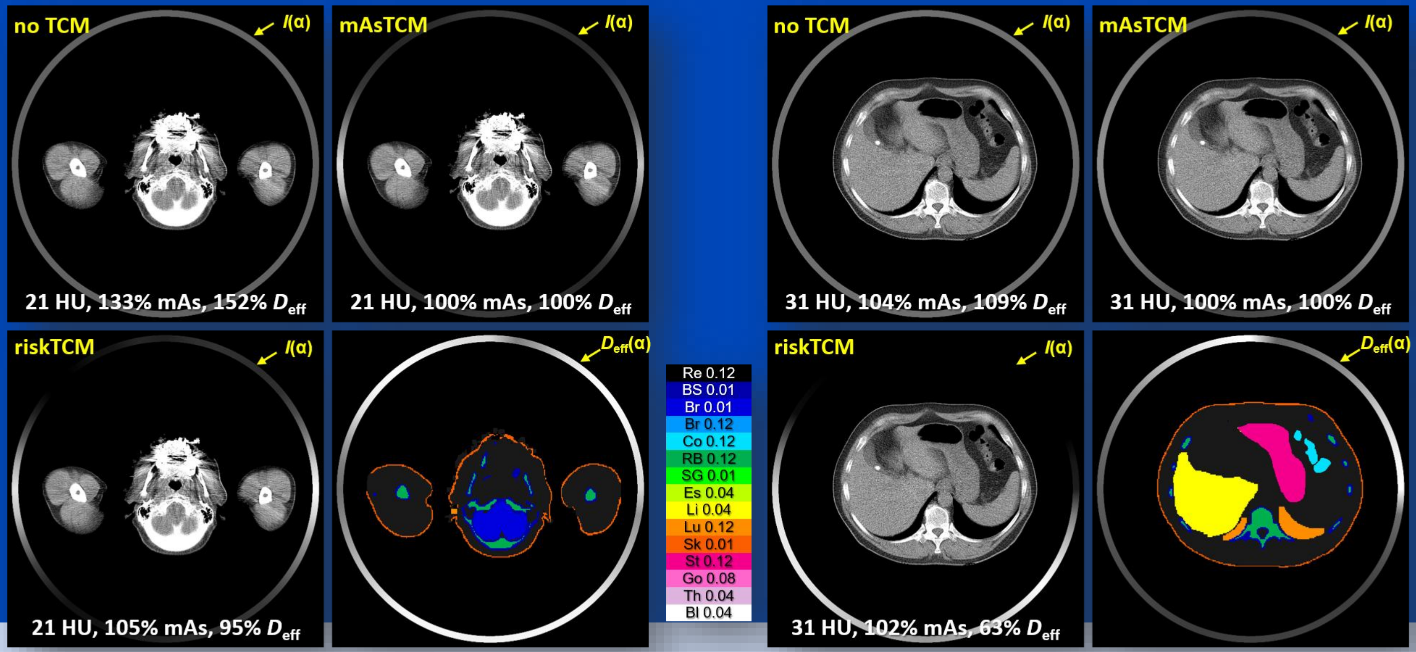
$$I^2(\alpha) \propto \frac{e^{p(\alpha)}}{D(\alpha)}$$

Dose per view per mA is assumed constant for mAsTCM.

SUREExposure (Canon)
SmartmA (GE)
DoseRight (Philips)
CARE Dose (Siemens)

Beyond the (Simplified) Theory, riskTCM …

- considers noise throughout the patient and not just in the isocenter,
- accounts for patient risk per view instead of assuming $D(\alpha)$ = *const.*,
- balances between direct and complementary rays,
- and therefore requires numerical optimization.



C = 25 HU, W = 400 HU

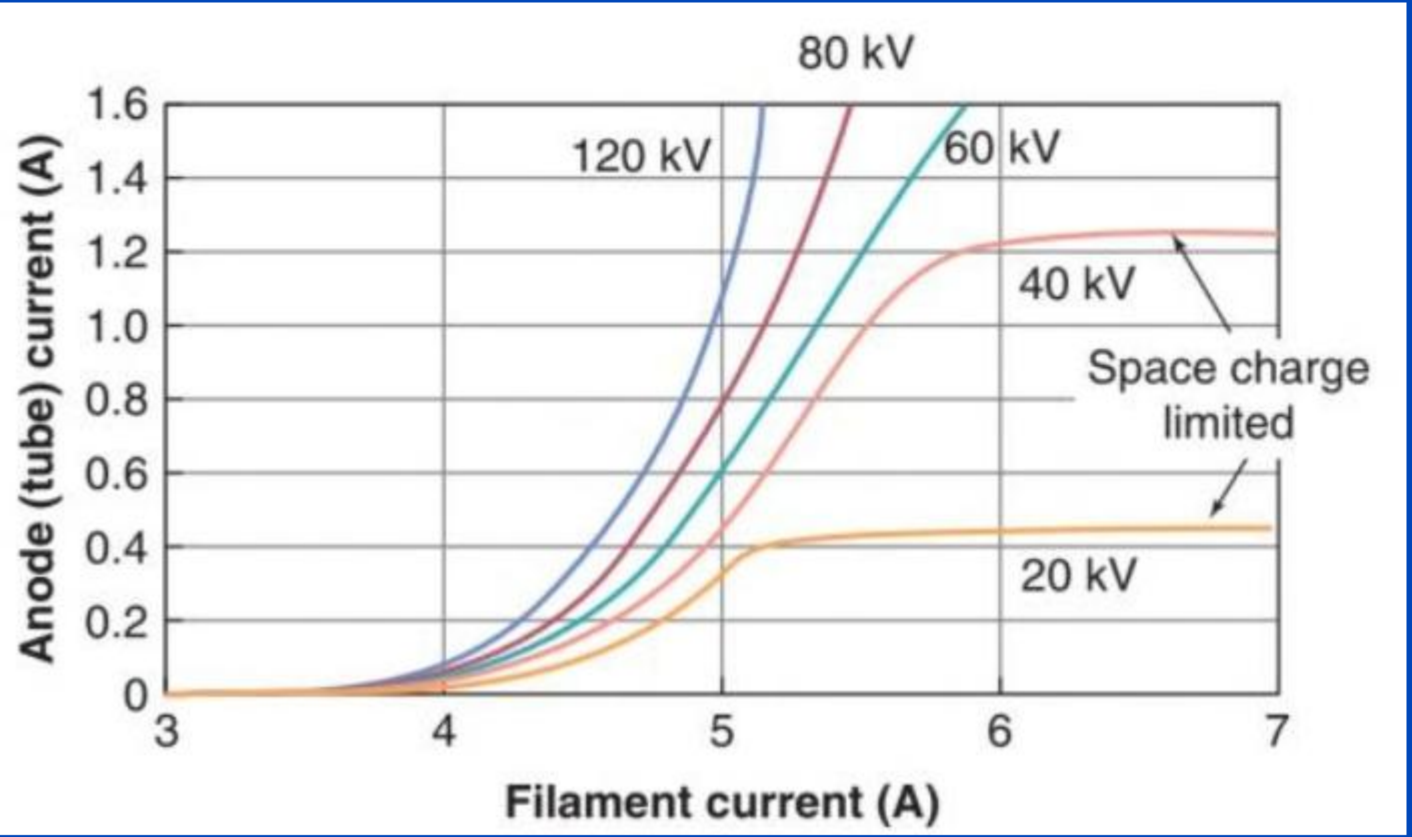
C = 25 HU, W = 400 HU

Tube Current Optimization Considerung Tube Current Latency

- Problem: The tube current cannot be changed arbitrarily quickly.
  - Lowering the tube current is particularly slow, since it requires cooling of the filament.
  - Option: turn off tube voltage for a “zero push”
- Solution: Find the optimal filament current curve $I_F(\alpha)$ rather than optimizing for the tube current curve $I(\alpha)$.
- Restrictions of this work:
  - Only investigate the latency while lowering the tube current
  - Only sequence scans

Filament Current and Anode Current for the Quasistatic Case

- The quasistatic dependency of the anode current on the filament current is typically known, e.g. by measurements.
- We are therefore free to define a normalized filament current I_F such that $I = I_F$ in the quasistatic case.
- We will call this normalized filament current I_F "filament current" in the following.



Bushberg, J. T. et al. (2011). The Essential Physics of Medical Imaging (3rd ed.). Lippincott Williams & Wilkins.

Filament Current Optimization

- Optimize the filament current instead of the tube current.
- Laws of thermodynamics are applied.
- Newton's law of heating and cooling

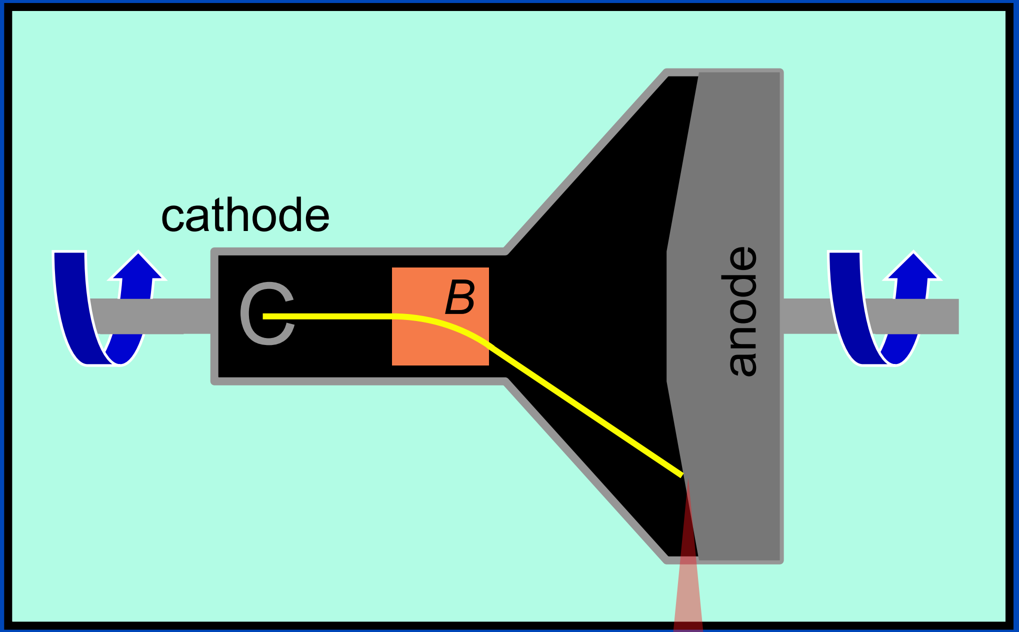
$$dT = \frac{dt}{k}(T_\mathrm{R} - T)$$

T = object temperature, T_R = reservoir temperature, k = heating/cooling constant, t = time

- Differential equation for the tube current

$$dI = \frac{dt}{k}(I_\mathrm{F} - I)$$

I = tube current, I_F = filament current, k = heating/cooling constant, t = time



Typical values:

k_{heat} = 10 ms
k_{cool} = 90 ms (standard x-ray tube)
k_{cool} = 45 ms (high performance tube)

Here, we consider cooling only.

MATERIALS

Incorporate Latency Gradients into the TCM Cost Functions

- **Gradient in optimizer changes**

$$\frac{\partial N}{\partial I_{\mathrm{F}}(n)} = \int w(r) \frac{-1}{2\sqrt{\int d\theta \frac{\mathrm{e}(p)}{I_{\mathrm{D}} + I_{\mathrm{C}}}}} \cdot \int \frac{\mathrm{e}(p)}{(I_{\mathrm{D}} + I_{\mathrm{C}})^2} \boxed{\frac{\partial I_{\mathrm{D}}}{\partial I_{\mathrm{F}}(n)}} d\theta \, dxdy$$

- **Important: Filament current affects later tube currents with $J(I_{\mathrm{D}})$: tube position index of I_{D}**

$$\frac{\partial I_{\mathrm{D}}}{\partial I_{\mathrm{F}}(n)} = \tau_n \prod_{j=n+1}^{J(I_{\mathrm{D}})} (1 - \tau_j)$$

- **Since $(1 - \tau_j) \approx 1$ for tube current decreases and $(1 - \tau_j) \approx 0$ for tube current increases**

$$\frac{\partial I_{\mathrm{D}}}{\partial I_{\mathrm{F}}(n)} = \begin{cases} \tau_n & J(I_{\mathrm{D}}) = n \\ 0 & \text{else} \end{cases}$$

We use the L-BFGS-B optimizer to determine the optimal tube current curve (in steps of 1°).

Zero Push: Pushing the Tube Current to 0 mA

- The tube current latency makes it difficult to quickly reach 0 mA.
- Solution: turn off tube voltage to enforce zero tube current.
- Incorporate zero push into optimizers as follows
  - Compute initial riskTCM curve without latency.
  - Set tube voltage to zero in the same tube positions where riskTCM without latency asks for zero tube current.

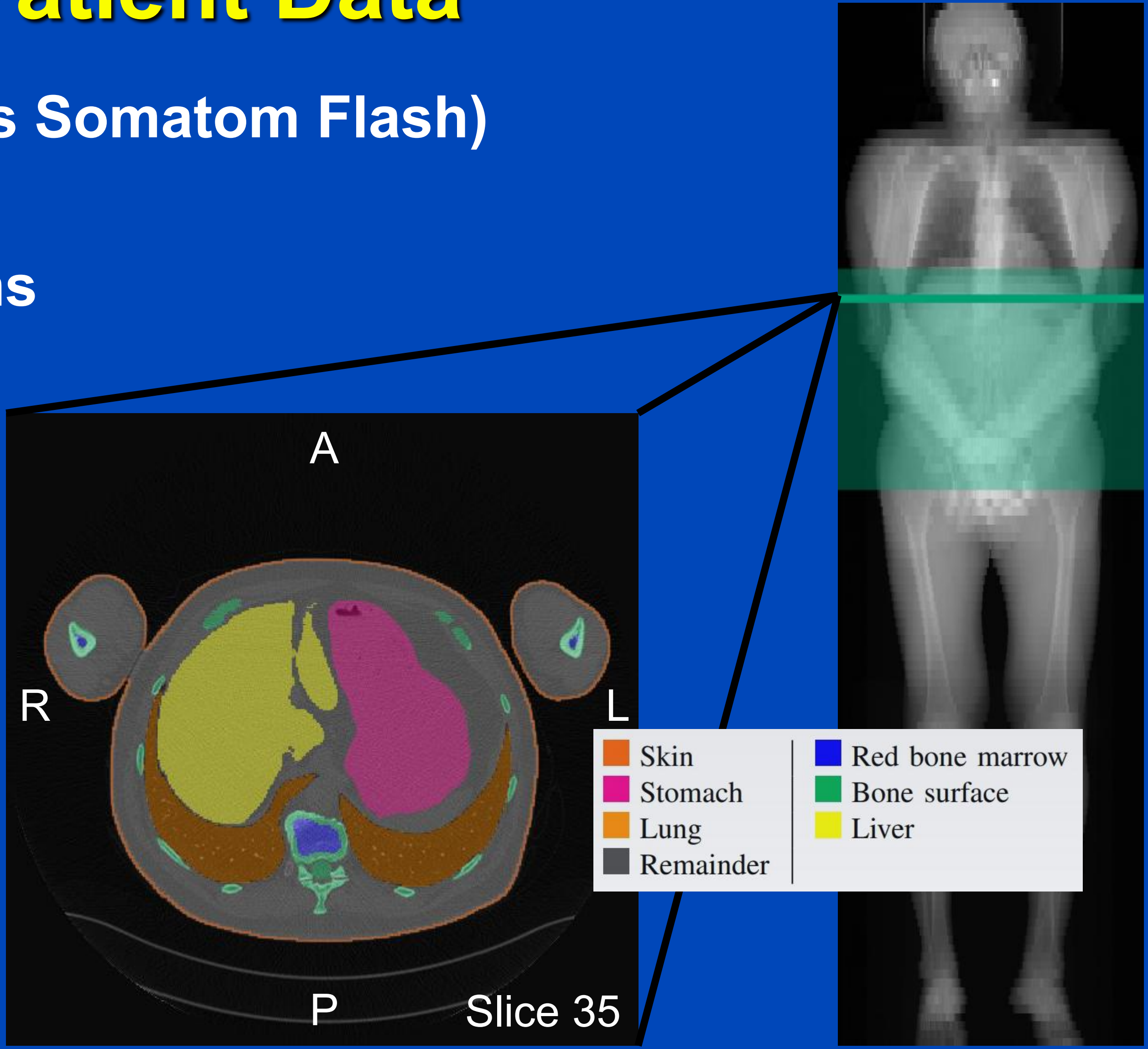
Baseline: mAsTCM

- Routinely used in clinical CT, today.
  - SUREExposure (Canon)
  - SmartmA (GE)
  - DoseRight (Philips)
  - CARE Dose (Siemens)
  - …
- Minimizes the tube current time product.
- Does not take the sensitivity of organs into account.
- We here compare with mAsTCM without tube current latency.

Patient Data

- Whole body CT scan (Siemens Somatom Flash)
- 122 slices of 15 mm thickness
- Segment 13 of the ICRP organs

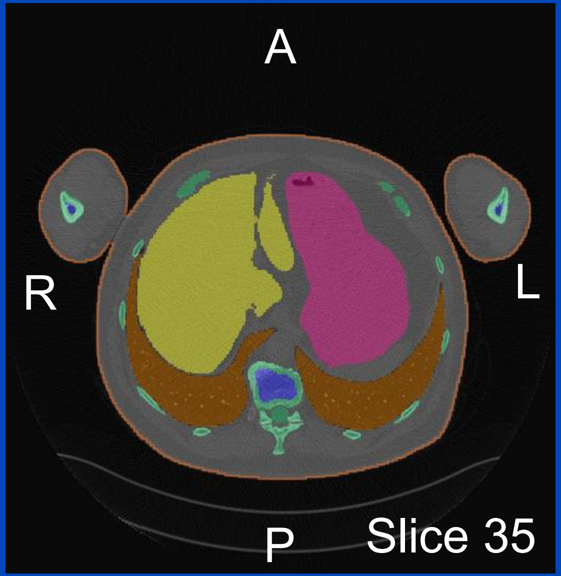
	Rotation	*k*
Abdomen	500 ms	45 ms or 90 ms
Head	1000 ms	
Neck	500 ms	
Pelvis	500 ms	
Thorax	250 ms, 330 ms	

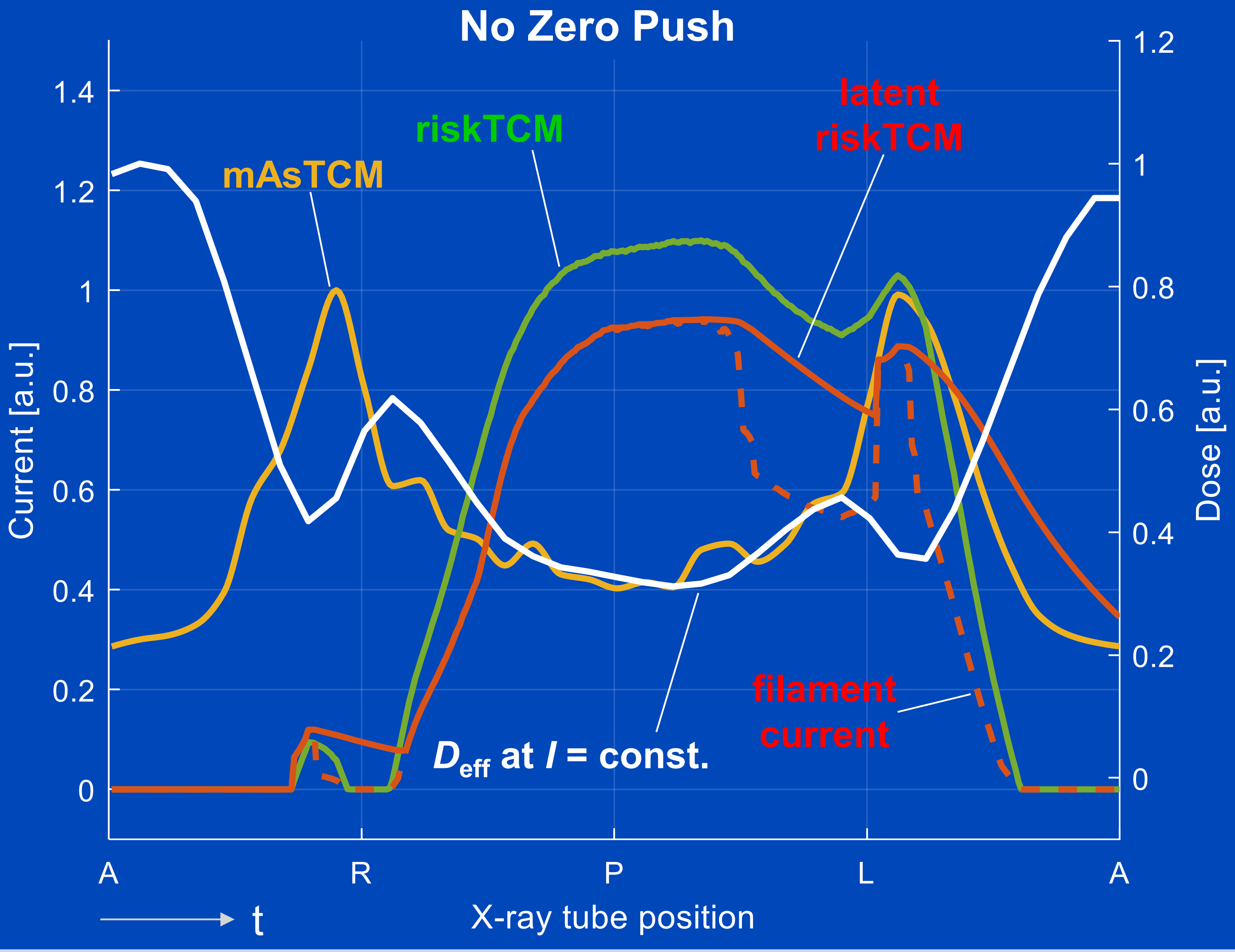


RESULTS

Results in Abdominal Region

- 0.5 s rotation
- k = 90 ms





All tube current curves are normalized to result in the same image noise.

Results in Abdominal Region

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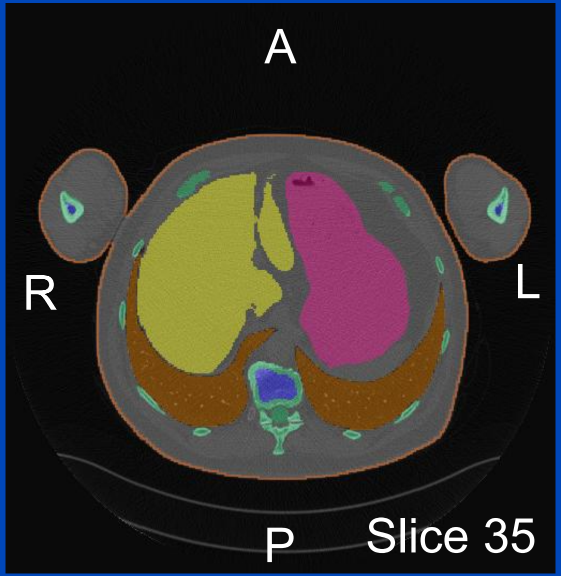

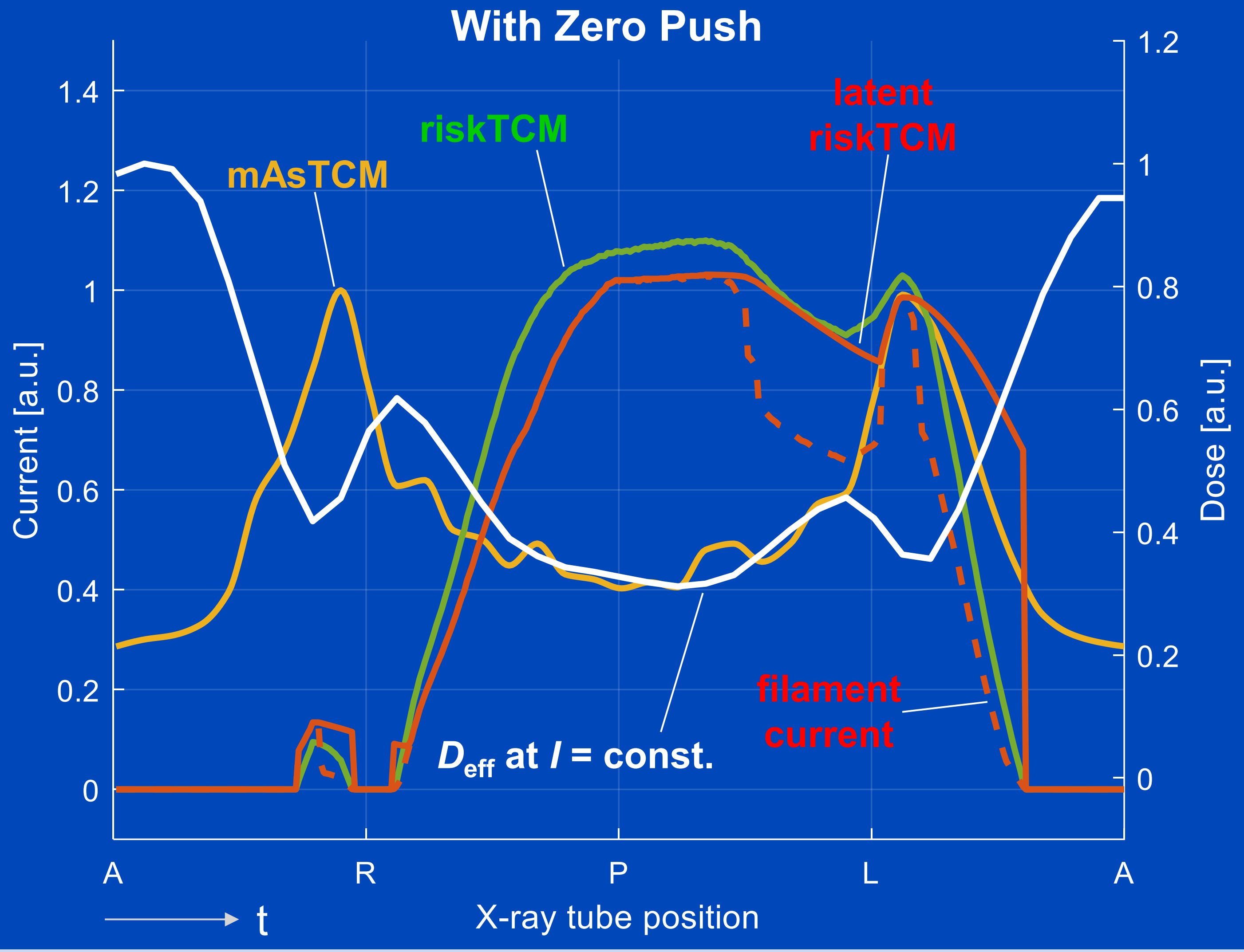

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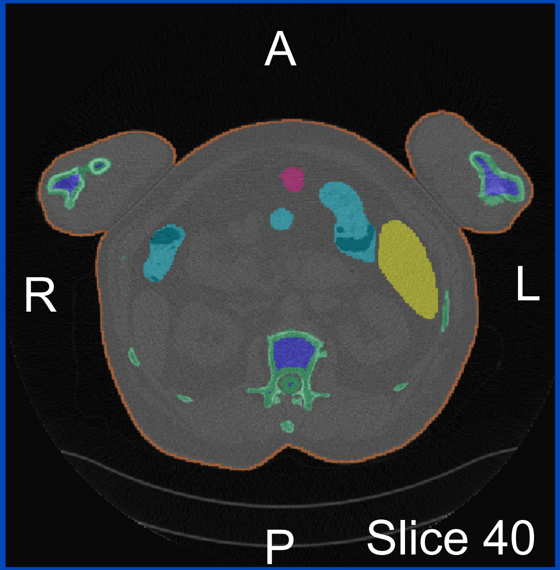
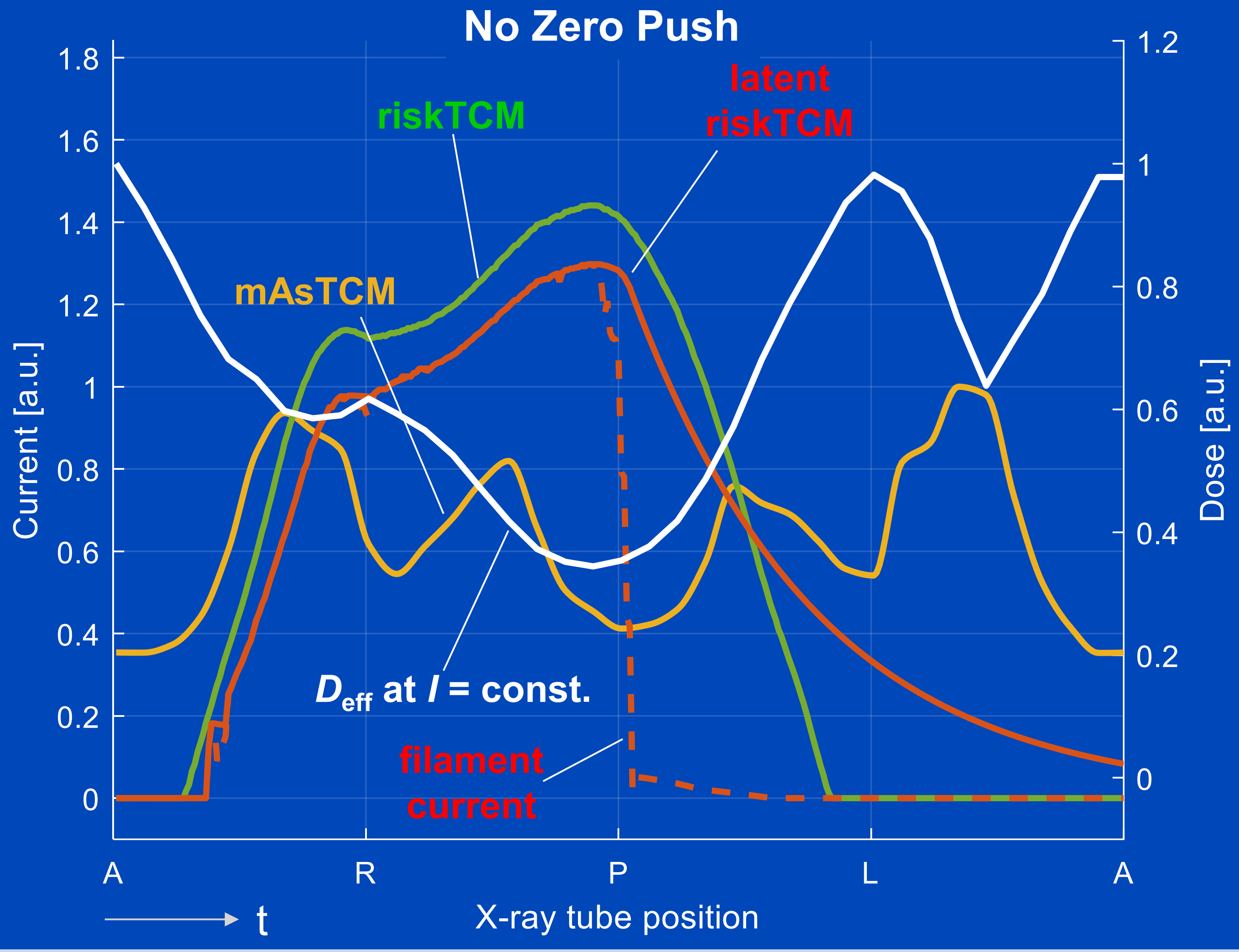
Results in Abdominal Region

- 0.5 s rotation
- *k* = 90 ms





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Results in Abdominal Region

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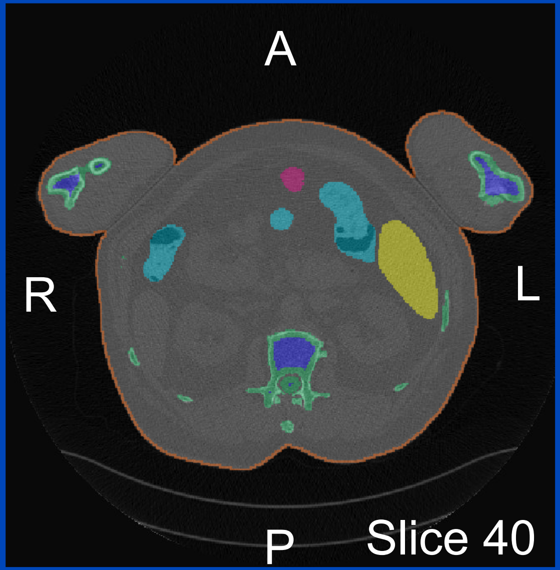

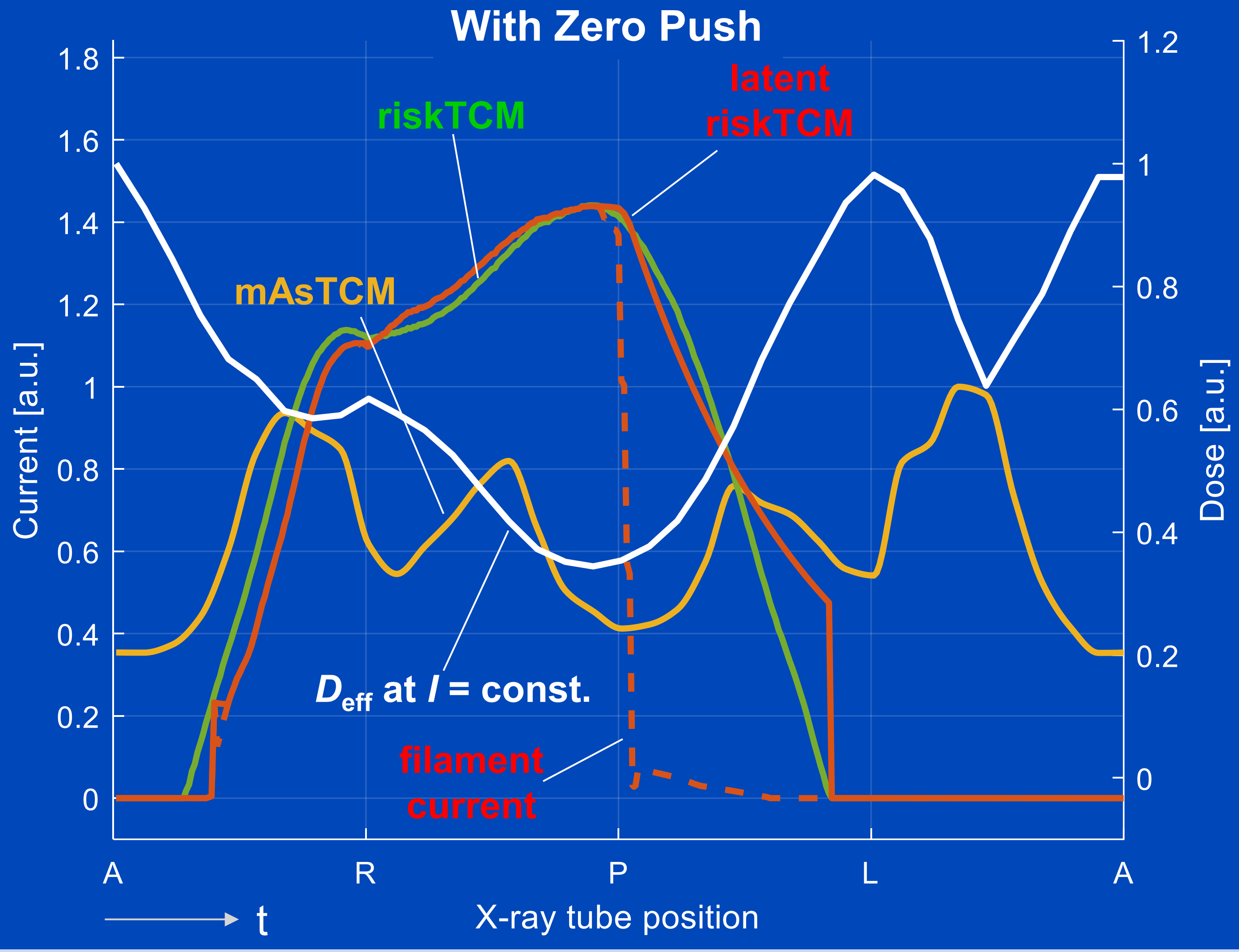

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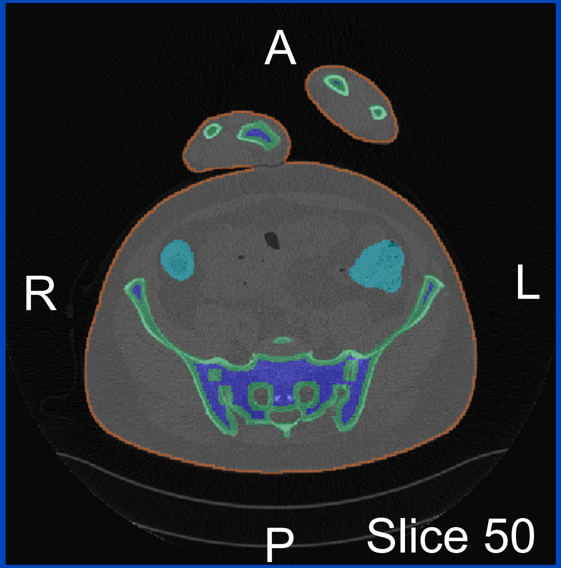

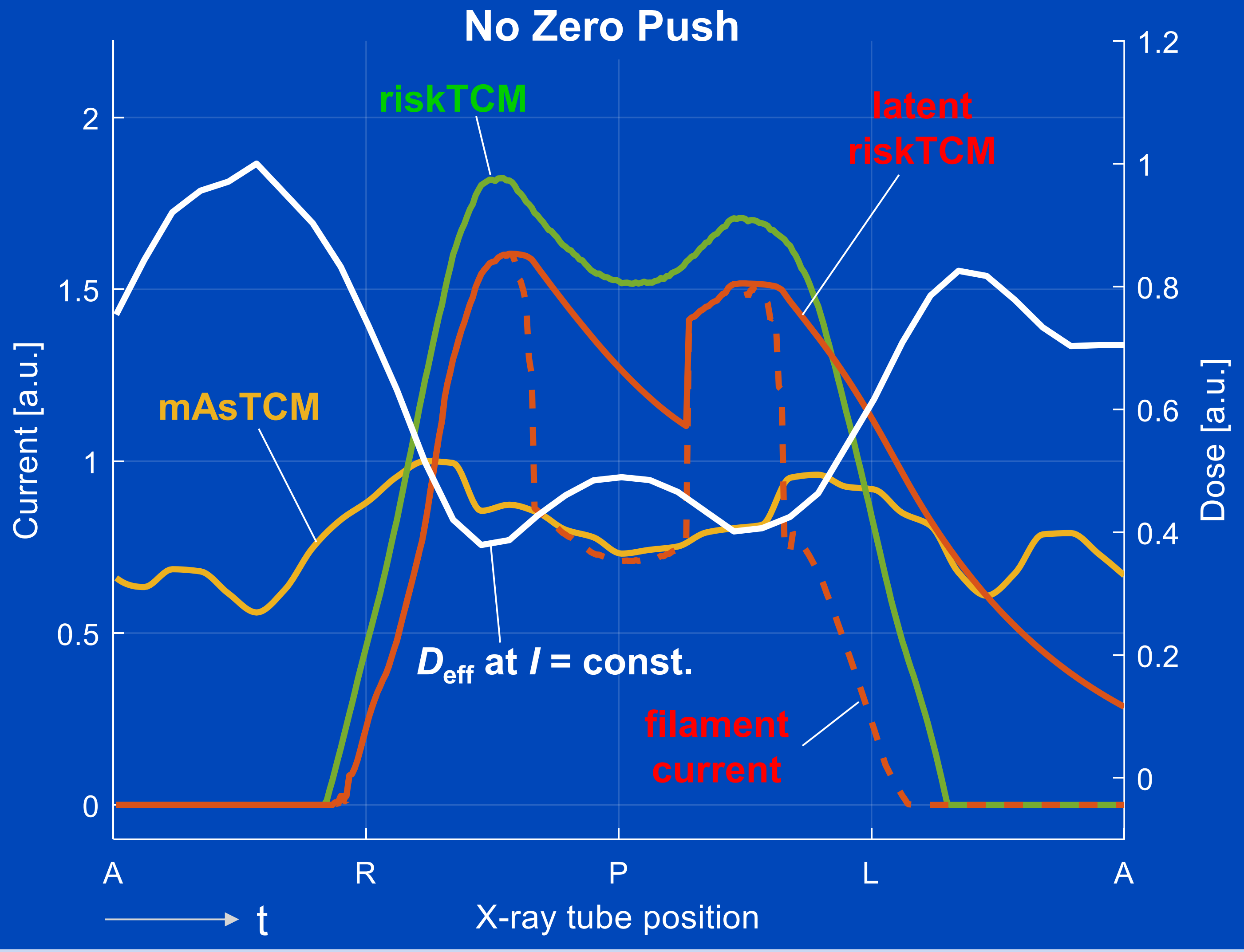

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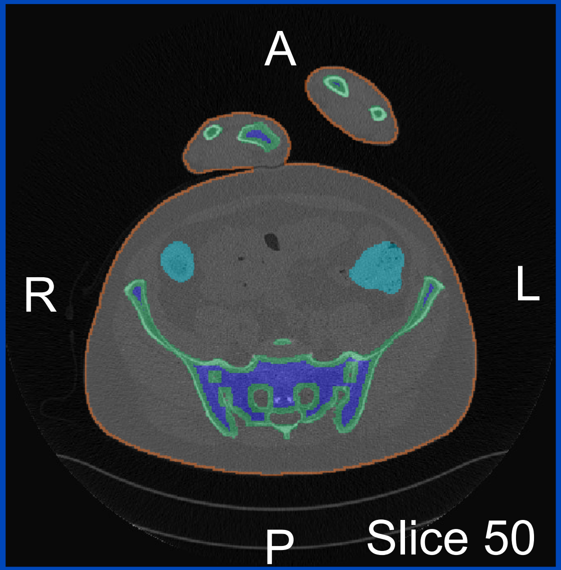

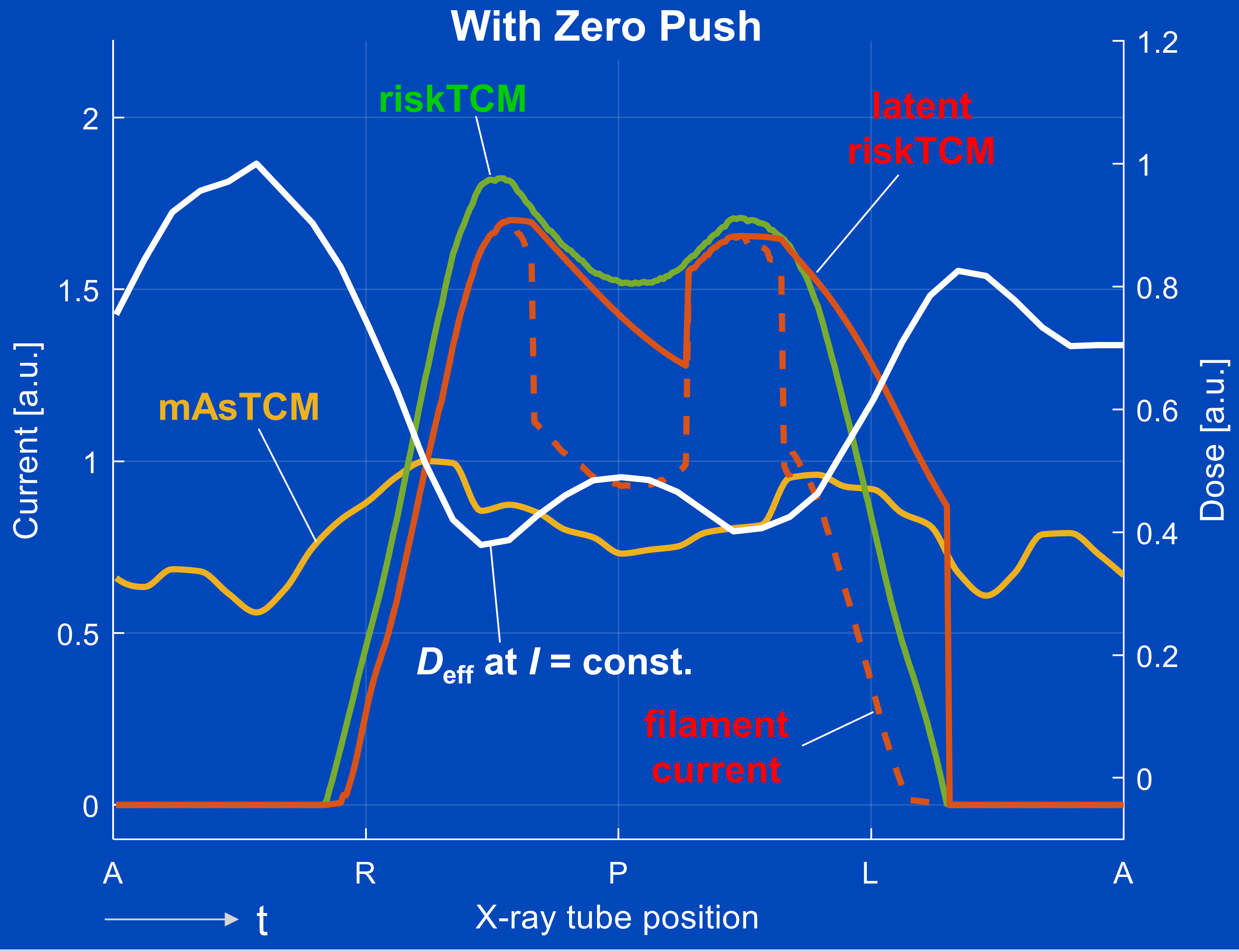

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All tube current curves are normalized to result in the same image noise.

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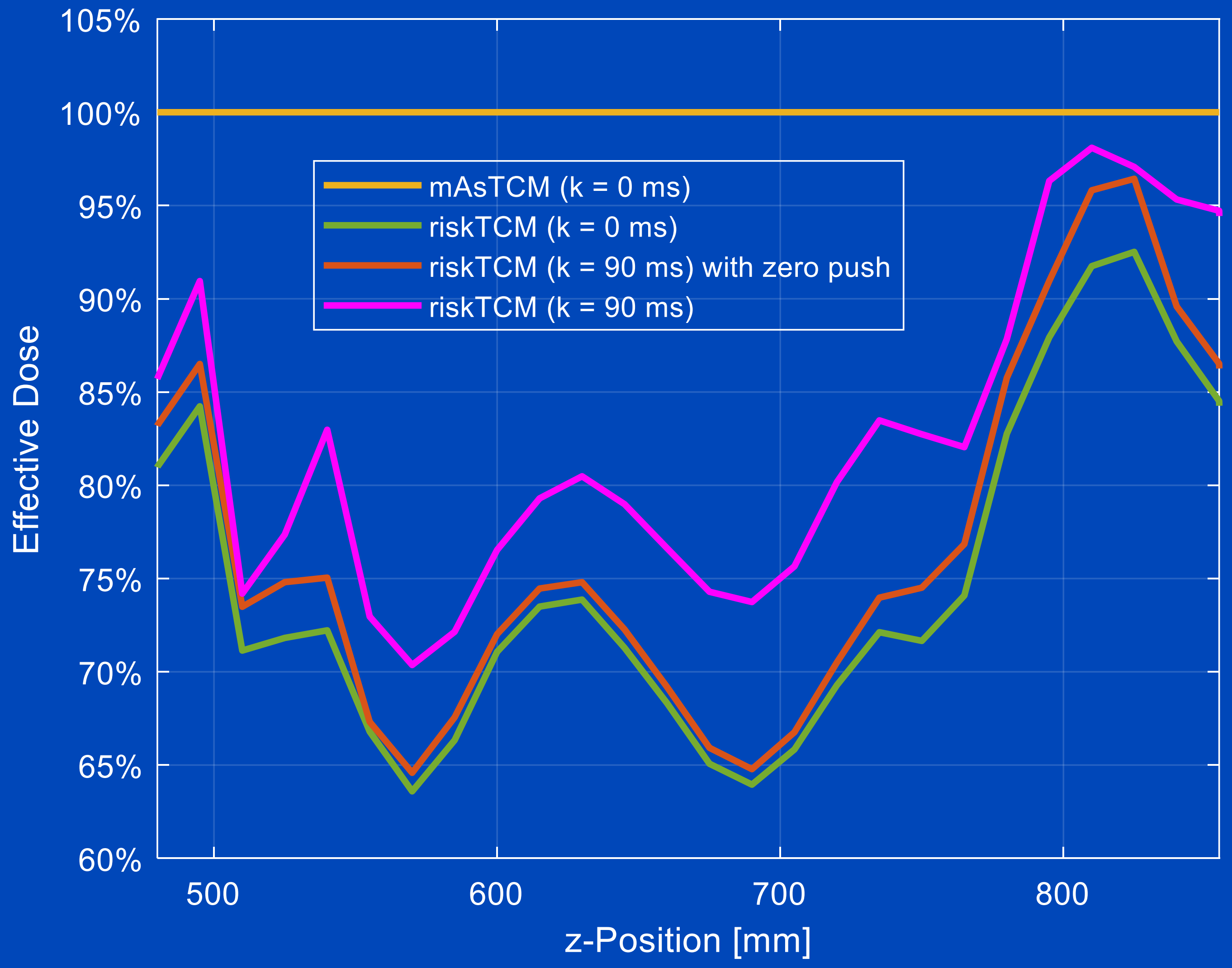
Achievable $D_{eff}(z)$ in the Abdominal Region

- **0.5 s rotation**
- ***k* = 90 ms**
- **Significant effective dose reduction even without zero push and close to riskTCM with zero push**



All D_{eff} values are normalized to mAsTCM (with k = 0), i.e. mAsTCM is 100%.

Mean D_{eff} in the Abdominal Region

- 0.5 s rotation
- Zero push
  - has larger effect on slower cooling time
  - makes it possible to almost reach riskTCM dose levels without latency.

	k = 0 ms	*k* = 45 ms	*k* = 90 ms
riskTCM	75%	78%	82%
riskTCM with zero push	75%	76%	77%

All D_{eff} values are normalized to mAsTCM (with k = 0), i.e. mAsTCM is 100%.

Mean D_{eff} in all Regions

		riskTCM (k = 0)	riskTCM (k = 90 ms)		riskTCM (k = 45 ms)	
			no zero push	zero push	no zero push	zero push
Abdomen	500 ms	75%	82%	77%	78%	76%
Head	1000 ms	91%	92%	91%	91%	91%
Neck	500 ms	76%	86%	77%	81%	77%
Pelvis	500 ms	80%	87%	82%	83%	81%
Thorax	330 ms	81%	89%	84%	-	-
	250 ms		-	-	87%	83%

All D_{eff} values are normalized to mAsTCM (with k = 0), i.e. mAsTCM is 100%.

Conclusions

- riskTCM can reach much lower effective dose values compared to mAsTCM even when incorporating tube current latency.
- Zero pushing noticeably further reduces the effective dose.
- Limitations
  - Only cooling latency considered
  - Simulation only – measurements upcoming
  - Evaluation restricted to a single patient

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.