Fast synthetic-CT-free dose calculation in MRgRT: A proof-of-concept study in prostate cases

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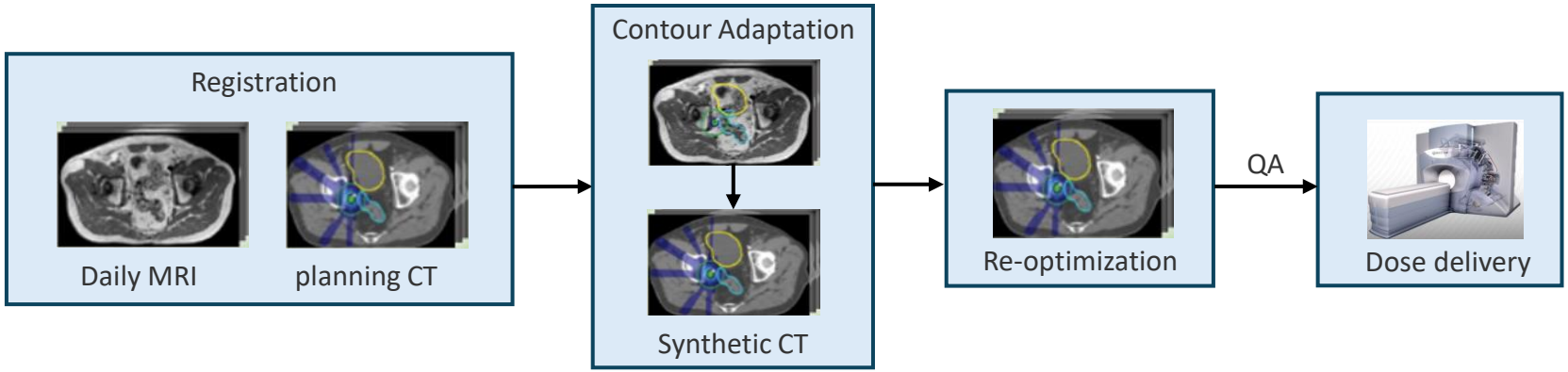
MR-guided online adaptive photon radiotherapy

- **MR-Linac**
  - High soft-tissue contrast of MR images
  - No additional radiation from MR scanning
  - Online-replanning due to daily geometry changes

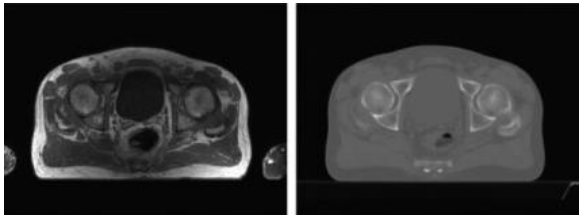
- **Online adaptive MR-guided radiotherapy workflow[1]**

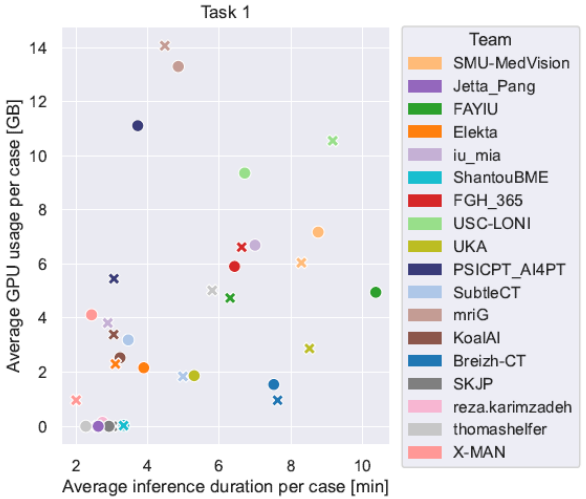


[1] Werensteijn-Honingh AM. Feasibility of stereotactic radiotherapy using a 1.5 T MR-linac. *Radiother Oncol*. 2019.

AI synthetic CT (sCT) generation

- **Deep learning (DL)-based sCT methods for dose calculation**
  - MRI has no tissue attenuation information required for accurate dose calculations
  - Convert MRI to CT-equivalent images:
    - Convolutional neural networks (CNNs)
    - Generative adversarial networks (GANs)
    - Transformers/Diffusion models
  - SynthRAD2023 Challenge Report [2] :
    - Gamma pass rates (2%/2mm) > 98% for full photon plans
    - sCT generation time per patient > 2 mins (4.0±4.8 GB GPU)
  - sCT studies in 2025[3][4] :
    - sCT generation time per patient: 1-2 min
    - Limitations for real-time plan adaptation

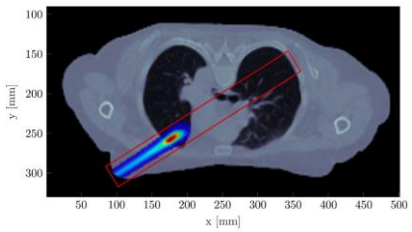


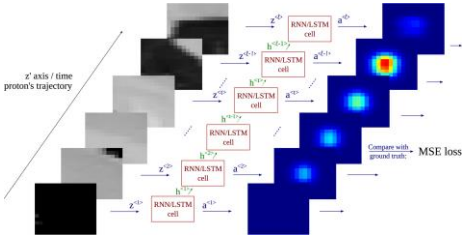


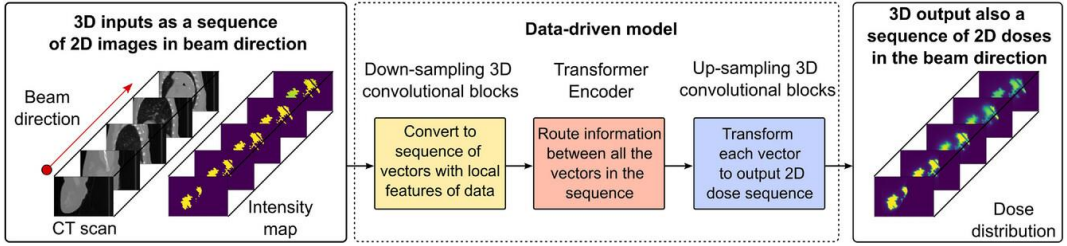
[2] Huijben EMC. Generating synthetic computed tomography for radiotherapy: SynthRAD2023 challenge report. *Med Image Anal*. 2024
[3] Vellini L. A deep learning algorithm to generate synthetic computed tomography images for brain treatments from 0.35 T magnetic resonance imaging. *Physics and Imaging in Radiation Oncology*. 2025
[4] Tulip R. Synthetic Computed Tomography generation using deep-learning for female pelvic radiotherapy planning. *Physics and Imaging in Radiation Oncology.* 2025

AI dose calculation on CT

- **DL-based dose calculation for acceleration**[5][6]
  - **Millisecond speed (~10ms)** with accuracy close to Monte Carlo (MC) simulation
  - Models focus on the individual beamlet from Beam's Eye View (BEV)
  - Treat the extracted 3D cuboid as a sequence of 2D slices traveling from upstream to downstream



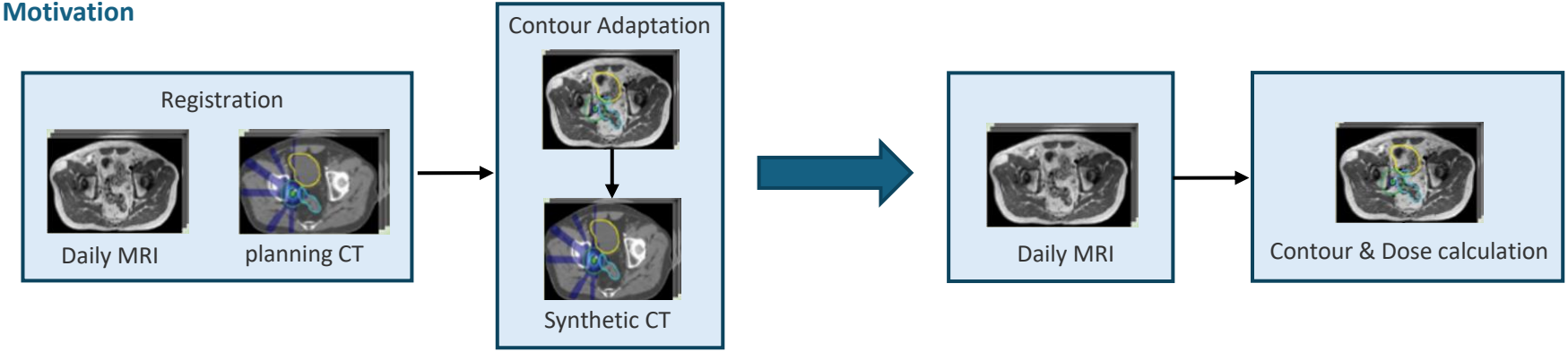




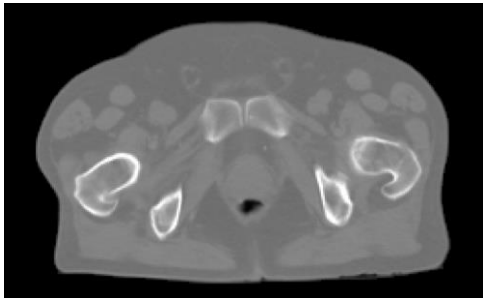
[5] Neishabouri A, Long short-term memory networks for proton dose calculation in highly heterogeneous tissues. *Med Phys.* 2021.
[6] Pastor-Serrano O. Sub-second photon dose prediction via transformer neural networks. *Med Phys.* 2023.

AI dose calculation directly on MRI?

- **Motivation**

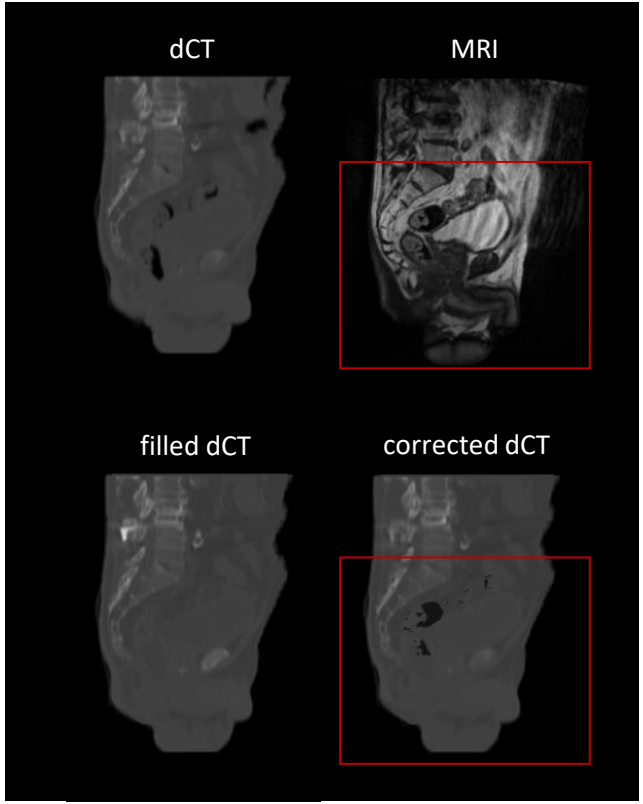


- **Challenges**
  - Consistency between CT and MRI
  - Low signal areas for soft tissues in MRI



Methods & Materials

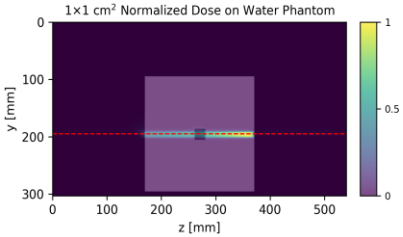
- **Patient data (from the 0.35 T MR-Linac at LMU Hospital)**
  - 34 prostate cancer patients
    - **Train : validation : test = 20 : 4 : 10**
  - MR-CT pairs
    - 0.35 T planning MRI & deformed planning CT (dCT) registered to MRI
    - Deformable registration via an intensity-based algorithm from ViewRay TPS[7]
    - Voxel size: 1.5x1.5x1.5 mm^3
- **Air cavity (AC) correction**
  - Fill original ACs in dCT (threshold < -300 HU)
  - Manually AC contour on MRI (red box area)
  - Insert contoured AC mask into filled dCT
    - Assigned AC values: -700 HU[8]
  - Corrected dCT for dose simulation

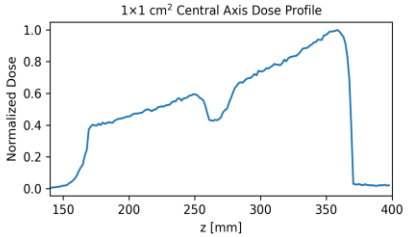


[7] Acharya S. Online magnetic resonance image guided adaptive radiation therapy: first clinical applications. *International Journal of Radiation Oncology* Biology* Physics.* 2016
[8] Lemus OMD, Influence of air mapping errors on the dosimetric accuracy of prostate CBCT-guided online adaptive radiation therapy. *J Appl Clin Med Phys*. 2023

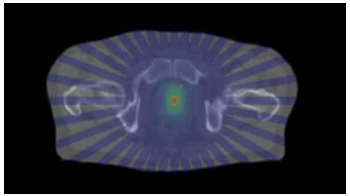
Methods & Materials

- **MC simulation (Geant4 v11.0)**
  - Simulation setup:
    - B field: 0.35 T
    - **Idealized parallel photon beam** (a plane source from G4 GPS)
    - **Uniform square field size**: 1×1 cm²
    - Energy spectrum: ELEKTA_PRECISE_6MV (from IAEA website)
    - Source axis distance: 100 cm
  - Simulation on prostate corrected dCT
    - Train: 10800 beams for 20 patients (5M photons/beam)
    - Validation: 2160 beams for 4 patients (50M photons/beam)
    - Test (50M photons/beam):
      - 1080 beams (through PTV) for 10 patients
      - Two 9-field intensity-modulated plans
        - Each field (9×9 cm²): 81 parallel beams (1×1 cm²)
        - Beam weights optimized by open-source toolkit pyRadPlan[9]

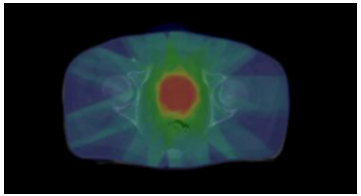




gantry angles 0°–350° (Δ10°) with varied isocenters



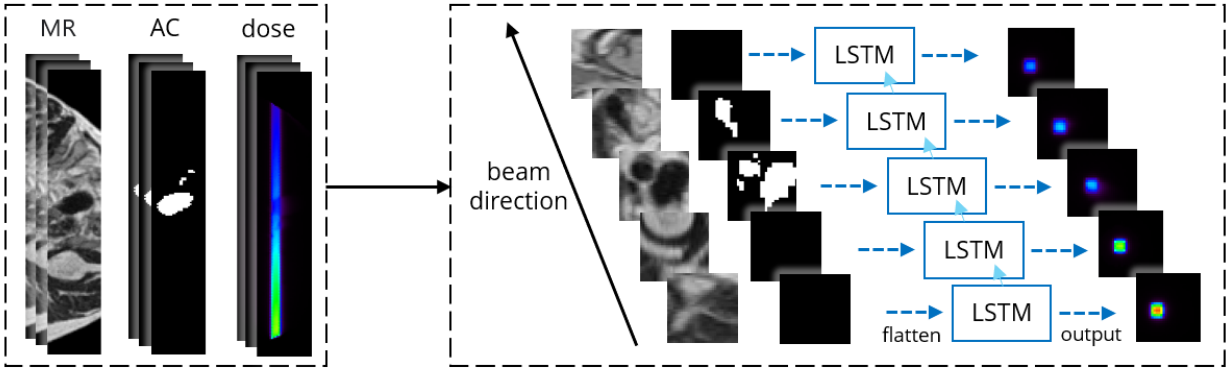
An optimized 9-field plan using 1x1 cm² beams



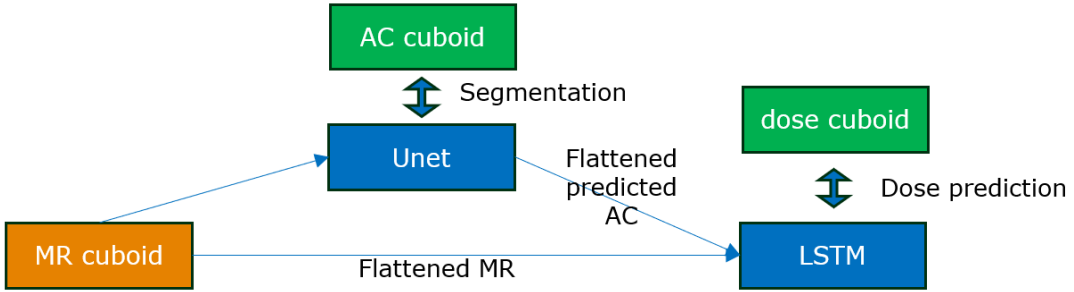
[9] T. Becher, L. Bucher, F. Leininger, G. Stanic, T. Ortkamp, and N. Wahl, pyRadPlan. 2025

Methods & Materials

- **BEV Cuboid extraction**
  - 3D dose/MR/AC cuboids
  - Cuboid size: 32×32×200
  - Voxel size: 2×2×2 mm³
- **DL Models:**
  - LSTM: MR + Manual AC -> dose
  - 3D Unet: MR -> predicted AC

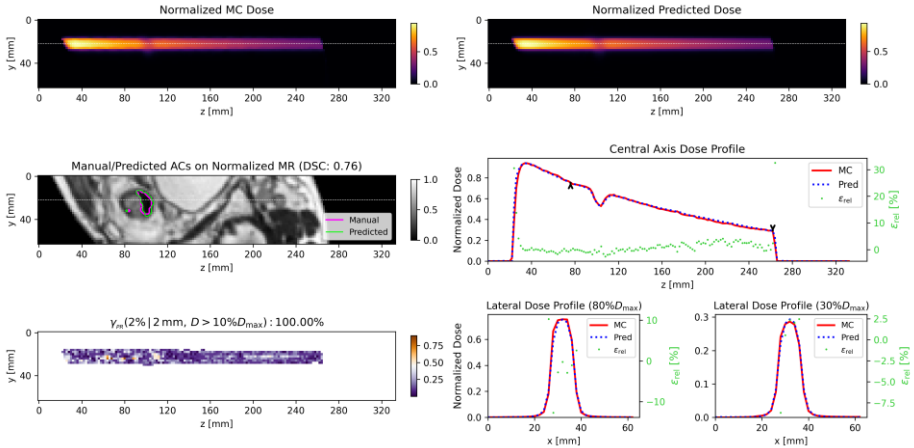


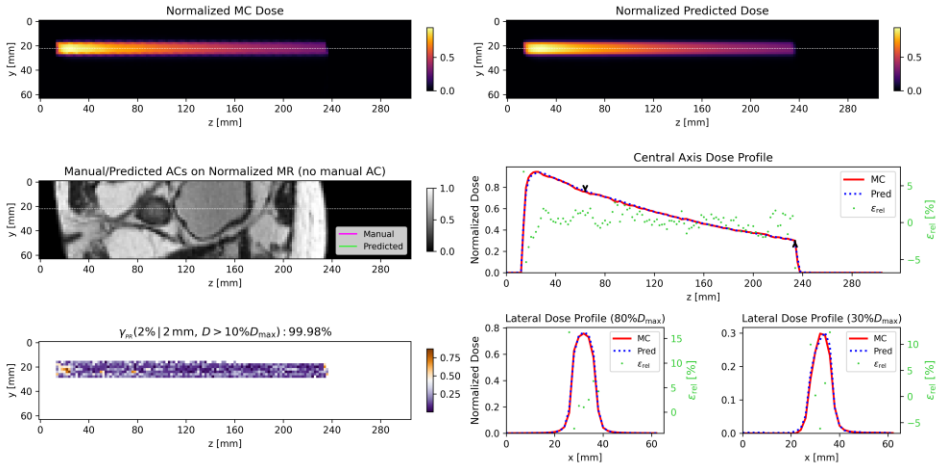
- **Training parameters:**
  - Loss:
    - LSTM: MSE (Mean Square Error) +10*AC*MSE
    - Unet: BCE (Binary Cross Entropy)
  - Optimizer: Adam, leaning rate: 10^{-5}
  - Training time: two days (RTX A6000 GPU, 48 GB)



Results

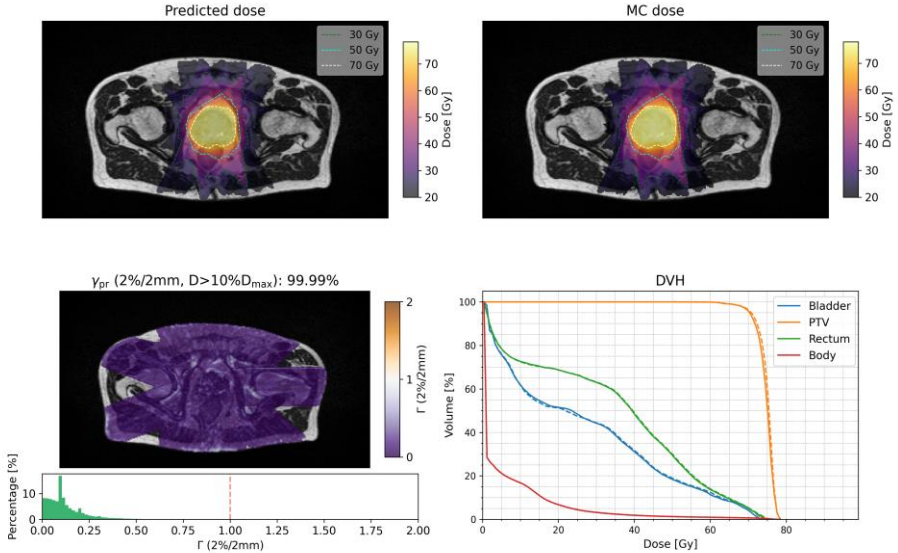
Total 2%/2mm γ_{pr} (mean±SD, min)	2%/2mm γ_{pr}, dose through AC (mean±SD, min)	DSC (mean±SD)
99.68±0.87 (91.93)	99.66±0.91 (94.45)	0.62±0.20

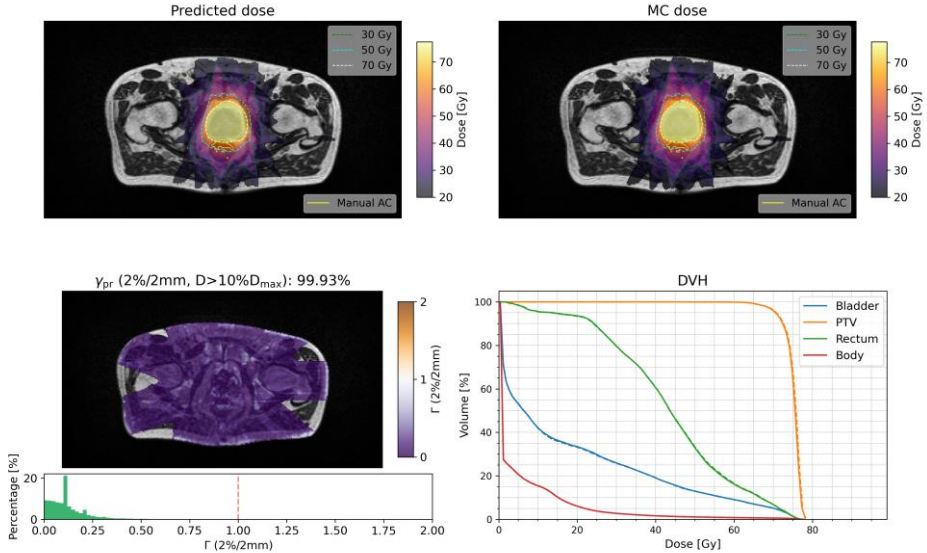




Results

- **9-field plan results**





Results

- **Tested on an Intel(R) Xeon(R) Gold 6354 3.00 GHz CPU and an NVIDIA RTX A6000 GPU**
- **GPU cost: 2GB**

Model	Averaged inference time/beam (ms)
LSTM	7
Unet	5
Total	12

Conclusion

- DL-based photon dose calculation directly on 0.35T MRI is feasible in prostate cases

Outlook

- Incorporate MLC modelling into MC simulation
- Compare AI dose calculation methods with synthetic CT methods
- More challenging treatment sites, e.g., lung

Thank you for your attention!

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Gemeinsam. Fürsorglich. Wegweisend.

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