Development of an Ultra Fast and Setup Robust Deep Learning RBE Dose Engine for Carbon Ion Therapy Using a Conditional Mednext Architecture

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BACKGROUND

Monte Carlo–based biological dose evaluation in carbon-ion radiotherapy is accurate but computationally expensive.

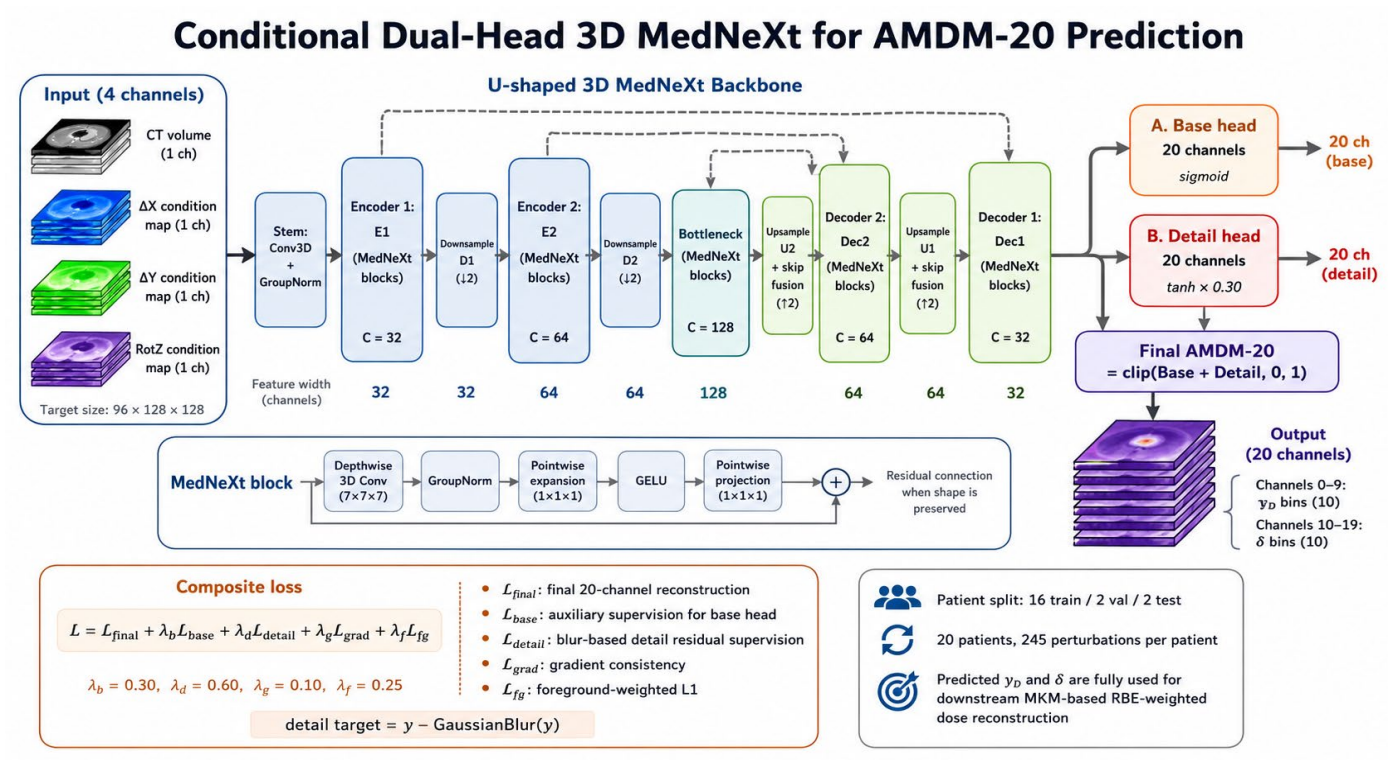
This limits routine robustness analysis during commissioning and QA, particularly when many setup-perturbation scenarios must be evaluated.

OBJECTIVES

To evaluate a setup-conditioned deep-learning framework for predicting AMDM-20 microdosimetric distributions and reconstructing RBE-weighted dose in single-beam carbon-ion radiotherapy.

METHODS

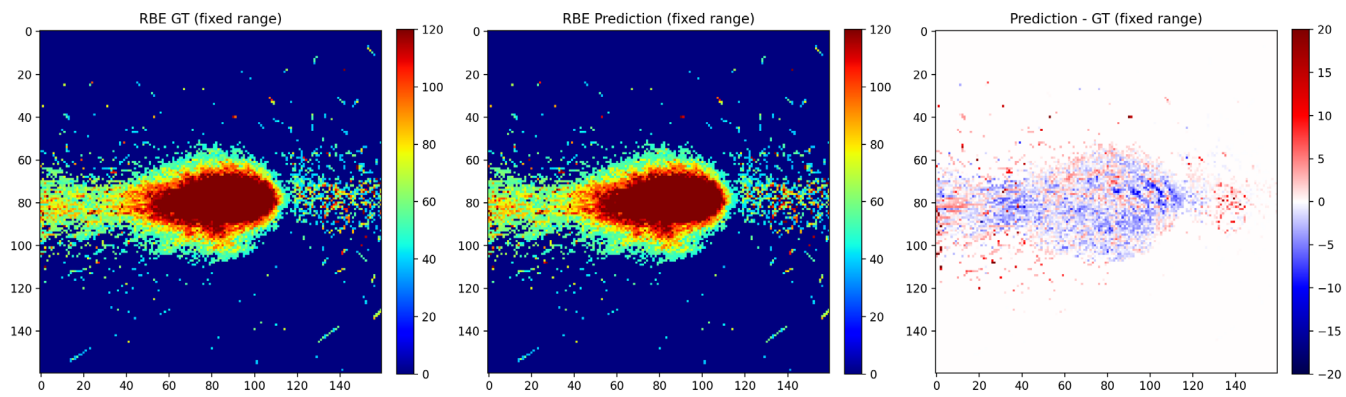
- **Overall Framework Pipeline:**
  - OpenTOPAS-based MC reference generation
  - setup-conditioned dual-head prediction
  - downstream MKM-based RBE biological dose reconstruction for evaluation.
- 20-patient cohort
- 245 setup perturbations per patient
- Input: CT + ΔX/ ΔY/RotationZ maps
- Target: AMDM-20 (10 yD bins + 10 Δ bins)
- Conditional dual-head 3D MedNeXt
- Predicted yD and Δ fully used for MKM-based RBE-weighted dose reconstruction
- Validation metric: 3%/3 mm gamma passing rate



RESULTS

Representative slice comparisons showed close agreement between predicted and reference RBE-weighted dose distributions, with localized residual differences concentrated near the distal falloff and edge regions. Across the evaluated **four patient dataset**, the mean **3%/3 mm gamma passing rate was 96.27 ± 0.72%**.

These findings indicate that the proposed model preserved the dominant biological dose pattern while maintaining strong downstream agreement with Monte Carlo reference.



DISCUSSION

Joint prediction of all 20 AMDM channels (10 yD bins and 10 Δ bins) preserved biologically relevant spatial features and supported accurate downstream MKM-based RBE-weighted dose reconstruction.

The strong mean 3%/3 mm gamma passing rate (96.27 ± 0.72%) across the evaluated five-patient dataset suggests that the model can serve as a rapid surrogate for scenario-based robustness screening.

Residual discrepancies remained concentrated near the distal falloff and edge regions, where steep microdosimetric gradients make prediction more challenging; future work will extend the framework to multi-beam evaluation and larger cohorts.

CONCLUSION

The proposed framework enabled rapid **AMDM-20 prediction** and accurate downstream **RBE-weighted dose reconstruction**, supporting its potential use as a fast surrogate for setup-perturbation screening during carbon-ion commissioning and QA.