High-Fidelity Abdominal Synthetic CT Generation for MR-Only Radiotherapy on an MR-Linac Using a Diffusion Model

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INTRODUCTION

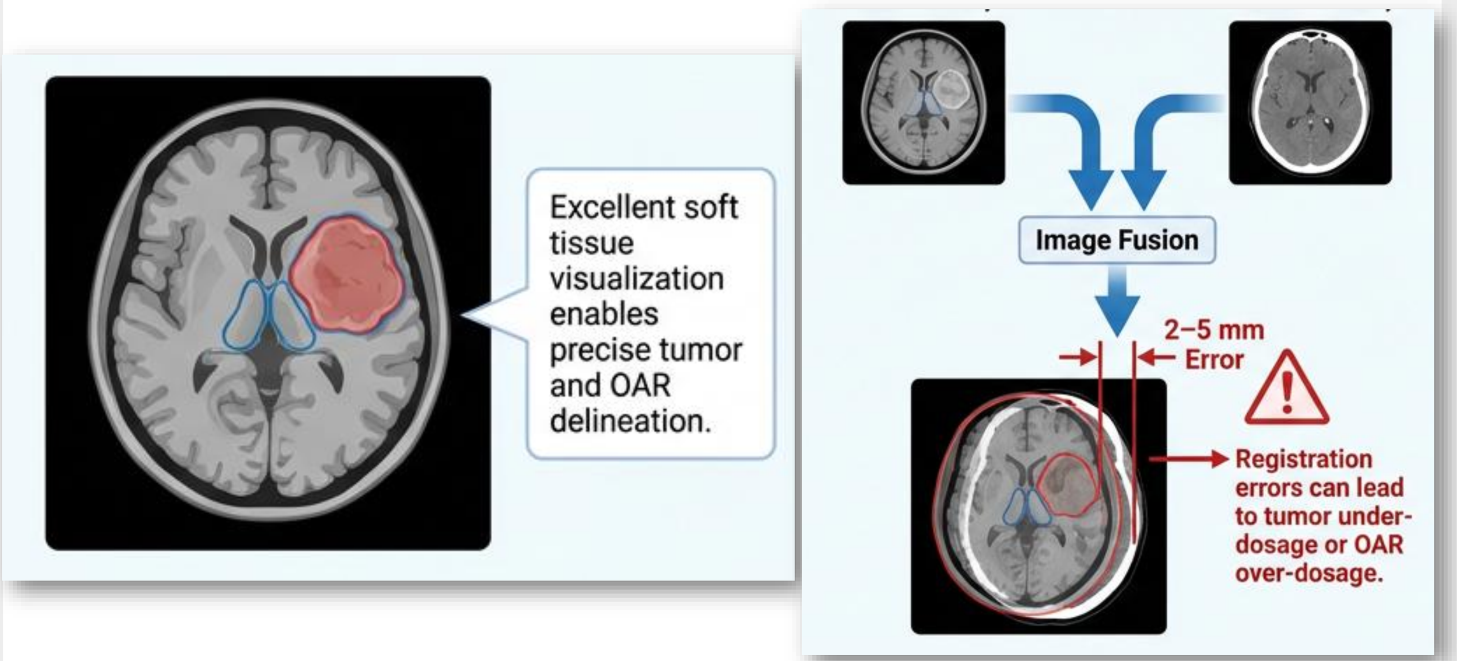
Magnetic Resonance (MR) Imaging in Radiotherapy:

MR images are widely used in radiotherapy due to a multiple of factors

- Superior visualization: excellent soft-tissue contrast enables precise delineation of tumour targets and organs-at-risk (OARs) [1-2]

Challenges with Current Workflows

- Missing dosing data: MRI lacks electron-density information, requiring an additional planning CT
- Registration error: MR-to-CT fusion introduce 2–5 mm geometric error [3-4]



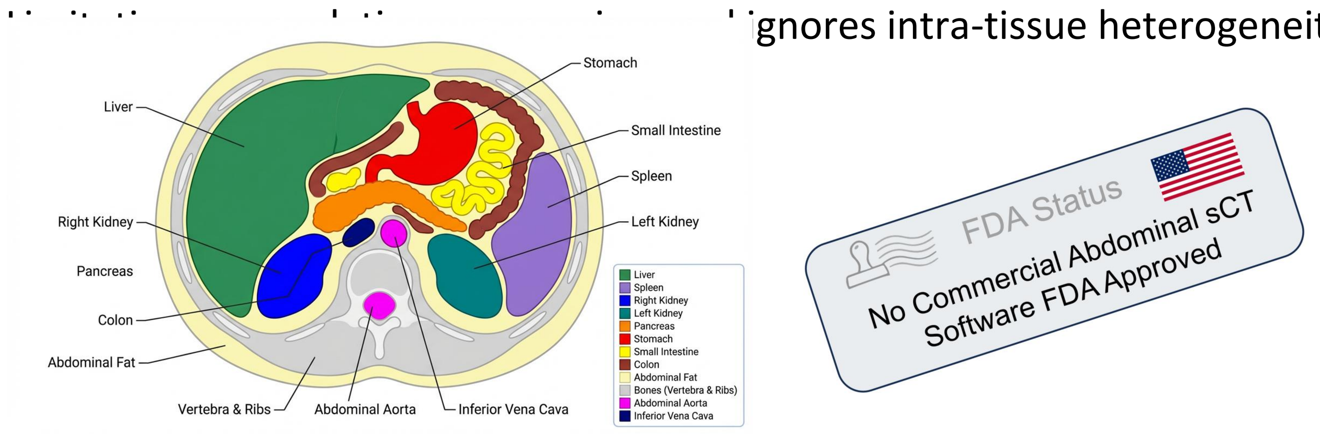
Synthetic CTs:

The Shift to MR-Only Radiotherapy (Using Synthetic CT)

- Strategic goal: eliminate the planning CT to remove geometric discrepancies
- Reduces registration uncertainty
- Decreases clinical workload
- Lowers patient radiation exposure

Conventional Methods (Bulk Density Override):

- Method: segments MRI into tissue classes (air, bone, soft tissue, fat), assigning each a single homogeneous electron density
- ignores intra-tissue heterogeneity

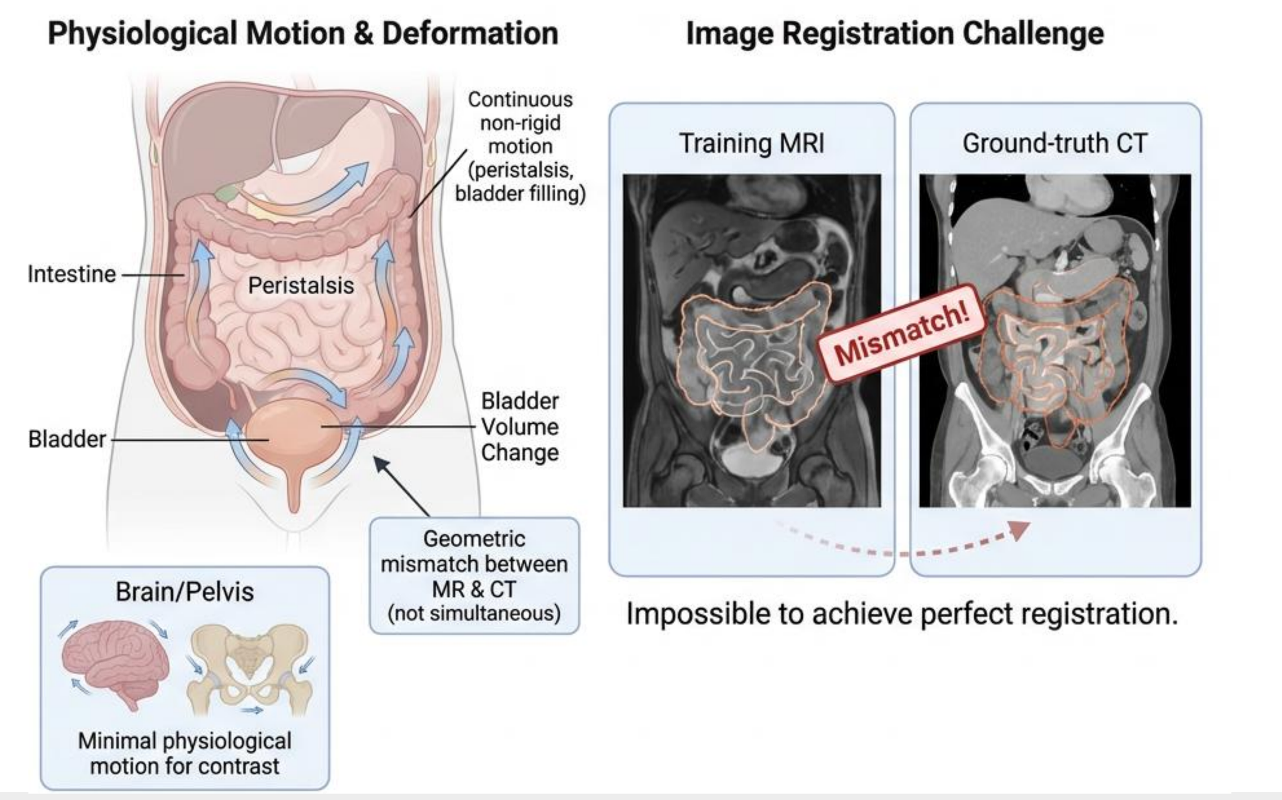


Shift to Deep Learning:

- Introduced in 2017 [5], deep-learning sCT is faster and more accurate than atlas- or bulk-density methods
- Despite progress, no commercial abdominal sCT software is FDA-approved

Abdominal sCT Challenges?

- Complex dynamics: unlike brain or pelvis, the abdomen undergoes continuous non-rigid motion (peristalsis, bladder filling)
- Impact: geometric mismatches between non-simultaneously acquired training MR and ground-truth CT
- Perfect registration is effectively impossible

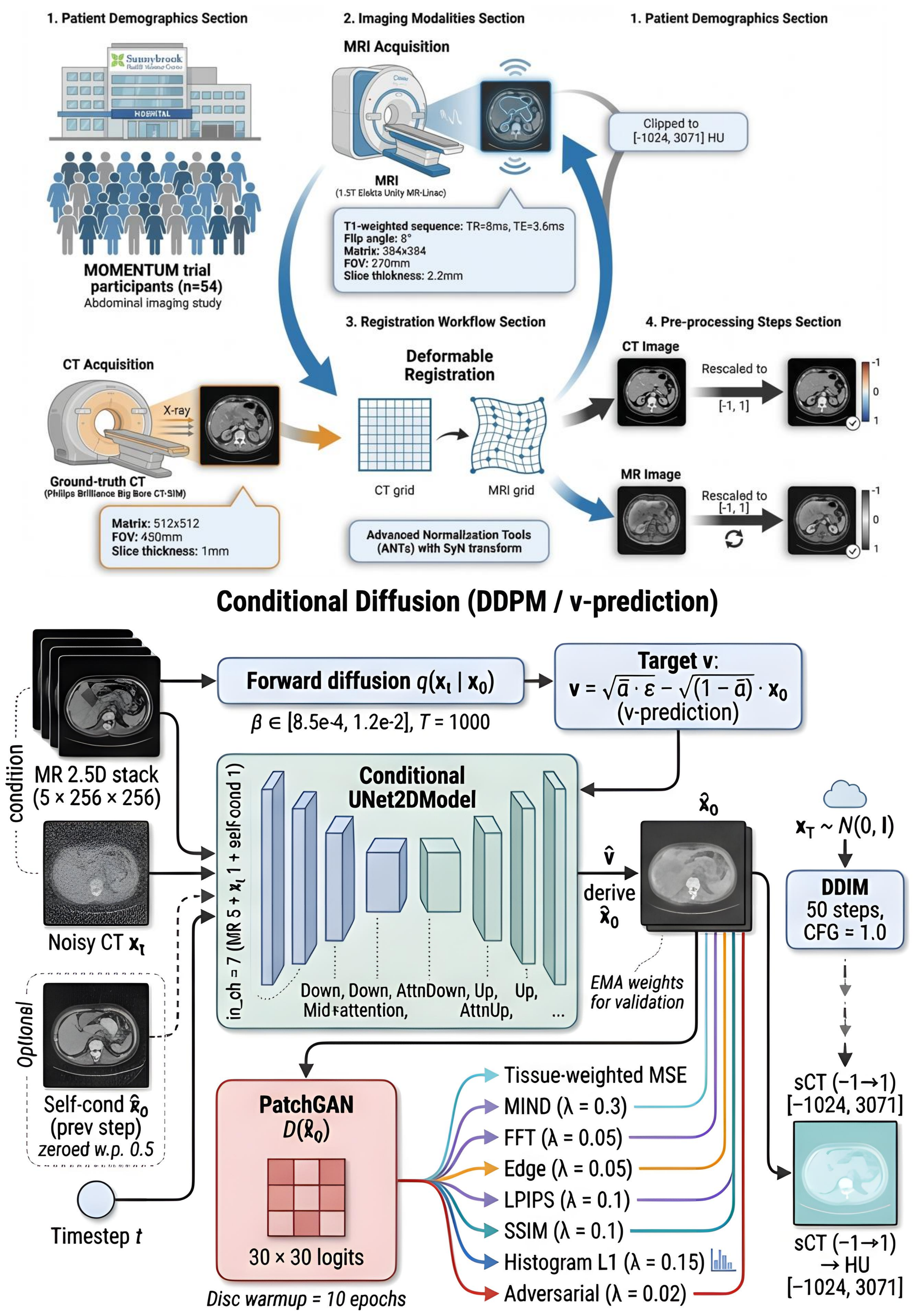


Objective and Hypothesis

Objective: To develop a high-fidelity synthetic CT (sCT) generation pipeline for the challenging abdominal region using a novel diffusion model, enabling a streamlined MR-only workflow on the MR-Linac.

Hypothesis: We hypothesize that a diffusion-based architecture will produce high-fidelity synthetic CTs that statistically replicate ground-truth planning CTs (superior MAE/RMSE and NCC) while achieving clinically competitive accuracy at inference times of several minutes, compatible with online adaptive radiotherapy workflows

Methods



1. **MAE — Mean Absolute Error** *(HU accuracy):* mean absolute voxel difference; validates electron-density accuracy for dose calculation (clinically acceptable: <80–100 HU).

$$\text{MAE}=\frac{1}{N}\sum_{i=1}^{N}|y_i-\hat{y}_i|$$

2. **RMSE — Root Mean Square Error** *(outlier sensitivity):* penalizes large errors, confirming no severe artifacts or outliers.

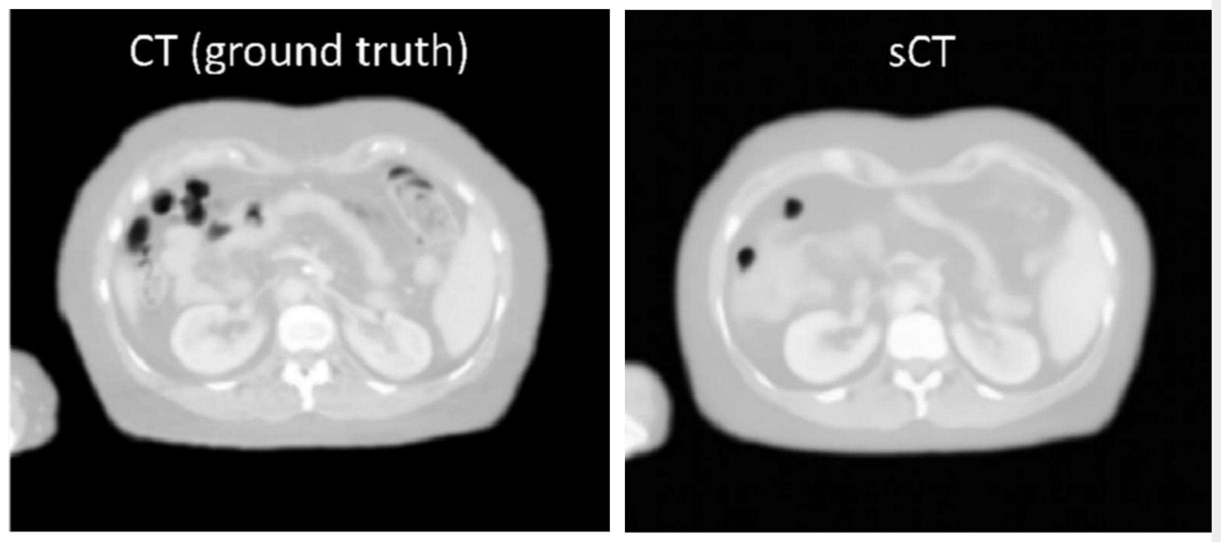
$$\text{RSME}=\sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i-\hat{y}_i)^2}$$

3. **NCC — Normalized Cross-Correlation** *(structural fidelity, −1 to 1):* measures structural similarity, preserving organ boundaries and bowel-gas pockets.

$$\text{NCC}=\frac{\sum(y_i-\bar{y})(\hat{y}_i-\bar{\hat{y}})}{\sqrt{\sum(y_i-\bar{y})^2}\cdot\sqrt{\sum(\hat{y}_i-\bar{\hat{y}})^2}}$$

where y_i, $\bar{y}$ = ground-truth CT (gCT) voxel and mean; $\hat{y}_i$, $\bar{\hat{y}}$ = synthetic CT (sCT) voxel and mean.

RESULTS



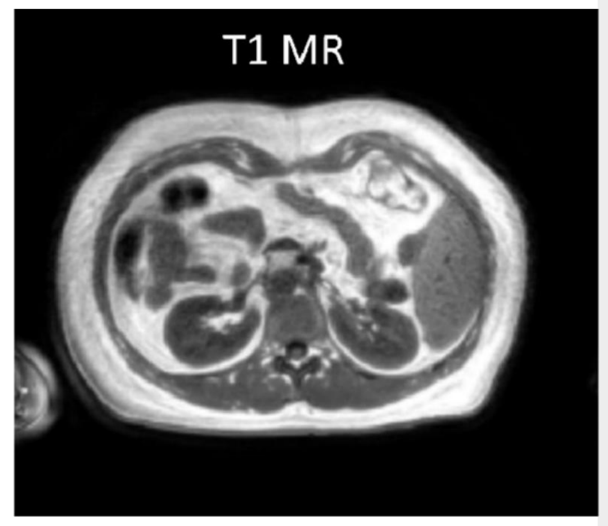


Figure 1: Representative axial slice from test patient showing ground truth planning CT (top-left), synthetic CT (top-right), and T1-weighted MR input (bottom-right). The sCT demonstrates accurate reproduction of soft tissue boundaries, vertebral bone, and bowel gas regions critical for accurate dose calculation in abdominal radiotherapy.

MR Sequence	MAE (HU)	RMSE (HU)	NCC	Inference Time
T1	88±8	138±15	0.81±0.03	~15 min

Table 1: Results

DISCUSSION

Limitations:

- Small test cohort (n=4)
- Missing dosimetric validation not yet performed
- Single-center, single MRI sequence study
- Prospective clinical evaluation needed
- Long inference time for online adaptive radiotherapy

Future Direction:

- Expand cohort
- Comprehensive dosimetric evaluation (Gamma analysis, DVH comparison)
- Multi-center validation study
- Faster inference times for integration with online adaptive workflow

Key Takeaways:

1. Novel approach: Diffusion for abdominal sCT generation from MR-Linac
2. Superior image quality: MAE 88±6 HU, RMSE 138±15 NCC 0.81±0.03 outperforms published GAN methods
3. Clinically practical: ~15-minute inference compatible with offline adaptive RT workflows
4. MR-only potential: Enables elimination of CT simulation, avoiding 2-5mm registration errors

CONCLUSIONS

- Diffusion models offers a promising paradigm for MR-only abdominal radiotherapy planning, combining state-of-the-art accuracy with clinical feasibility.

REFERENCES

1. Schmidt and Payne, 2015
2. Corradini et al., 2019
3. Daisne, 2005
4. Edmund and Nyholm, 2017
5. Han, 2017