Multi-Stage Volumetric Synthetic CT Reconstruction from Diagonal X-Ray Images for Carbon Ion Radiotherapy

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2026 JULY 19–22 VANCOUVER, BC
JOINT AAPM | COMP MEETING

ABSTRACT

PURPOSE - To reconstruct treatment-day volumetric synthetic CT (sCT) from two routine diagonal verification X-rays acquired in carbon ion radiotherapy (CIRT).

METHODS - The dataset comprised 401 prostate CIRT cases; 109 had paired planning CT and in-room X-ray data. Full-field projection completion and FDK reconstruction were followed by coarse, slice-wise, and volumetric refinement. Twenty independent cases were evaluated.

RESULTS - The proposed method achieved 75.7 HU MAE, 27.3 dB PSNR, 0.773 SSIM, and 0.077 LPIPS, outperforming 2D-to-3D and X2CT-GAN.

CONCLUSION - Routine verification images can be used to generate coherent 3D sCT without additional acquisition hardware.

INTRODUCTION

- In carbon ion radiotherapy (CIRT), treatment-day patient position verification is commonly performed using paired two-dimensional (2D) X-ray images [1].
- Although effective for bone-based alignment, this approach provides limited three-dimensional (3D) anatomical information, thereby constraining comprehensive evaluation of anatomical consistency with respect to the planning CT [2].
- This study aims to investigate the feasibility of reconstructing volumetric synthetic CT (sCT) images from diagonally acquired verification X-rays to enable improved anatomical verification in CIRT.

METHODS AND MATERIALS

- Patients & Data
  - 401 prostate CIRT cases
  - 109 paired planning CT/X-ray cases
  - Independent test set: 20 patients
- Overall Workflow
  1. Complete the truncated X-ray field of view
  2. Reconstruct an initial volume using FDK
  3. Apply coarse, slice-wise, and volumetric refinement
- Evaluation
  - Mean absolute error (MAE) and peak signal-to-noise ratio(PSNR) for voxel accuracy
  - Structure similarity index measure (SSIM) and learned perceptual image patch similarity (LPIPS) for perceptual similarity
  - Comparisons with 2D-to-3D [3] and X2CT-GAN[4]

RESULTS

• As summarized in Table 1, the proposed method achieved the best performance for all four metrics on the independent test set (n = 20).

• MAE was 75.7 ± 14.2 HU and LPIPS was 0.077 ± 0.015, representing reductions of 56% and 66% versus 2D-to-3D.

• PSNR was 27.3 ± 0.8 dB and SSIM was 0.773 ± 0.059.

• Compared with X2CT-GAN, MAE and LPIPS decreased by 12% and 53%, respectively.

• Figure 2 demonstrates improved anatomical definition and more spatially consistent error in axial, coronal, and sagittal views.

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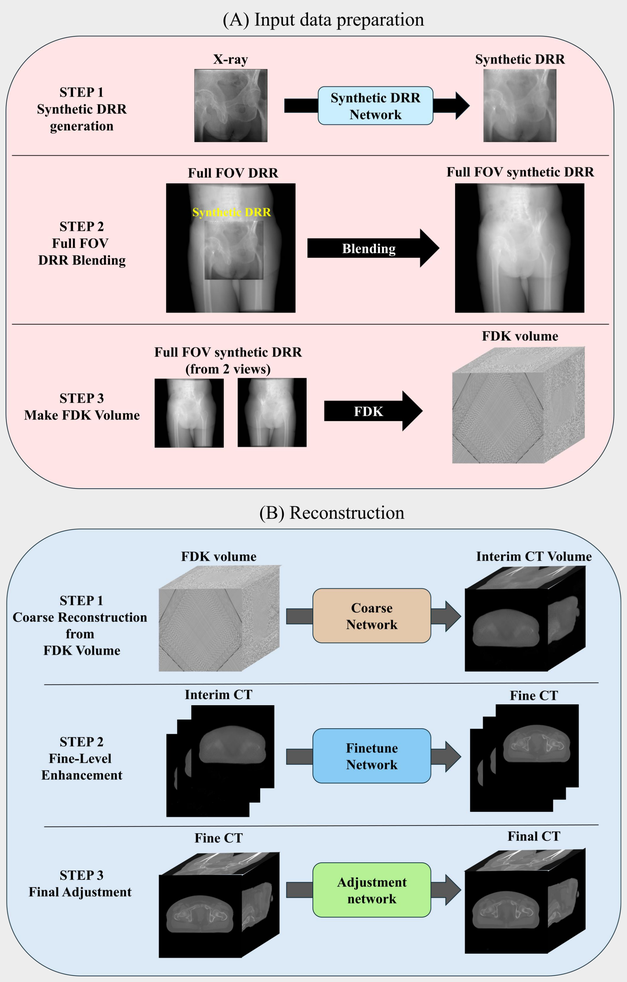

Figure 1. Full-FOV completion, FDK initialization, and multi-stage sCT refinement workflow.

DISCUSSION

- Full-field projection completion reduced truncation artifacts and provided a physics-constrained initialization for FDK reconstruction.
- Sequential refinement recovered global volume, slice detail, and 3D continuity, with ablation confirming the importance of the slice-wise and volumetric stages.
- The results suggest that routine limited-view verification images can support patient-specific volumetric assessment.
- However, prospective multi-center validation is needed to evaluate robustness to anatomical changes, registration errors, and acquisition artifacts, including image registration and dose recalculation.

CONCLUSIONS

- A multi-stage, physics-guided framework reconstructed volumetric sCT from two routine diagonal X-rays. In 20 independent cases, the proposed method outperformed previous methods in MAE, PSNR, SSIM, and LPIPS. The approach may enable 3D anatomical verification in CIRT without additional imaging hardware.

Table 1. Quantitative comparison on the independent test set (mean ± SD).

Metric	Proposed	2D-to-3D	X2CT-GAN
MAE (HU) ↓	75.7 ± 14.2	172.8 ± 36.8	86.5 ± 13.7
PSNR (dB) ↑	27.3 ± 0.8	21.8 ± 1.3	27.1 ± 1.0
SSIM ↑	0.773 ± 0.059	0.634 ± 0.051	0.760 ± 0.046
LPIPS ↓	0.077 ± 0.015	0.226 ± 0.029	0.165 ± 0.013

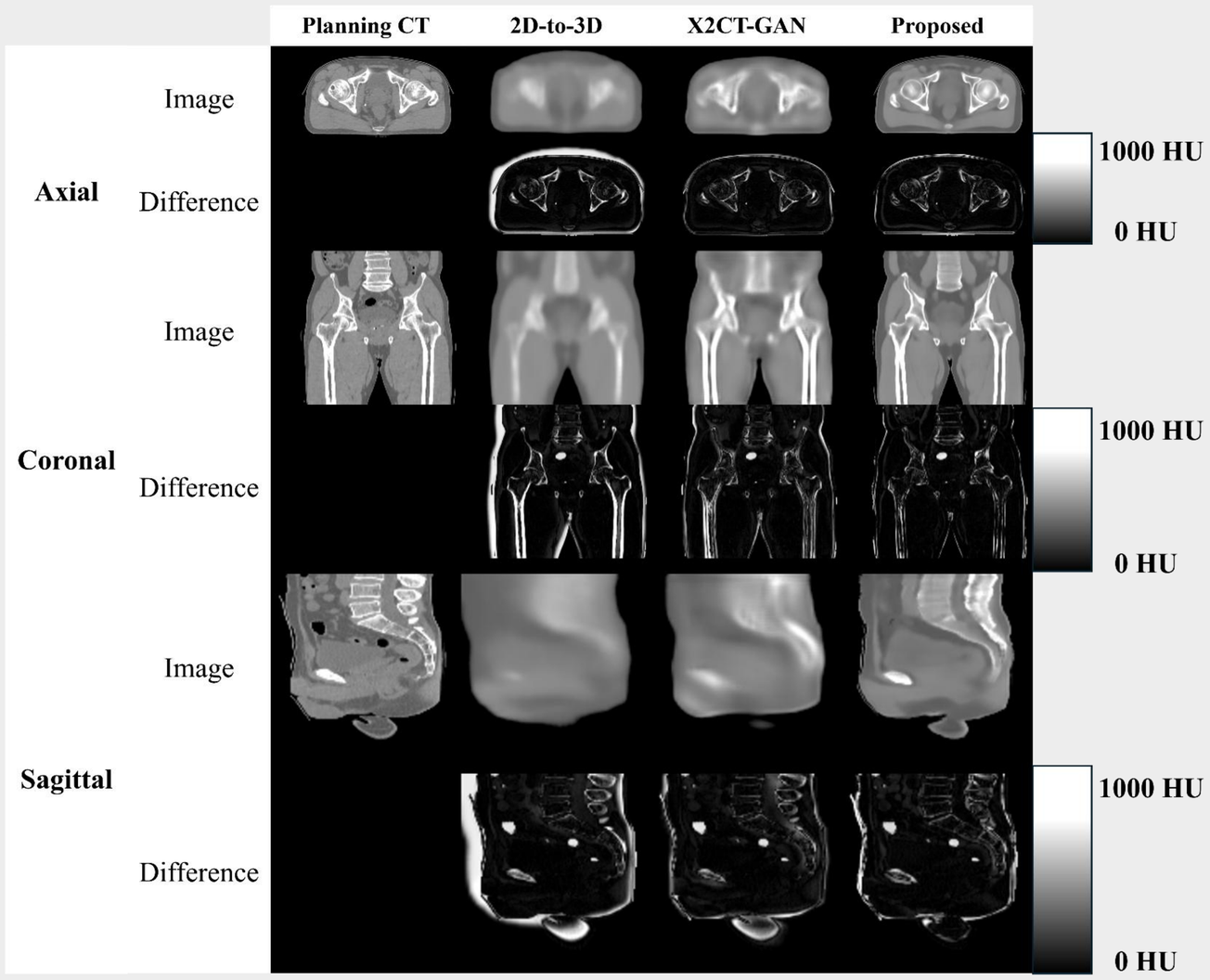

Figure 2. Planning CT, reconstructed sCT, and difference maps in three anatomical planes.

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