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

PADR-Net: Phase-Aware Dual-Branch 4DCT-4DCBCT Deformable Registration for Lung Cancer Radiotherapy

Zixin Li[1], Xinye Ni[1]
[1]Medical Physics Research Center, The Third Affiliated Hospital of Nanjing Medical University

ABSTRACT

Problem: Conventional 3D CT–CBCT registration is usually performed at a single respiratory phase, ignoring 4D respiratory motion and temporal consistency.

Method: PADR-Net was developed as a phase-aware dual-branch deformable registration framework for planning 4DCT and treatment 4DCBCT. The 4DCT branch models phase-consistent respiratory motion, while the 4DCBCT branch performs phase-matched cross-modality alignment. CMHM further coordinates temporal deformation across phases.

Results: On a clinical lung cancer dataset, PADR-Net improved Dice from 0.952 to 0.986 and achieved a mean HD95 of 2.6 mm.

Conclusion: PADR-Net provides spatiotemporally consistent 4D registration for dose accumulation and adaptive lung radiotherapy.

CONTACT

Zixin Li
Medical Physics Research Center,
The Third Affiliated Hospital of Nanjing Medical University
Changzhou No. 2 People's Hospital,
Changzhou, China
Email: nxy@njmu.edu.cn

INTRODUCTION

4DCT acquired during treatment planning provides respiratory motion information, while 4DCBCT acquired during treatment captures patient anatomy at the time of irradiation. Accurate 4D registration is critical for adaptive radiotherapy and 4D dose accumulation. However, conventional phase-specific registration methods may suffer from poor temporal continuity and phase mismatch. To address these challenges, PADR-Net was developed to jointly align planning 4DCT and treatment 4DCBCT within a unified respiratory reference frame.

METHODS

- Dual-branch network with separate branches for 4DCT and 4DCBCT.
- Shared 3D Swin-Transformer U-Net backbone for deformation estimation.
- Phase embeddings injected into both branches to encode respiratory phase information.
- CMHM module coordinates temporal deformation and improves phase-consistent motion.
- Outputs are spatially and temporally consistent warped 4DCT and 4DCBCT sequences.

RESULTS

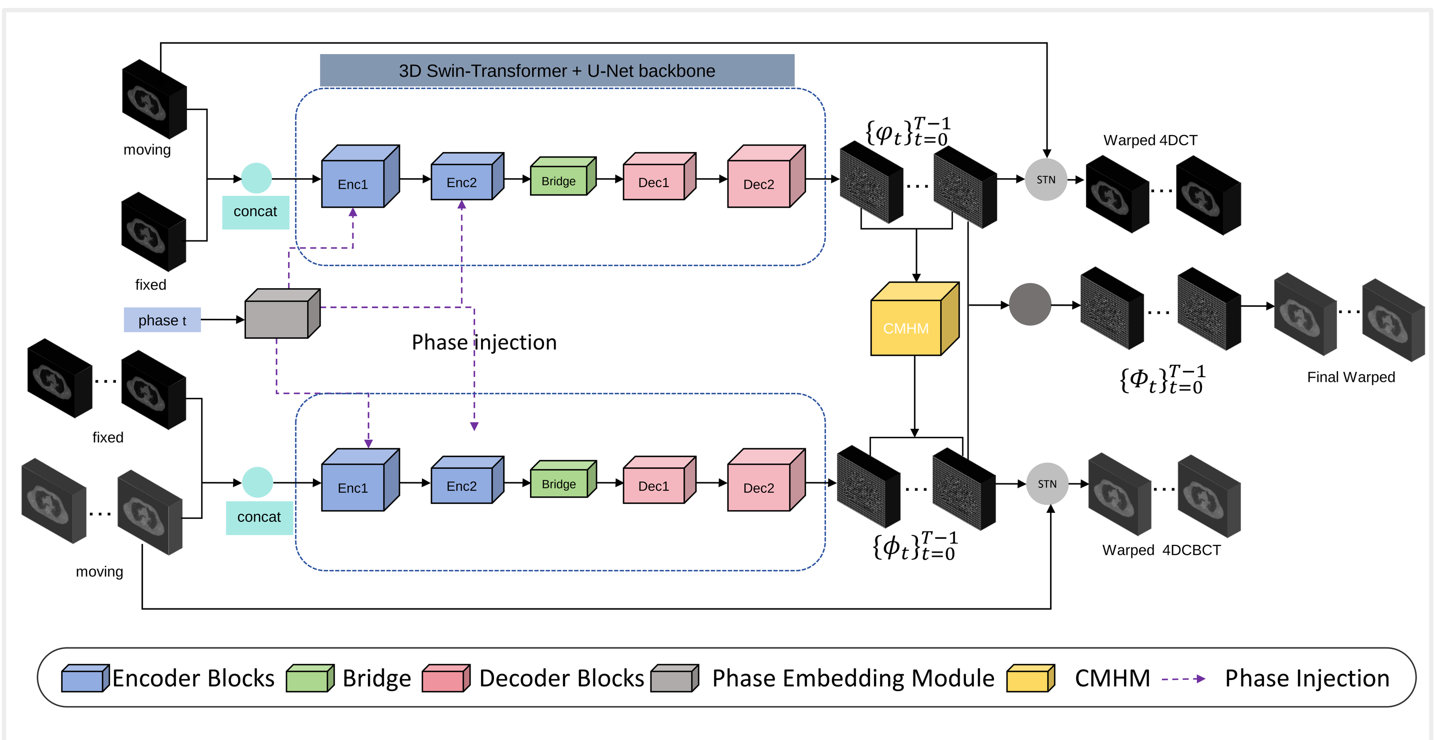
Quantitative **Results**

Method	LNCC ↑	TRE (mm) ↓	Dice ↑	HD95 (mm) ↓
Affine	0.930 ± 0.020	4.36 ± 0.80	0.952 ± 0.015	4.3 ± 1.5
NiftyReg	0.864 ± 0.018	5.11 ± 0.79	0.899 ± 0.012	5.2 ± 1.3
UTSRMorph	0.945 ± 0.015	2.44 ± 0.62	0.964 ± 0.010	3.7 ± 1.0
TransMorph	0.962 ± 0.016	2.21 ± 0.65	0.972 ± 0.011	3.5 ± 1.1
VoxelMorph	0.968 ± 0.017	2.23 ± 0.74	0.977 ± 0.011	3.2 ± 1.2
PADR-Net	**0.965 ± 0.012**	**2.19 ± 0.50**	**0.986 ± 0.008**	**2.6 ± 0.8**

*PADR-Net achieved the highest Dice and LNCC, with the lowest TRE and HD95 among all compared methods.

Qualitative Comparison

Pipeline



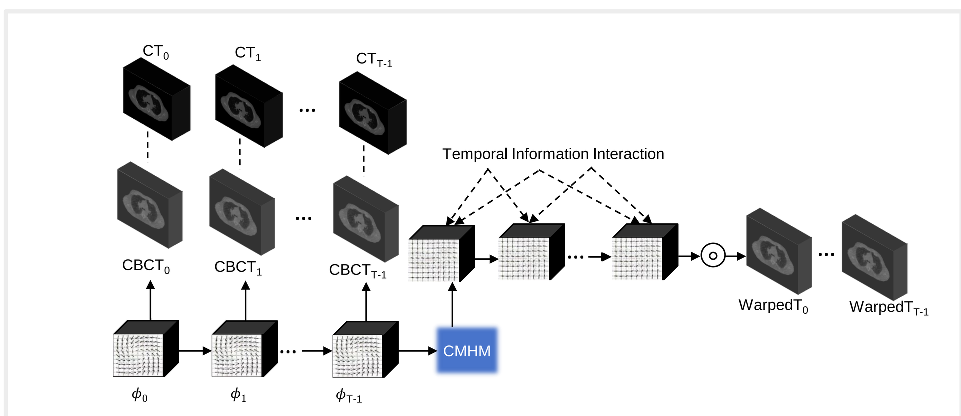
Network

PADR-Net jointly processes multi-phase 4DCT and 4DCBCT images to estimate phase-resolved deformation fields. The 4DCT branch builds a phase-consistent respiratory motion prior by mapping each phase to the mid-ventilation reference. The 4DCBCT branch performs phase-matched cross-modality alignment guided by the 4DCT motion prior, while CMHM coordinates temporal deformation across phases.

Training Objective

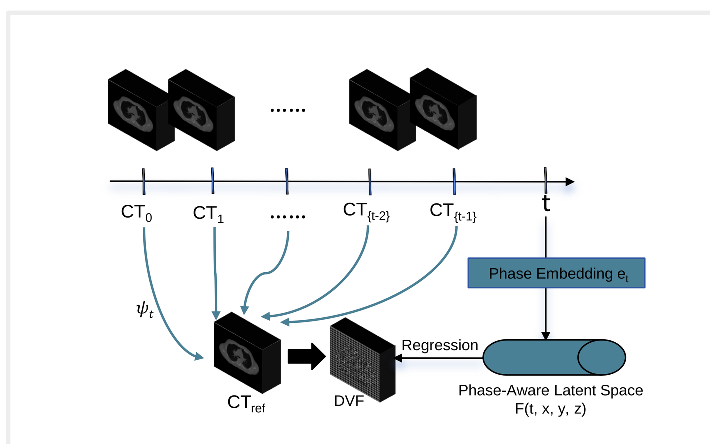
The network is optimized with image similarity, spatial smoothness, and temporal phase-motion consistency losses to achieve accurate and stable 4DCT–4DCBCT registration.

Phase-Aware 4DCT-4DCBCT Registration



Multi-phase 4DCT and 4DCBCT images are jointly modeled to estimate phase-resolved deformation fields. The 4DCT branch provides a phase-consistent respiratory motion prior, while the 4DCBCT branch performs phase-matched treatment-to-planning alignment. CMHM coordinates temporal information across respiratory phases, improving deformation smoothness and phase-to-phase registration consistency.

Phase-Aware Motion Modeling



Relative respiratory phase information is encoded as phase embedding and injected into the registration network. By conditioning deformation estimation on phase-specific latent features, PADR-Net learns phase-aware deformation fields and improves the consistency of respiratory motion representation across different phases.

DISCUSSION

PADR-Net improves anatomical alignment and lung-shape consistency across respiratory phases. By incorporating phase embedding and temporal coordination, the model reduces phase mismatch and local deformation instability, supporting more reliable 4D dose accumulation and adaptive lung radiotherapy.

Acknowledgement

This work was supported by the National Natural Science Foundation of China (62371243). We thank Prof. Xinye Ni for guidance and the research group for support in algorithm design and manuscript preparation.