Quantifying Primary and Lymph Node Tumor Volume Reduction and Mass Loss During Radiotherapy

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Lopamudra Nayak[1], Jue Jiang[1], Harini Veeraraghavan[1], Pengpeng Zhang[1], Aditya Apte[1], Nancy Lee[2], Joseph O. Deasy[1]
[1]Department of Medical Physics, Memorial Sloan Kettering Cancer Center, New York, NY
[2]Department of Radiation Oncology, Memorial Sloan Kettering Cancer Center, New York, NY

ABSTRACT

Purpose: Early assessment of radiotherapy response is essential for adaptive treatment planning and digital-twin development. Longitudinal quantification of tumor volume and mass changes depends on reliable deformable image registration (DIR), which remains challenging. This study compared an AI-based DIR model (ProRSeg) with ANTs for CT alignment in head and neck cancer (HNC) and evaluated deformation-derived quantitative features.

Methods: CT data from 104 HNC patients were analyzed with scans acquired pre-RT and ~3 weeks into treatment. ProRSeg (3D convolutional LSTM + U-Net encoder, fine-tuned on 62 HNC patients) and ANTs were compared using DSC and HD95. Jacobian maps derived from deformation vector fields were correlated with volume/mass change rates.

Results: ProRSeg achieved higher DSC (0.73 vs 0.66) and lower HD95 (6.69 mm vs 9.14 mm). Tumors showed mean volume/mass losses of 0.4%/0.5% per day (primary) and 0.4%/0.4% per day (lymph nodes). Jacobian metrics correlated with % change metrics (Spearman ρ ≈ 0.4, p < 0.001) .

Conclusion: ProRSeg provided accurate mid-treatment CT alignment with quantitative tumor volume and mass estimates, supporting digital-twin–based adaptive radiotherapy.

INTRODUCTION

- Accurately tracking early response to radiotherapy is critical for adaptive treatment planning and improving outcomes in head and neck cancer patients.
- Tumor volume and mass changes are key indicators of treatment effectiveness.
- Deformable image registration (DIR) is essential for aligning longitudinal CT scans to observe anatomical changes over time.
- High-precision DIR enables accurate comparison of tumor and organ structures across different time points.
- Without reliable registration, quantifying tumor response is error-prone and may lead to incorrect clinical decisions.
- We compare an AI-based DIR model (ProRSeg) with ANTs for longitudinal CT alignment in head and neck cancer and quantify tumor volume and mass loss in support of digital-twin–based adaptive radiotherapy.

DATASET PREPARATION

Dataset:
- Data from 102 **head and neck** cancer patients
- Each patient had two CT scans:
  First scan: before radiotherapy
  Second scan: ~ three weeks after radiotherapy

Image Processing:
- Images cropped to focus on body regions
- First CT scan rigidly registered to the second scan

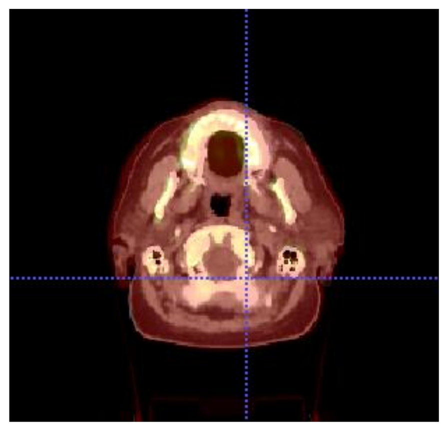


Fig 1: Overlay of the rigidly registered scan onto the second scan.

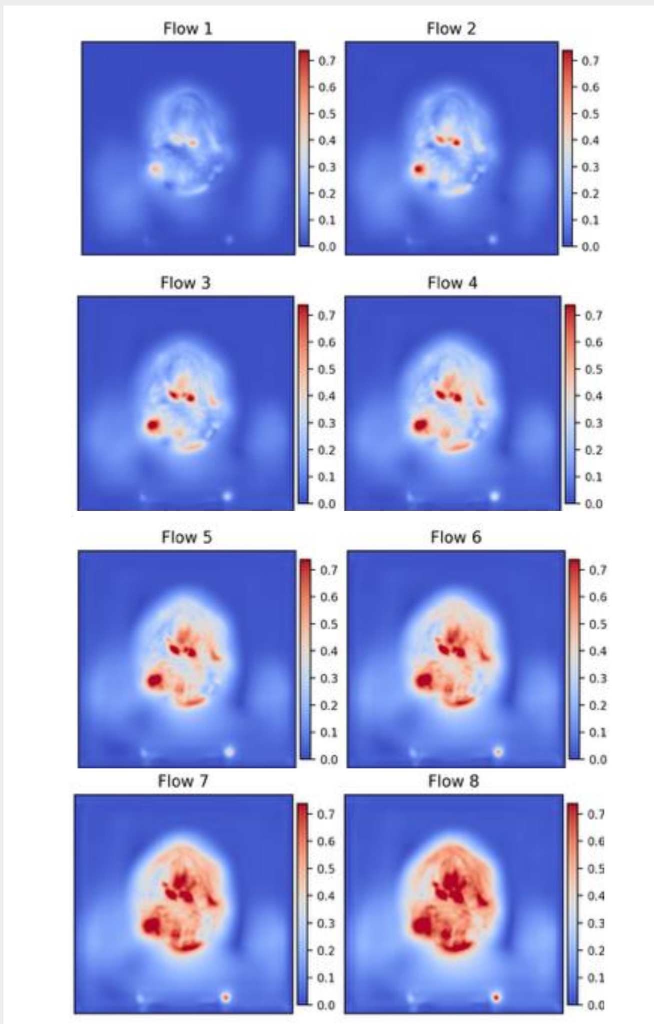


Fig 3: This figure shows the progressive deformation vector fields predicted with AI-DIR model for alignment of longitudinal CT scans

DEFORMABLE IMAGE REGISTRATION

Model Architecture
- ProRSeg: U-Net encoder (with 3D convolutional LSTM) + CNN decoder (Jiang et al., Med Phys)
- Fine-tuned on head & neck anatomy (62 patients)
- Fixed & moving image + masks → DVF → warped image + mask

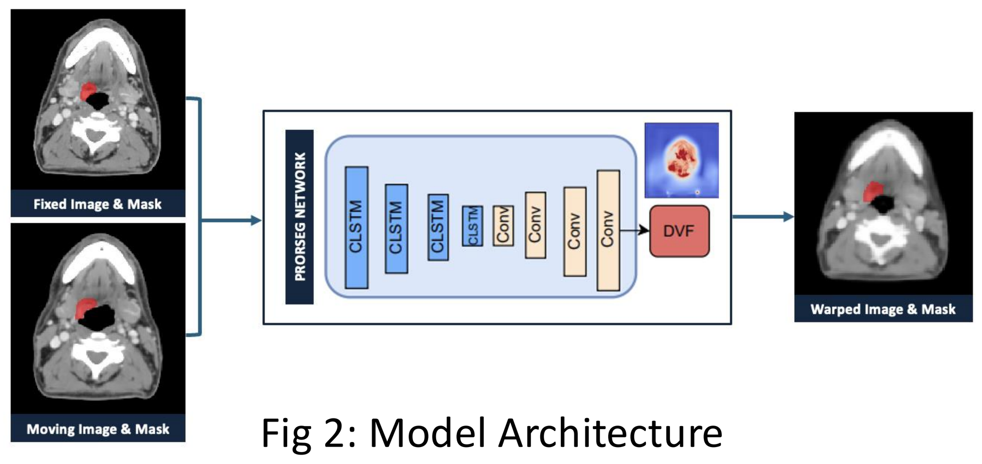
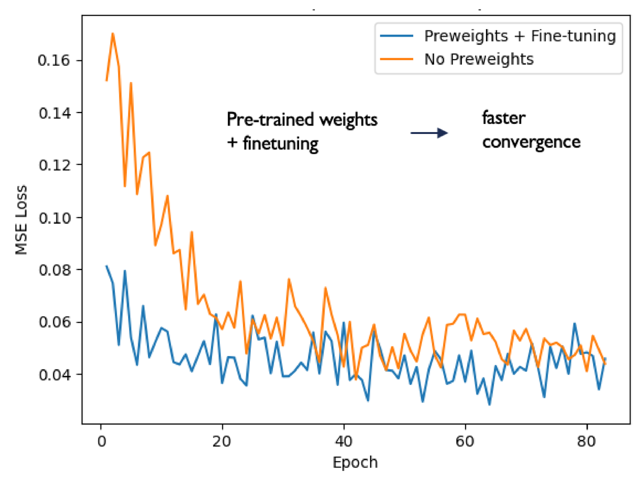


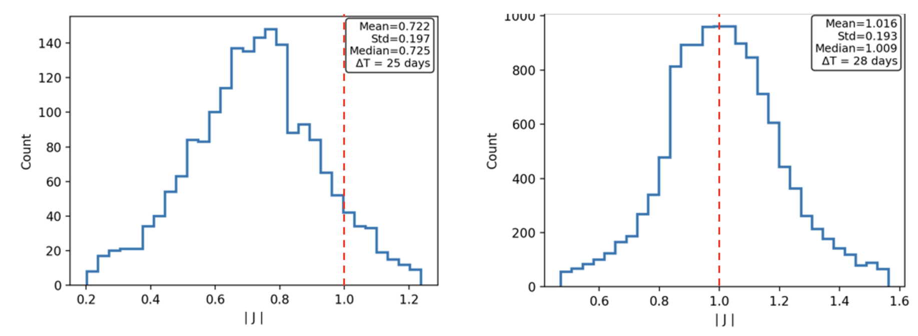
Fig 2: Model Architecture

Data Split:
- Train 60%, Validation 20%, Test 20%

Training:
- CT intensity windowed to [−135, 215] HU (Soft Tissue: WW:350 WL:40), normalized to [0, 1]
- Loss = MSE(y, ŷ) + (1 − DSC) α_{DSC} + ∇(DVF) λ_{smooth}



Jacobians:
- Computed from the AI-predicted deformation vector field (Fig. 3) between first and second CT scans.
- Measure voxel-wise local volume changes after deformable registration.



Network evaluation:
- Compared with SyN, ProRSeg (Fig 4) improved DSC (0.73 vs. 0.66 for GTVp; 0.75 vs. 0.54 for GTVn) and reduced HD95 (6.69 vs. 9.14 mm; 5.80 vs. 10.56 mm).

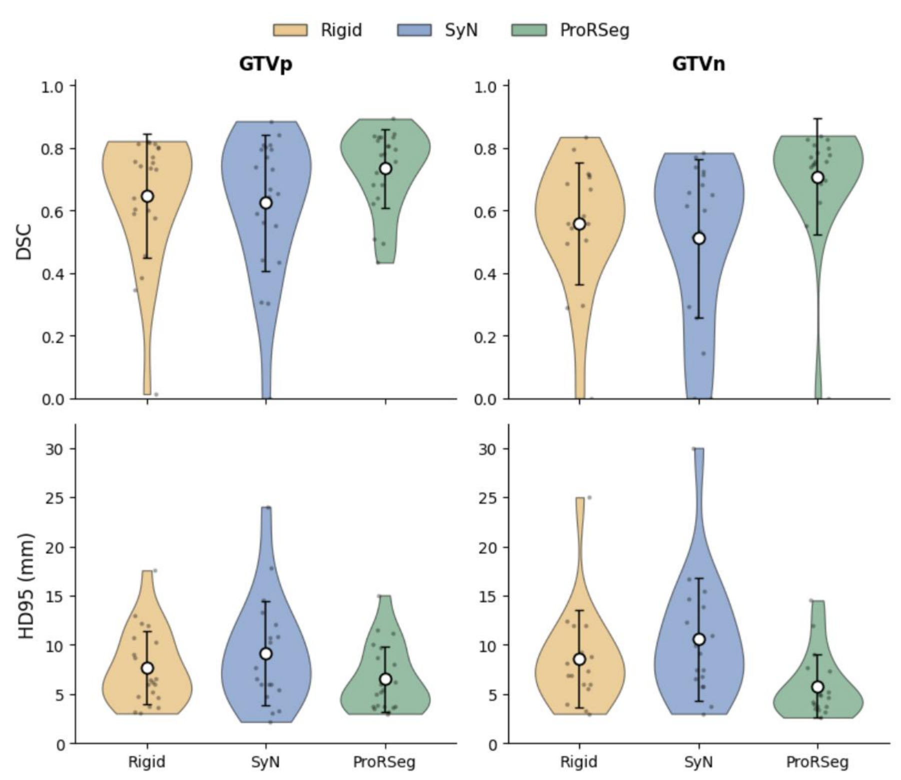
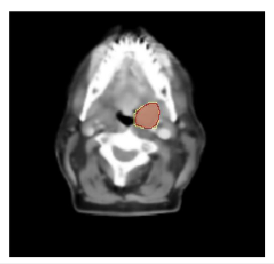


Fig 4: Network evaluation on held-out dataset



Dice score = 88%
(example case)

RESULTS

Regression rates per day:
- Both primary tumors and lymph nodes showed progressive regression during treatment, with median daily losses of approximately 0.4% in volume (Fig 5A) and 0.4–0.5% in mass (Fig 5B).

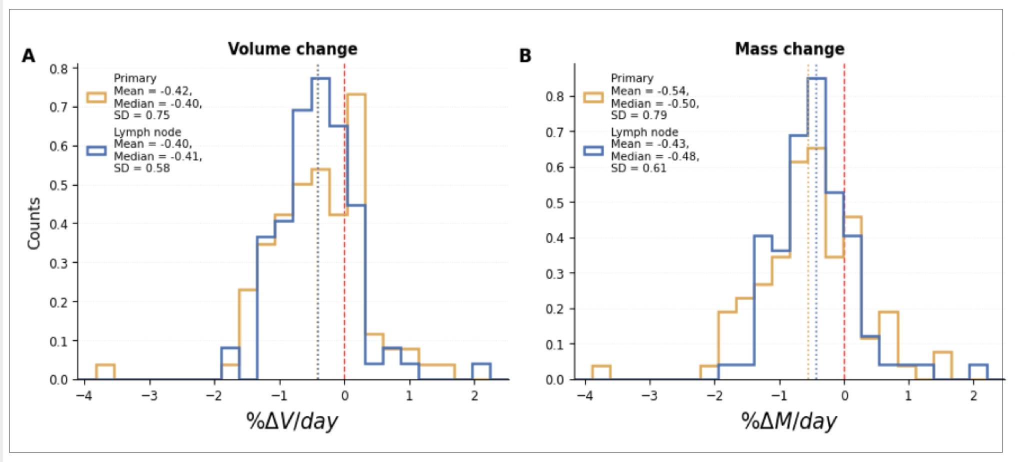
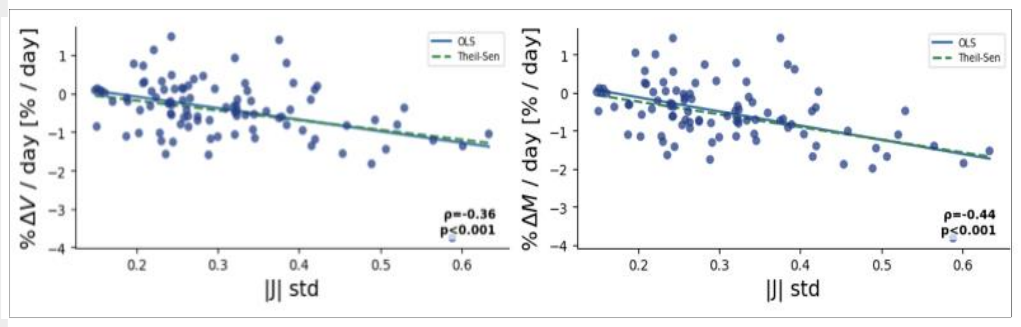


Fig 5: (A)% volume loss per day
(B) % mass loss per day

|J| correlation with regression rate:
- Jacobian-derived features moderately correlated with % volume and mass loss (Spearman ρ ~ 0.4*, p < 0.001).

Primary



Lymph Node

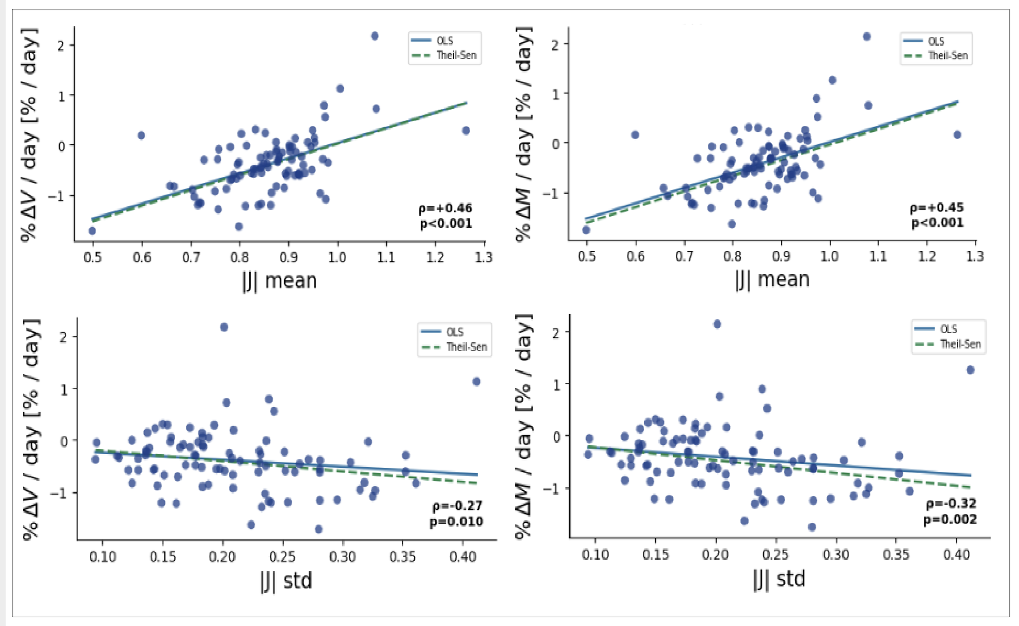


Fig 6: scatter plot between regression rates vs |J| for primary (top) and lymph node (bottom)

SUMMARY

- ProRSeg applied to mid-treatment HNC CT images provided results consistent with ground-truth, resulting in quantitative estimates of tumor specific volume and mass loss.
- Future work will quantify the predictive value of these features, supporting digital-twin–based adaptive radiotherapy.

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CONTACT

Lopamudra Nayak, PhD / Joseph O. Deasy, PhD
Memorial Sloan Kettering Cancer Center
Department of Medical Physics
1275 York Avenue, New York, NY 10065
AAPM Annual Meeting 2026
Email: nayakl@mskcc.org / DeasyJ@mskcc.org