A Clinically Scalable AI-Based Deformable Image Registration Framework for Planning-to-Repeat CT Alignment in Proton Therapy

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~80×
faster inference
17.62 s → 0.22 s per CT pair

89.0%
mean image SSIM
up from 72.60% (+22.6%)

58.2%
CTV Dice coefficient
vs. 55.61% conventional DIR

Purpose

Misalignment between planning and repeat CT in proton therapy — from patient positioning, physiological motion, and anatomical change — degrades contour propagation and plan adaptation. Conventional deformable image registration (DIR) is slow and fragile under large variation, and most AI-based DIR relies on idealized assumptions and small datasets. We build a robust, clinically scalable DIR framework trained on large-scale, heterogeneous clinical data.

Methods

- Transformer-based foundation model with a progressive coarse-to-fine strategy for large anatomical variation.
- Integrates clinical priors — organ contours, dose maps, treatment plans — via foreground-aware optimization, anatomy- & risk-guided attention, and text-conditioned priors.
- Trained on a large-scale institutional proton-therapy dataset (since 2016) across diverse sites, diseases, populations, and imaging standards.

Highlights

- Foundation DIR model built for real clinical proton-therapy data, not idealized phantoms.
- Clinically-informed guidance — contours, dose, and plans steer the registration.
- Consistent gains in image similarity (SSIM, MSE) and CTV alignment across anatomical sites.
- Near real-time inference enables practical online adaptive workflows.

Clinical Role

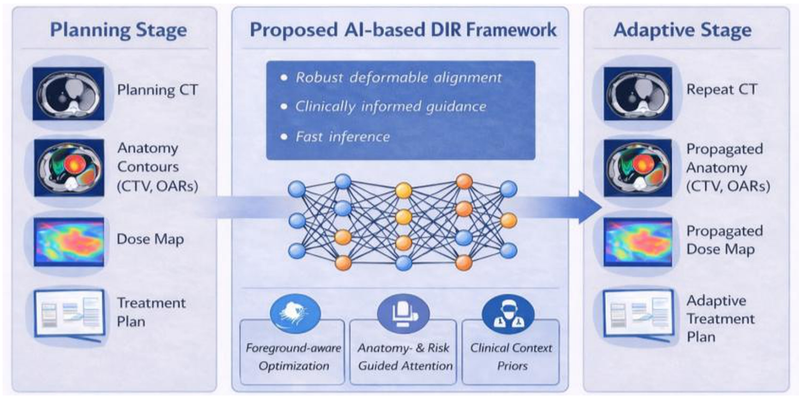

Fig. 1 Clinical role of the AI-based registration framework.

Advantages over DIR

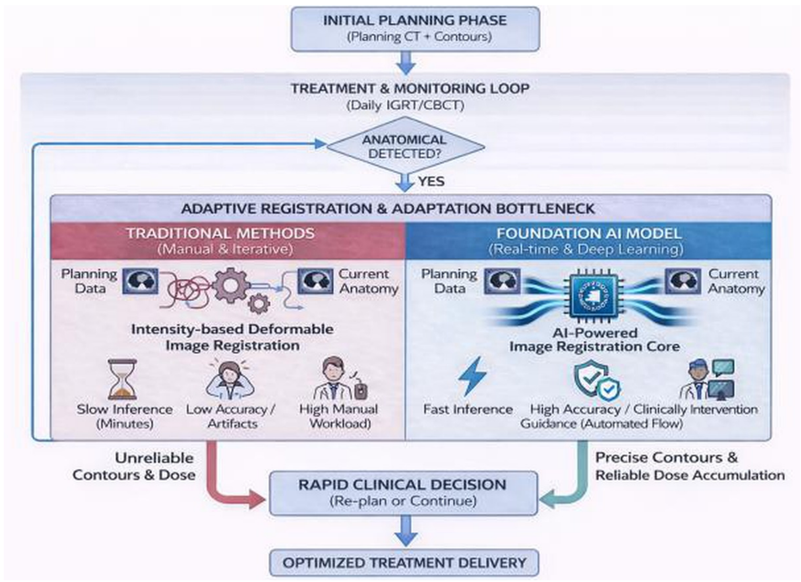

Fig. 2 AI-based vs. conventional clinical registration workflow.

Dataset Diversity

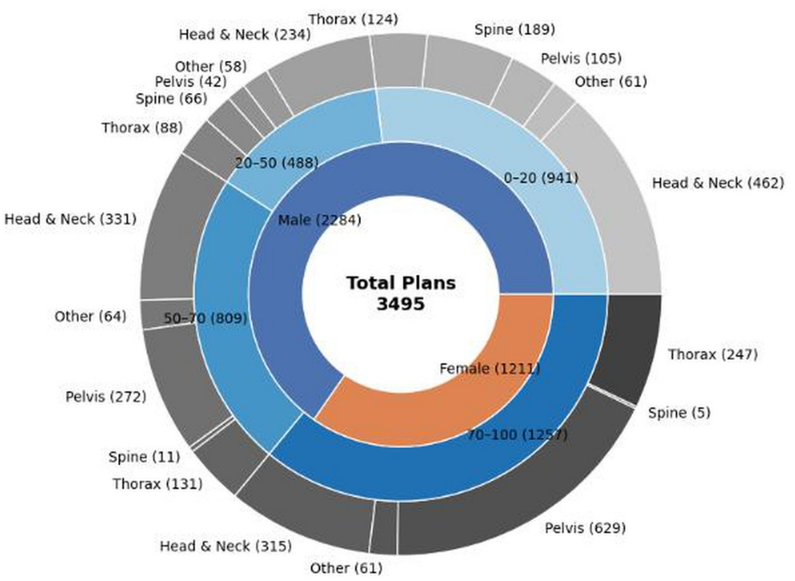

Fig. 3 Demographic & anatomical distribution (3,495 plans).

Quantitative Evaluation

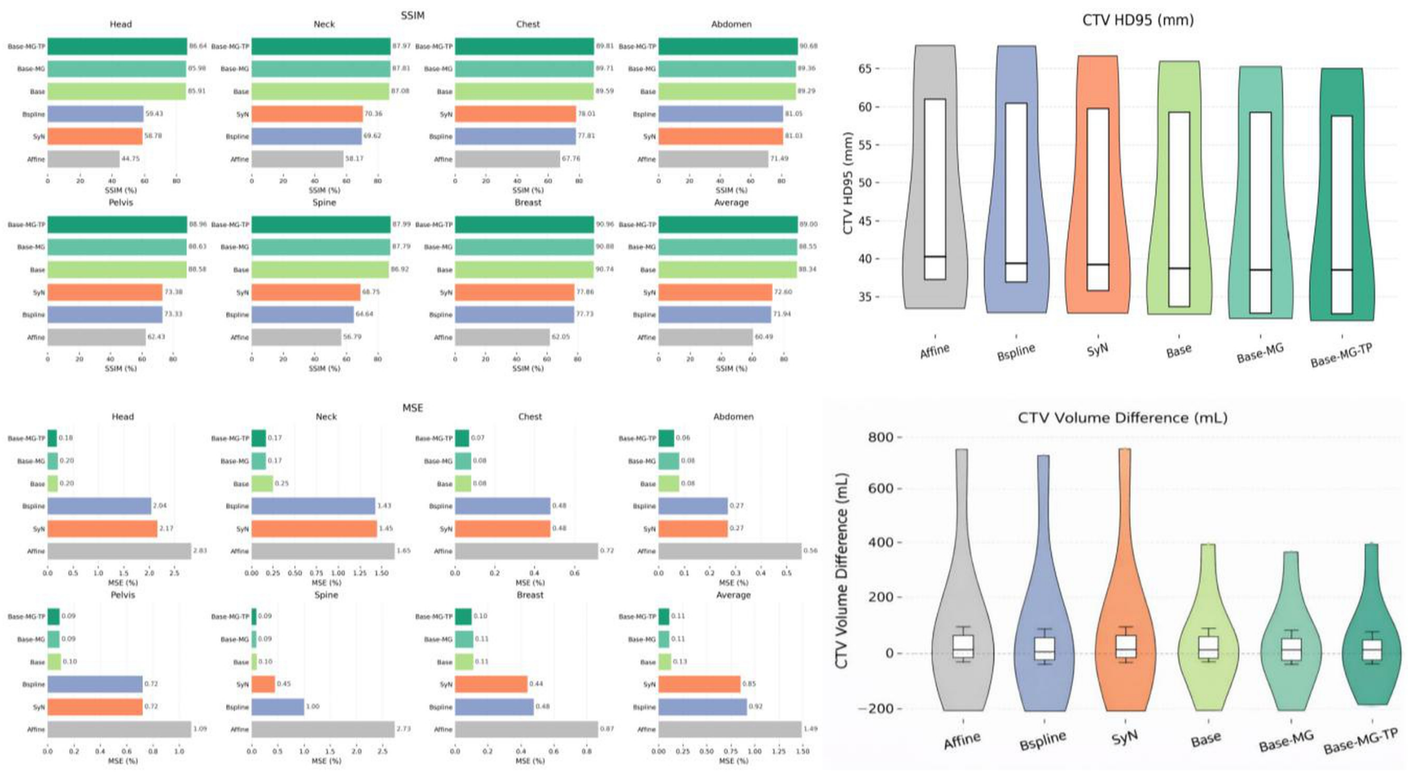

Fig. 4 Quantitative comparison of registration performance across anatomical sites (SSIM, MSE, CTV HD95 & volume difference).

Qualitative Visualization

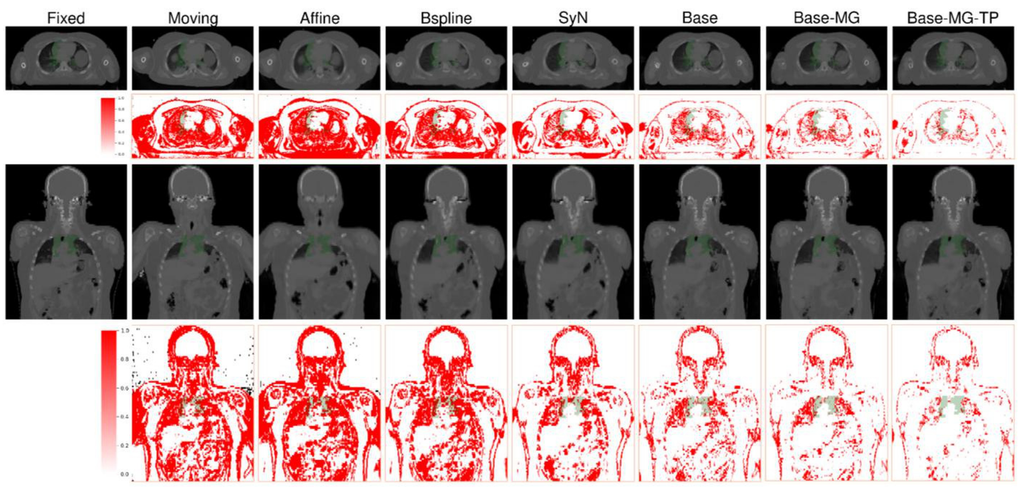

Fig. 5 Qualitative comparison of warped CT and difference maps (CTV in green).

CONCLUSION

The AI-driven DIR framework enables fast, accurate planning-to-repeat CT alignment across diverse proton-therapy scenarios, substantially improving the efficiency and precision of routine clinical adaptive workflows.