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Geometry-Aware Automated Correction of Brachytherapy Needle Trajectories In 3D Transrectal Ultrasound

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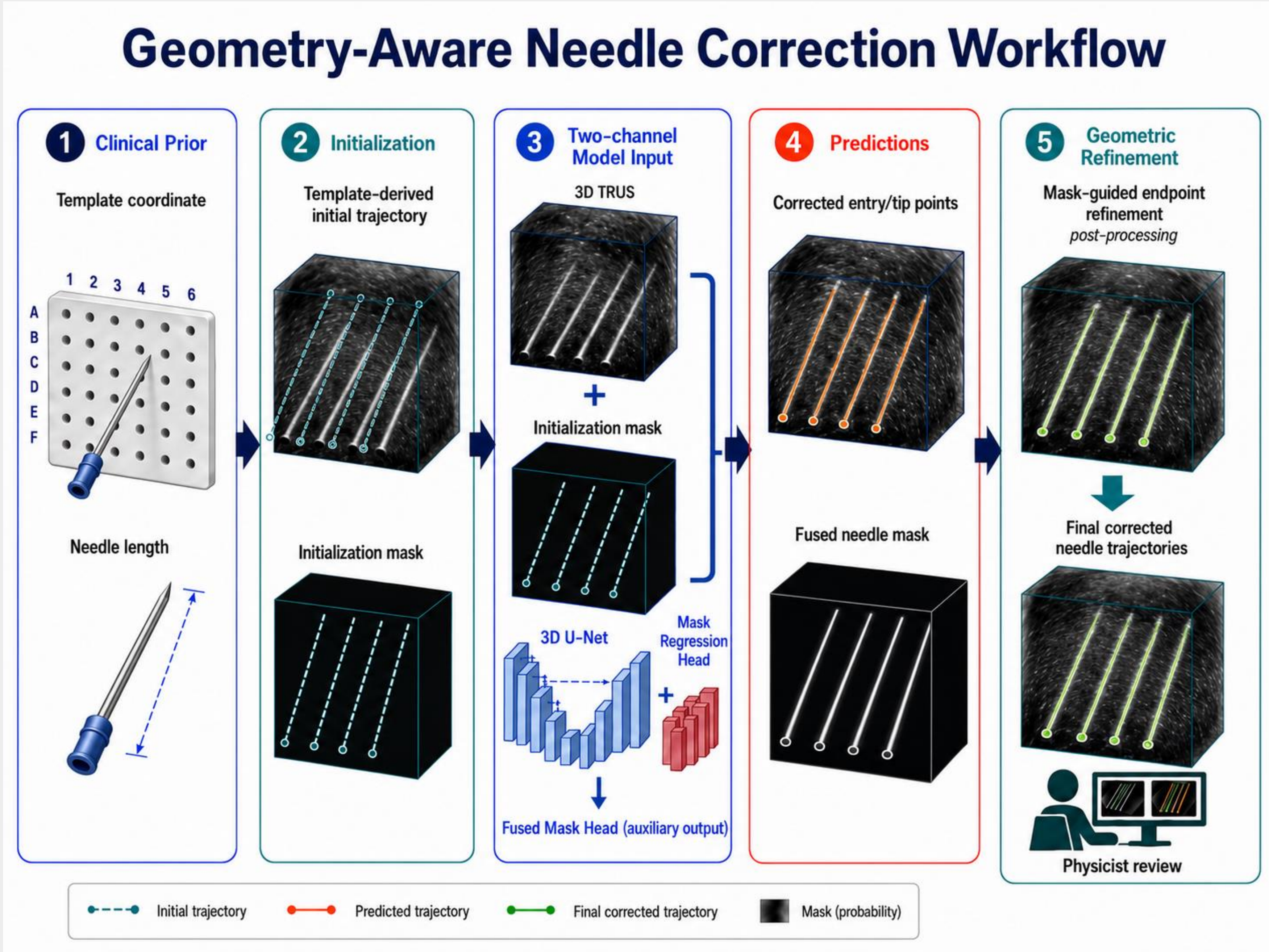
INTRODUCTION

- Accurate needle reconstruction is essential in HDR prostate brachytherapy because reconstructed trajectories determine source dwell positions and the resulting dose distribution [1].
- In 3D transrectal ultrasound, needle deflection, tissue deformation, acoustic shadowing, and ambiguous needle echoes can cause the observed trajectory to differ from the ideal template path [2, 3].
- Automated TRUS needle-reconstruction methods have included classical image-processing and deep-learning approaches [1–3].
- Standard HDR workflows already provide strong geometric information: the planned template coordinate and clinically measured needle length.
- **Purpose:** Develop and evaluate a geometry-aware method that uses these clinical priors to correct template-derived needle trajectories in 3D TRUS, rather than detecting needles de novo.



METHODS AND MATERIALS

- **Dataset:** Retrospective single-institution cohort of 1,460 cropped 3D TRUS volumes from HDR prostate brachytherapy procedures.
- **Data split:** 1,314 volumes were used for model development with 5-fold cross-validation; 146 held-out scans containing 2,128 needles were reserved for final testing.
- **Reference standard:** Needle trajectories were manually reconstructed by one qualified medical physicist and independently reviewed by a second using the clinical Vitesse workflow.
- **Geometry-aware input:** Each case combined the 3D TRUS volume with a fused initialization mask generated from the known template coordinates and needle-length information.
- **Model:** A 3D U-Net-based network predicted corrected needle entry and tip coordinates, with an auxiliary mask-regression head producing a fused needle mask.
- **Inference:** Predictions from the five-fold specific models were ensembled with left-right flip test-time augmentation, followed by mask-guided endpoint refinement.
- **Evaluation:** The primary endpoint was mean slice-wise in-plane needle error. Needle depth was constrained in the primary analysis to emulate the clinically length-informed reconstruction workflow.

RESULTS

- Held-out test cohort: 146 scans containing 2,128 needles.
- Median per-needle mean slice-wise x-y error decreased from 6.692 mm at template initialization to 0.503 mm after correction.
- Median pooled per-slice x-y error decreased from 6.536 mm to 0.491 mm.
- This corresponded to a 92.5% reduction in median shaft error.
- The 95th percentile of per-needle mean xy error decreased from 14.8 mm to 1.3 mm.

Table 1. Needle correction metrics on held-out test set: 146 scans, 2,128 needles.

	Initialization	Corrected
Median Shaft Error	6.69mm	0.50mm
Median Slice-wise Error	6.54mm	0.49mm
Median Tip Error	n/a	0.56mm
Median Tip Error (no depth correction)	n/a	1.41mm
***92.5% median shaft reduction**		

DISCUSSION

- The method reduced template-to-needle discrepancy to **submillimeter median in-plane error**.
- The principal benefit was **lateral shaft correction**, which addresses the residual uncertainty after template position and needle length are known.
- Framing the task as **correction rather than de novo detection** preserves compatibility with the existing HDR prostate workflow.
- The final output remains an interpretable needle geometry for **physicist review and verification**.

CONCLUSIONS

- Geometry-aware correction reduced median in-plane needle trajectory error to approximately 0.5 mm.
- Incorporating template coordinates and needle length as geometric priors supports workflow-compatible, physicist-reviewed needle reconstruction in 3D TRUS.

REFERENCES

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