Uncertainty of Skull Tracking for Cervical Spine Radiosurgery

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INTRODUCTION

- Cervical spine (C2) radiosurgery requires effective tracking across major platforms — ZAP-X, CyberKnife, and Gamma Knife.
- ZAP-X currently relies on skull-based kV tracking only. The ZAP-X table and planning system allow C2-level targets to remain treatable, but the associated tracking uncertainty has not been quantified with clinical patient data.
- This study uses retrospective proton-therapy QA-CT imaging as a surrogate to evaluate intra- and inter-fractional motion at the C2 level under skull-based tracking
- The aim of this study is To quantify the dosimetric and geometric uncertainty of skull-based tracking for C2 cervical spine targets, by comparing skull-based vs. C2-based registration on QA-CT imaging

METHOD

- Designing an effective tracking strategy for cervical spine radiosurgery is challenging across all major treatment modalities, including ZAP-X, CyberKnife, and Gamma Knife.
- Five head-and-neck (HN) patients and three cranial patients treated with the Mevion proton therapy system were selected for this study.
- Patient setup for proton therapy was performed using kV-pair image alignment, which is comparable to the setup workflow used in ZAP-X radiosurgery.
- Head-and-neck (HN) patients represent treatment setups in which chin extension and shoulder positioning are carefully reproduced, whereas cranial patients represent setups in which these factors are not explicitly controlled.
- During the treatment course, three to four quality-assurance CT (QA-CT) images were acquired for each patient. Each QA-CT was obtained with the patient positioned on the treatment table using a mobile CT scanner under treatment-setup conditions. For each setup, alignment was achieved through registration of kV-pair images with digitally reconstructed radiographs (DRRs).
- Decomposition matrices of region-based image registration were analyzed to quantify translational and rotational deviations of C-spine area, assuming patients were set up and tracked using skull tracking during ZAP-X treatment.

RESULTS

The Mevion proton therapy system employs skull-based tracking using kV imaging, with quality-assurance CT (QA-CT) images acquired under identical patient setup conditions following treatment (Figure 1).

Figure 2 shows the corresponding ZAP-X patient setup and kV imaging configuration. In all cases, kV imaging demonstrated accurate skull alignment.

The fusion of the planning CT and QA-CT is shown in Figure 3. The green box highlights residual misalignment of the C2 vertebra despite successful skull alignment. Registration decomposition between skull-based and C2-based registrations quantifies discrepancies in translational components (Tx, Ty, Tz) and rotational components (roll, pitch, yaw) in Figure 4 and Figure 5.

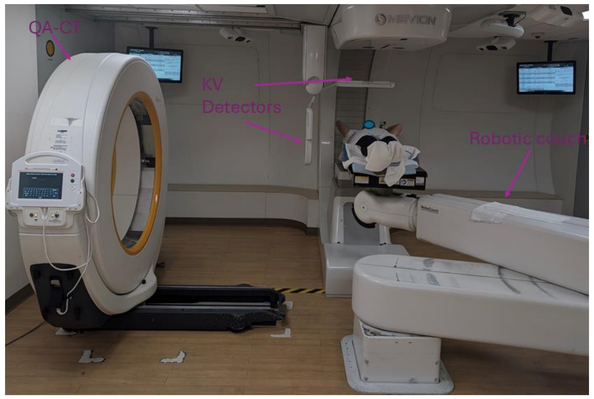

Figure 1. KV-pair patient setup in Mevion proton therapy in GUH.

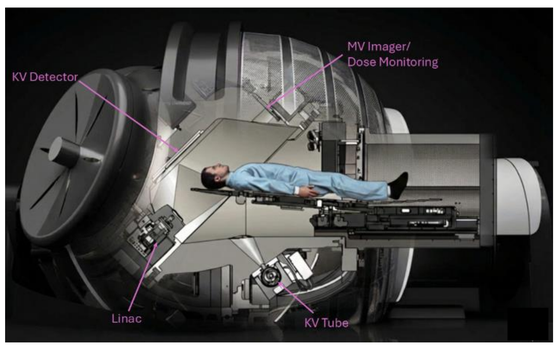

Figure 2. ZAP-X corresponding patient setup and KV- patient setup in GUH.

Figure 3. Skull fusion comparison and C2 vertebra (Green box) between CT and QA-CT

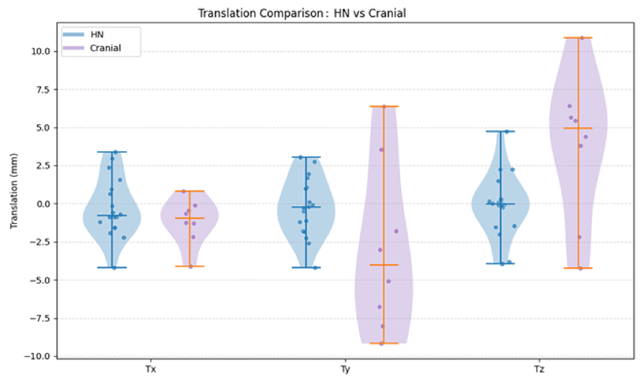

Figure 4. Translational motion comparison between HN and Cranial patients

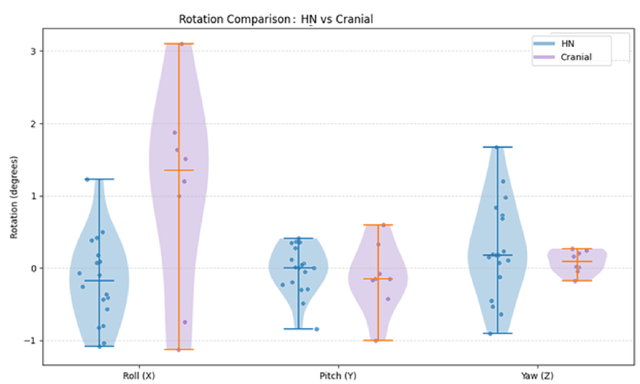

Figure 5. Angular motion comparison between HN and Cranial patients

CONCLUSIONS

- This study demonstrates that using skull tracking for ZAP-X treatments targeting the C2 cervical spine is challenging due to differential motion between the skull and upper cervical vertebrae.
- Differential motion between the skull and upper cervical vertebrae persists even after successful skull-based alignment.
- This uncertainty is clinically significant — up to 11 mm translational and 3° rotational deviation, particularly in cranial (non-HN) setups.
- ZAP-X treatments targeting the C2 region may require an additional treatment margin, an alternative tracking strategy, or HN-style immobilization to safely manage this uncertainty.

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