Safety and Precision in a Same-Day, MRI-Only Simulation with Adaptive VMAT SRS/SRT Workflow: Integrating Synthetic CT and AI-Driven Quality Assurance

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ABSTRACT

Purpose: The efficacy of stereotactic radiosurgery (SRS) and radiotherapy (SRT) for brain metastases is often compromised by tumor growth and soft tissue changes between simulation and treatment. To eliminate these latencies, we clinically implemented a novel same-day workflow combining MRI-only simulation with non-coplanar volumetric modulated arc therapy (VMAT) for intracranial SRS/SRT. Here we report on the workflow design, commissioning, and the integration of a deep learning-based auto-segmentation tool as a Quality Assurance (QA) safety net.
Methods: On the day of treatment, patients undergo MRI simulation in the treatment position. Target definition is completed on a T1-weighted MPRAGE MRI. To mitigate the risk of missed lesions during the accelerated planning timeline, an AI auto-contouring prototype by Siemens was integrated to provide a "second check" for GTV detection and OAR delineation. Treatment planning is completed using MRI-defined targets with dose calculation and reference image generation based on a deep-learning-based FDA-approved synthetic CT (sCT) solution. A preliminary plan based on diagnostic imaging is adapted to the treatment-day anatomy and re-optimized (HyperArc/VMAT). Commissioning included: 1) dosimetric comparison of sCT vs. CT plans, 2) verification of CBCT-to-sCT positioning accuracy, and 3) validation of the AI-QA tool's sensitivity on a retrospective cohort of 436 patients.
Results: Dosimetric analysis demonstrated a D95% dose difference of -0.04 ± 0.72% between sCT and CT plans, with Gamma indices exceeding 99% (1%/1mm). CBCT-to-sCT alignment achieved sub-millimeter accuracy. The AI-QA demonstrated a sensitivity of 93.3% for detecting metastases >0.1 cc with robust segmentation (median Dice >0.79).
Conclusion: The same-day MRI-only workflow is clinically feasible and robust. The integration of AI-driven contouring QA provides a safety layer, addressing the challenges of accelerated timelines by ensuring comprehensive target delineation. A trial to assess whether this workflow may allow for the safe omission of PTV margins through adaptation to anatomical changes is currently underway.

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INTRODUCTION

Context: Brain metastasis growth and soft tissue displacement between simulation and treatment limit stereotactic radiosurgery (SRS) efficacy.
Problem: Standard workflows require dedicated CT simulations and multimodality MRI-CT registrations, introducing errors and delaying treatment. Larger PTV margins are necessary but increase neurotoxicity risk. Missed lesions require salvage treatments.
Solution: Develop a same-day, MRI-only SRS workflow combined with a deep learning-based target auto-segmentation tool as a Quality Assurance (QA) safety net to eliminate latencies, accelerate care, and ensure comprehensive targeting.

METHODS AND MATERIALS

Simulation (Morning): Single, high-resolution MRI simulation in treatment position on the day of treatment.
AI QA: A Siemens AI auto-contouring prototype is integrated to provide a rapid "second check" for GTV detection and OAR delineation.
Synthetic CT (sCT): FDA-approved deep-learning sCT combined with an in-house digital model of the MRI-invisible fixation device.
Plan Adaptation (Mid-day): Preliminary HyperArc VMAT plan (from prior diagnostic MRI) is re-segmented and re-optimized in Eclipse to match anatomy of the day using sCT.
Delivery (Afternoon): Delivered on a Varian TrueBeam.
Validation: 1) Retrospective dosimetric comparisons (sCT vs. CT), 2) patient setup accuracy testing (CBCT-to-sCT), and 3) validation of the AI-QA tool's sensitivity on a retrospective cohort of 436 patients.

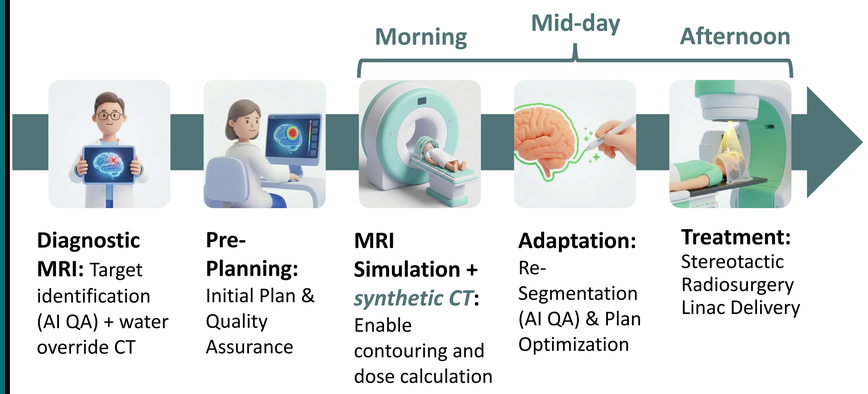

Figure 1. Schematic of the proposed same-day, MRI-only simulation SRS/SRT workflow. The process leverages a prior diagnostic MRI for preliminary treatment planning and quality assurance. On the treatment day, an MRI simulation is acquired in the morning and utilized to generate a synthetic CT. This enables the rapid creation of an adapted plan-of-the-day based on up-to-date patient anatomy, followed by treatment delivery on a C-arm Linac in the afternoon.

RESULTS

Dosimetry: High agreement between sCT and CT plans. Mean PTV D95% dose difference was minimal: -0.041 ± 0.718%.
3D Gamma Pass Rates: 99.6 ± 0.4% (1% DD / 1mm DTA, 10% threshold, local); 100.0% (3% DD / 2mm DTA, 10% threshold, global)
Setup Accuracy: CBCT-to-sCT alignment achieved sub-millimeter precision, fully comparable to standard CT-based workflows.
AI-QA Validation: The AI-QA demonstrated a 93.3% sensitivity for detecting metastases >0.1 cc, with robust segmentation (median Dice >0.79).

Figure 2. Dosimetric validation of the sCT workflow. A side-by-side evaluation of a representative clinical treatment plan illustrates dose calculations performed on the standard planning CT (left) versus the corresponding deep-learning-generated sCT, which incorporates the digital fixation model structures (right).

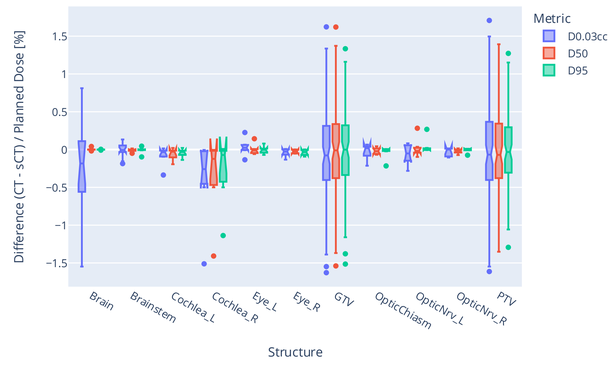

Figure 3. DVH dose statistics differences (sCT - CT) normalized by the planned dose across various target and organ-at-risk (OAR) structures. Data demonstrate minimal differences in absolute target coverage and OAR sparing.

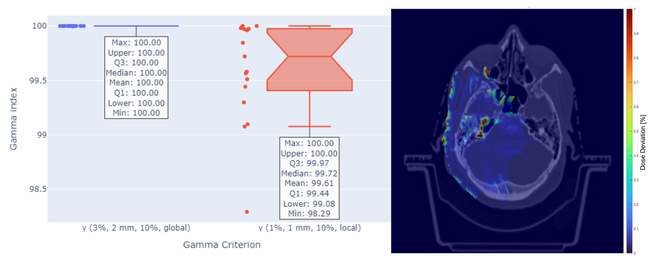

Figure 4. (left) Gamma Index distribution comparing sCT to pCT plans. The box plots illustrate the pass rates for both the standard clinical 3% / 2 mm (global normalization) criteria and the 1% / 1 mm (local normalization) criteria, demonstrating dosimetric agreement. (right) Gamma evaluation map illustrating the dose distribution for the worst-case point, which also corresponds to the case exhibiting the minor cochlea dose deviation in Fig. 3.

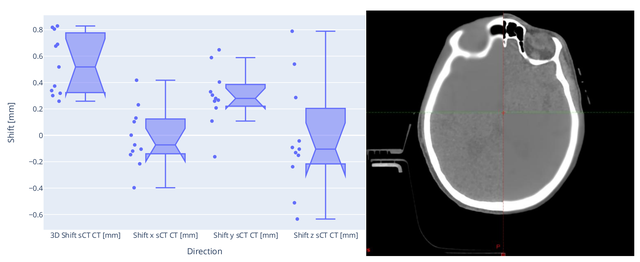

Figure 5. (left) Retrospective setup verification box plots showing the translational shift discrepancies (Δx, Δy, and Δz) and resulting 3D vector differences when comparing CBCT registrations matched to the sCT versus the standard pCT in offline review. The sub-millimeter variance supports the suitability of the sCT as a reference image for volumetric setup. (right) Representative orthogonal view of a 3D volumetric image registration, illustrating alignment between the pre-treatment CBCT and the reference sCT.

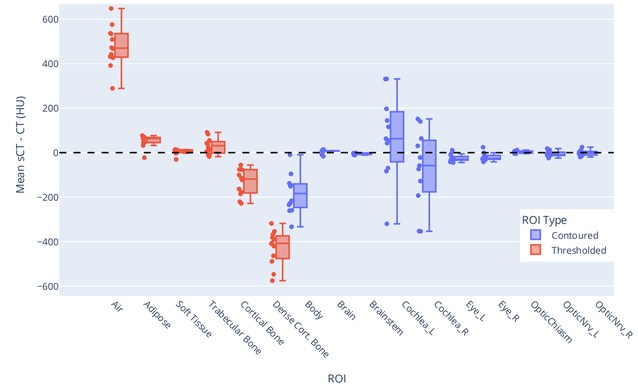

Figure 6. Quantitative mean HU differences evaluated within specific contoured regions of interest (ROI) and threshold-derived density masks, showing consistent tissue classification regions accuracy outside of air and dense bone.

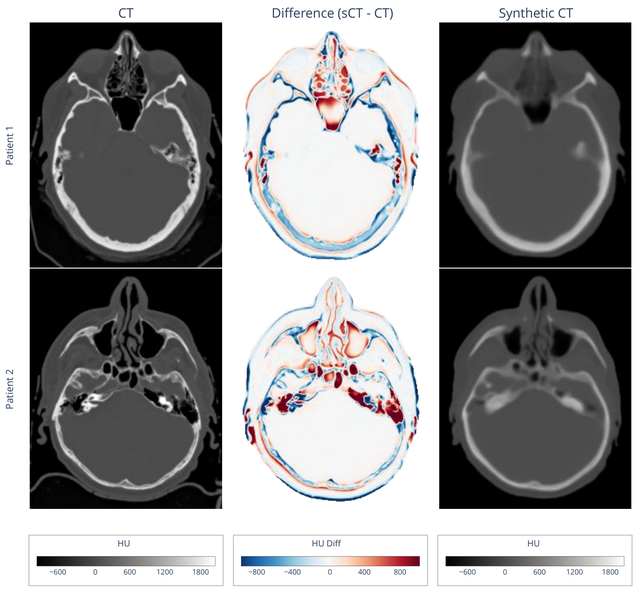

Figure 7. Qualitative comparison showing the reference CT, difference map, and deep-learning synthetic CT for representative patients.

CONCLUSIONS

- A same-day MRI-only simulation workflow for SRS is clinically feasible and dosimetrically robust.
- The integration of AI-driven contouring QA provides a critical safety layer, addressing the challenges of accelerated timelines by ensuring comprehensive target delineation (see poster SU-315-GPD-T-541 for more details).
- Utilizing up-to-date anatomy enhances targeting precision, potentially enabling 0 mm PTV margins. Margin reduction to 0 mm yields a 38 ± 8% treatment volume reduction (compared to 1 mm), heavily sparing healthy brain tissue.

Next Steps: A clinical trial assessing whether this adaptively delivered workflow allows for the safe omission of PTV margins (0 mm) is currently underway.