3D Modeling–Based Collision Analysis for Verification of Non-Coplanar Stereotactic Radiosurgery Treatments

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ABSTRACT

Non-coplanar stereotactic radiosurgery improves dose conformity but increases the risk of mechanical collisions during treatment delivery. This work presents a patient-specific 3D modeling workflow for pretreatment collision assessment in non-coplanar SRS. Clinical DICOM data were used to extract the external body contour and treatment isocenter using 3D Slicer; these structures were then integrated into a virtual TrueBeam STx treatment environment in Blender. Collision analysis was performed using bounding volume hierarchy detection during systematic gantry–couch angle sweeps. The resulting collision maps allowed identification of safe angular combinations, potential collision regions, and planned arc trajectories. This approach provides a practical tool to support patient-specific collision screening and treatment deliverability evaluation before SRS delivery.

INTRODUCTION

Non-coplanar stereotactic radiosurgery enables highly conformal dose delivery but increases the risk of collisions between the gantry, couch, patient, immobilization devices, and collimation accessories[1].

Conventional collision checks are commonly performed manually in the treatment room and may not fully account for patient-specific anatomy, isocenter location, and setup geometry[2].

This work investigates a patient-specific 3D modeling approach to support pretreatment collision verification for non-coplanar SRS treatments.

METHODS AND MATERIALS

A patient-specific collision analysis workflow was implemented using a Python-based graphical user interface developed in Python v3.13 (Figure 1). Clinical DICOM data, including CT images, RT Structure Set, and RT Plan files, were imported to generate a patient-specific model. The external contour and clinical isocenter were automatically extracted using 3D Slicer v5.8.1 and exported for 3D scene construction. All collision simulations were performed on a Windows 11 Home 64-bit computer with an Intel Core i7-9750H CPU, 16 GB RAM, and an NVIDIA GeForce GTX 1660 Ti GPU.

A virtual treatment environment based on the framework developed by Guyer et al.[3] was employed, using a model of a Varian TrueBeam STx linear accelerator. The model was extended in Blender v4.2.3 by incorporating the Brainlab Cranial 4Pi immobilization system, cone holder, and conical collimator. The patient model was aligned to the machine isocenter to reproduce the planned SRS treatment geometry, as shown in Figure 2.

Collision analysis was performed by systematically sweeping the gantry and couch angles using bounding volume hierarchy (BVH) collision detection. The resulting data were used to generate two-dimensional gantry–couch collision maps. Planned non-coplanar arc trajectories were overlaid on the maps to assess treatment deliverability and identify angular regions associated with potential collision or reduced clearance. Figure 3 illustrates the complete computational workflow used for collision map generation and trajectory evaluation.

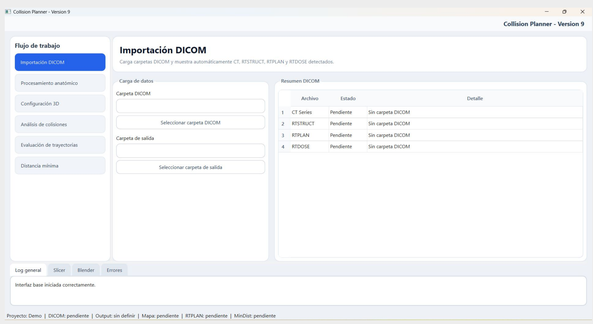

Figure 1. Python-based GUI for patient-specific collision analysis.

Collision-zone verification was performed using a confusion matrix analysis at seven clinically selected couch angles: 70°, 46°, 20°, 0°, 340°, 314°, and 290°. For each couch angle, a full 360° gantry sweep was evaluated at 2° resolution, resulting in 1260 gantry–couch combinations. Conservative safety margins were applied to the tabletop and couch base to reduce false-negative collision predictions. In addition, 3D animations of the treatment arcs were generated to visualize gantry and couch motion during field delivery.

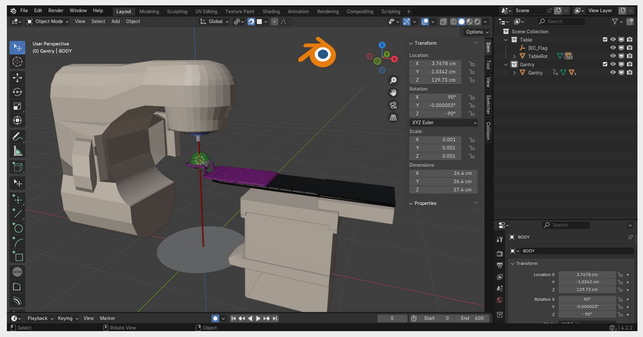

Figure 2. Blender-based 3D treatment scene including the TrueBeam STx geometry, 4Pi couch, collimator cone, and patient head.

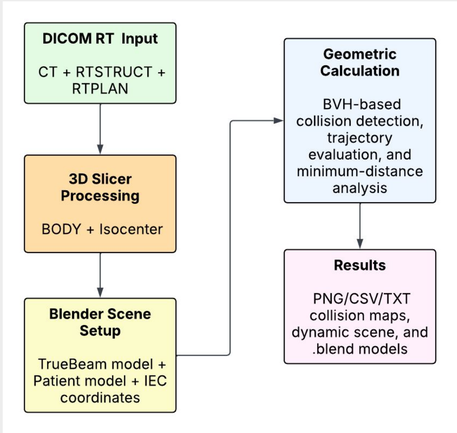

Figure 3. Computational workflow for patient-specific collision analysis.

RESULTS

Patient-specific gantry–couch collision maps were generated from clinical SRS plans. Figure 4 shows a representative right-sided trigeminal neuralgia case with the 12 planned non-coplanar arc trajectories overlaid on the collision map. Dark regions indicate collision, whereas light regions indicate collision-free configurations. The map allowed identification of safe angular combinations and configurations close to a potential collision. The average computation time for collision-map generation was approximately 5 min 50 s.

After applying conservative safety margins of 3.5 cm to the tabletop and 6.5 cm to the couch base, false-negative collision predictions were eliminated. The confusion matrix analysis yielded a true-positive rate (TPR) of 100.0% and a true-negative rate (TNR) of 98.9% (Figure 5).

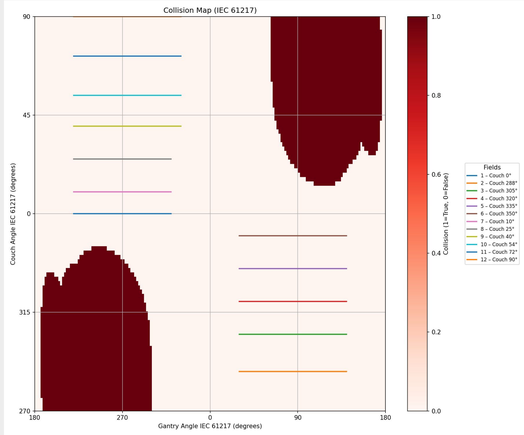

Figure 4. Collision map for a right-sided trigeminal neuralgia SRS case with 12 planned non-coplanar arcs overlaid.

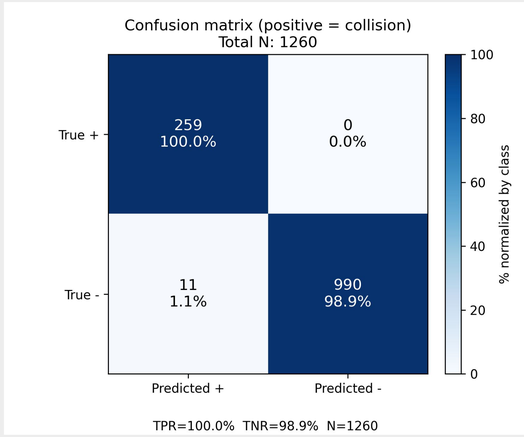

Figure 5. Confusion matrix for right-sided collision-zone verification after applying the conservative safety margin.

DISCUSSION

This method supports patient-specific pretreatment collision screening using gantry–couch collision maps generated from clinical DICOM data. Although demonstrated in trigeminal neuralgia SRS cases, it may be extended to other non-coplanar treatment sites and immobilization setups. Further clinical validation is required.

CONCLUSIONS

A patient-specific 3D modeling workflow was developed to generate gantry–couch collision maps from clinical DICOM data. The system integrates patient geometry, isocenter location, immobilization devices, and machine geometry to support pretreatment collision verification in non-coplanar SRS treatments. The overlay of planned arc trajectories and the confusion matrix analysis suggest that this approach may assist in identifying safe angular combinations before treatment delivery.

REFERENCES

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