An Automated Patient-Specific Collimator Positioning Tool for Minibeam Radiotherapy

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PURPOSE

BACKGROUND

X-ray Minibeam Radiotherapy (MBRT) is an emerging technology that has recently been translated to first-in-human treatments.[1,2] MBRT uses narrow beamlets generated by specialized collimators to produce spatially fractionated dose distributions with high peak-to-valley dose ratios.[3] These ratios improve as the treatment collimator is positioned closer to the patient; however, placement must also maintain target coverage and avoid collisions with the patient surface. This creates a challenging six-degree-of-freedom positioning problem, particularly for patients with irregular surface anatomy or nearby obstructions such as ears or shoulders.

OBJECTIVE

This work presents an interactive, automated optimization application for patient-specific collimator placement in MBRT.

METHODS

A graphical user interface (GUI) was developed to support patient-specific minibeam collimator placement using simulation CT images and radiotherapy structure sets. The application extracts the external patient surface and GTV, initializes the collimator pose based on the spatial relationship between the target and patient surface, and models the collimator as a rigid three-dimensional object with a circular treatment aperture. Candidate collimator placements are parameterized by six degrees of freedom, including three translational and three rotational offsets from the initial pose.

OBJECTIVE FUNCTION

Collimator placement was optimized using an objective function that balances target coverage, collimator-to-target proximity, and collision avoidance:

$$J(\mathbf{p}) = w_{\text{cov}} L_{\text{cov}}(\mathbf{p}) + w_{\text{dist}} L_{\text{dist}}(\mathbf{p}) + w_{\text{coll}} L_{\text{coll}}(\mathbf{p})$$

where $\mathbf{p} = [t_x, t_y, t_z, \alpha, \beta, \gamma]$ defines the six-degree-of-freedom collimator pose. The coverage loss, $w_{\text{cov}} L_{\text{cov}}(\mathbf{p})$, penalized incomplete GTV coverage within the beam's-eye-view aperture projection.

DEVELOPED APPLICATION

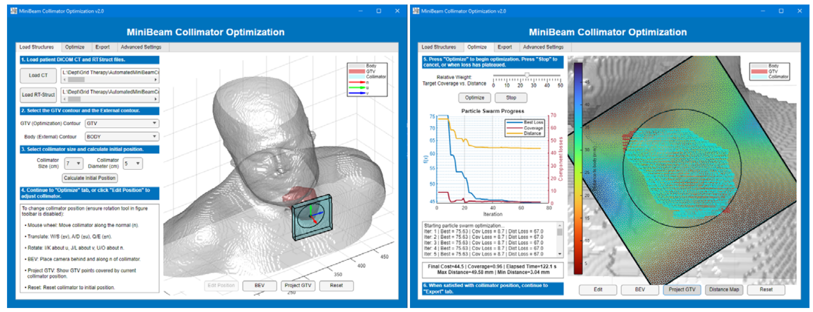


FIGURE 1 - Overview of the interactive collimator optimization workflow. Patient surface geometry and the gross tumor volume (GTV) are derived from simulation CT and used to initialize the collimator pose. User-defined distance and target coverage constraints guide a six-degree-of-freedom optimization process. Real-time visualization enables user interaction and verification. The finalized collimator geometry is exported as an RT-STRUCT for direct use in treatment planning.

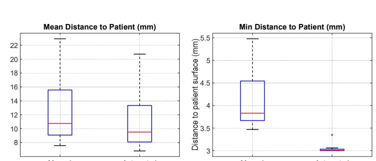
METHODS CONT.

The distance loss, $w_{\text{dist}} L_{\text{dist}}(\mathbf{p})$, penalized greater separation between the collimator aperture and the target using bidirectional nearest-neighbor distances. The collision loss, $w_{\text{coll}} L_{\text{coll}}(\mathbf{p})$, applied a large penalty when the sampled three-dimensional collimator body violated the minimum allowable separation from the patient surface.

The application provides real-time visual feedback, including three-dimensional renderings, surface distance heatmaps, and beam's-eye-view target coverage. Upon user acceptance, the optimized collimator geometry is exported as an RT-STRUCT to enable fabrication of a patient-specific 3D-printed collimator holder.

RESULTS

The application rapidly produced clinically acceptable collimator positions while maintaining target coverage. Compared to manual placement, optimized solutions achieved closer collimator proximity, with a mean reduction in collimator-to-surface distance of 1.35 ± 0.83 mm (n = 12), improved consistency, and substantially reduced planning time (~5 minutes versus ~65 minutes per case).



CONCLUSIONS

- An interactive, automated collimator optimization tool was developed to streamline patient-specific MBRT planning.
- Patient surface geometry derived from simulation CT enables individualized placement while accounting for irregular anatomy and nearby obstructions.
- Real-time visualization, including three-dimensional rendering, surface distance heatmaps, and beam's-eye-view target coverage, allows users to evaluate clinically relevant tradeoffs during optimization.
- By reducing reliance on manual or heuristic placement, this approach has the potential to improve positioning accuracy, planning efficiency, and reproducibility for MBRT treatment workflows.

REFERENCES

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