Analytical model for planar proton minibeam radiotherapy (pMBRT)

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Résumé

Analytical model for planar proton minibeam radiotherapy (pMBRT)
Modèle analytique pour la protonthérapie par minifaisceaux (pMBRT)

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Introduction: Proton minibeam radiotherapy (pMBRT) is an innovative therapeutic approach using a strong spatial dose modulation to create alternating high and low dose regions, combined with conformal proton therapy. Preclinical studies demonstrate that pMBRT increases normal tissue tolerance while providing equivalent or superior tumor control compared to conventional radiotherapy, significantly enhancing the therapeutic index1. Thus, pMBRT may benefit treatment of large or resistant tumors where toxicity limits dose escalation. In this work, we describe a fast analytical model for pMBRT dose computations, which we implement in the open-source TPS pyRadPlan.

Material and methods: The dose calculation is performed in Matlab, using an adapted version of an analytical model developed previously2. It incorporates dual-Gaussian directional anisotropy and error functions to account for specific minibeam collimators. The lateral beam width is split into initial divergence in air and multiple scattering in water. Model parameters were obtained using Monte Carlo reference data (OpenTOPAS/Geant4) of a custom-designed multislit brass collimator (five 400 μm slits, 4.12 mm spacing) used for pMBRT applications. Polynomial fitting to ensure continuous dose reconstruction was used to interpolate between 100 and 150 MeV proton beams. Validation compared the analytical model against MC dose distributions using voxel-wise dose differences, planar dose maps, central-axis PDD, and a 3D gamma index analysis using strict criteria (3%/1mm).

Results: The analytical model accurately reproduced MC reference data, with relative differences below ±3% in both air and water phantoms. Gamma index analysis (3%/1mm) showed over 99% pass rates, confirming high spatial accuracy despite minor distal uncertainties at the Bragg Peak (Figure 1). Furthermore, the implementation successfully generated

*Intervenant

Spread-Out Bragg Peaks (SOBP) for two configurations, demonstrating its ability to provide clinical dose homogeneity within the target volume. Computation time is reduced from hours with MC (_˜1 hour/core per million particles) to seconds with MATLAB, providing a foundation for real-time inverse optimization and complex preclinical beam planning.

Conclusion: This work describes a new analytical model accurately reproducing submillimetric pMBRT dose distributions with significantly reduced computation time compared to MC simulations. Despite limitations in heterogeneous media, this model represents a promising foundation for inverse optimization applications, with an implementation for dose calculation currently underway in the open-source TPS pyRadPlan.

References

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Mots-Clés: pMBRT, TPS, modèle analytique, calcul de dose