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Carbon-ion radiotherapy monitoring with secondary ions: exploiting multi-angle projections for 3D reconstruction of inter-fractional changes

Introduction

Carbon-ion radiotherapy (CIRT) enables highly precise dose delivery through its highly localized dose deposition and enhanced biological effectiveness. However, current treatment guidelines generally do not include daily control imaging throughout the course of a multi-day therapy. As a result, anatomical changes that may occur between fractions cannot be considered due to the lack of reliable evidence for their presence. This introduces uncertainty regarding the anatomical state at the time of treatment and, consequently, reduces confidence in the accuracy of dose delivery. Our research focuses on in vivo monitoring during treatment by detecting secondary charged particles emitted during irradiation using our group's custom detection system based on TimePix3 detectors. The goal is to reliably detect, localize, and 3D reconstruct inter-fractional anatomical changes, thereby reducing reliance on conventional imaging modalities such as computed tomography (CT), which involves additional radiation exposure for the patient.

Materials and Methods

To extract 3D localization information of potential anatomical changes, the presented method combines data from multiple projection angles into a unified 3D reconstruction. The low signal-to-noise ratio when comparing measurements from different treatment fractions presents a significant challenge to achieving the robustness required for clinical applicability. To address these challenges and ensure robustness in the presence of natural variations, our method combines information from projections in the spatial domain with insights gained through frequency domain analysis, specifically localized joint frequency band variations. In doing so, the method builds on our own detection and localization techniques while incorporating established principles of multi-perspective analysis in medical imaging, adapted to the characteristics of secondary particle data to enable robust and clinically meaningful detection of anatomical variations. These frequency-based features reflect local particle density changes between measurements, which serve as indicators of inter-fractional anatomical variation. Validation of the reconstruction approach was conducted through irradiation experiments at the Heidelberg Ion Beam Therapy Center (HIT). The experiments utilized homogeneous Polymethyl Methacrylate (PMMA) head phantoms containing coin-sized air cavities at varying depths, providing a controlled environment for detailed qualitative and quantitative assessment of the method.

Results

The modularity and flexibility of the proposed framework for localization and detection of changes within the patient were demonstrated by extending it with a multi-perspective analysis step. This extension aggregates multiple point cloud projections to enhance the detection and localization of inter-fractional anatomical changes in three dimensions. The 3D spatial change information obtained through this approach enables more accurate assessment of both the location and extent of anatomical variations. The accuracy of the 3D reconstruction was validated by comparing the estimated change locations with ground truth renderings of the experimental setups, demonstrating a high degree of spatial congruence and a mean centroid loss of <5mm over the test sets.

Conclusion

The results demonstrate that the information carried by secondary ions can be effectively harnessed for in vivo monitoring and has not yet been fully utilized in current clinical practice. When mapped to planning CT images, the resulting 3D reconstructions provide valuable spatial cues. These can support clinical decision-making by offering insights into anatomical changes occurring over the course of a treatment delivered in fractions across multiple consecutive days.

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Workshop topics

Applications

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