Sub-Millimeter Range Monitoring in Heavy-Ion Therapy with Filtered Interaction Vertex Imaging (IVI)

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Interaction Vertex Imaging

Interaction Vertex Imaging (IVI) is a proposed technique for range verification in heavy-ion therapy, believed to be capable of sub-millimeter accuracy and precision[1, 2]. Secondary particles produced by nuclear reactions between the beam and patient are detected during treatment by thin silicon detectors. Trajectories of these particles (tracks) are used to reconstruct sites of reaction (interaction vertices) along the beam path.

Filtered IVI

Our filtered IVI method refines reconstruction using the treatment beam axis and properties of detected particles. Tracks which do not pass sufficiently close to the beam axis are rejected. Additional filters, on particle energy deposit and coincidence window, preferentially select tracks which have not experienced significant change in scattering angle while exiting the patient. Prior simulations suggest that filtered IVI could achieve sub-millimeter precision clinically[3].

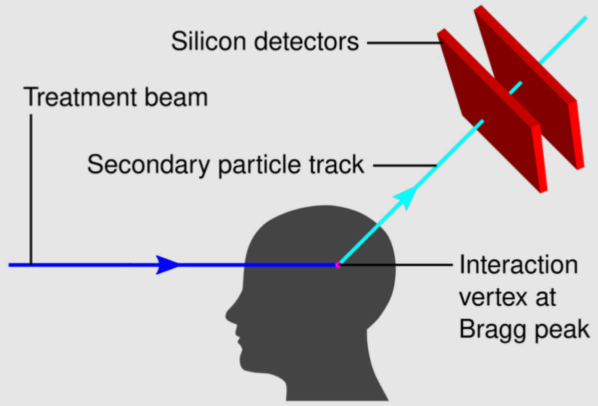

Figure 1: Schematic diagram of filtered IVI reconstruction using a single track. The track is extrapolated into the target (grey), to its closest approach with the treatment beam. The interaction vertex is the mean of the points of closest approach between the beam and the track.

Data Collection

A 150 MeV u^{-1} ^{16}O beam with intensity 20-50 pA was generated at the National Superconducting Cyclotron Laboratory, incident on a 51 mm × 51 mm PMMA target of 40 mm thickness. Although ^{16}O is not currently used in treatments, recent studies indicate potential clinical applications for similar setups[4]. Beam energy was adjusted using Al degraders in the beamline, and corresponding Bragg peak depth calculated with the LISE++ physical calculator[5]. Secondary particle data was collected at each depth on both trackers at 45 degrees off-axis for 300-600 seconds. The beam axis was then measured directly at lower intensity using a single tracker at zero degrees.

Figure 2: Light-tight tracker boxes in experimental setup. Trackers are aimed at a 30 mm Bragg peak depth. Inset: Detail view of tracker, two 20 mm × 20 mm × 300 μm position sensitive silicon detectors at 140 mm separation.

Results

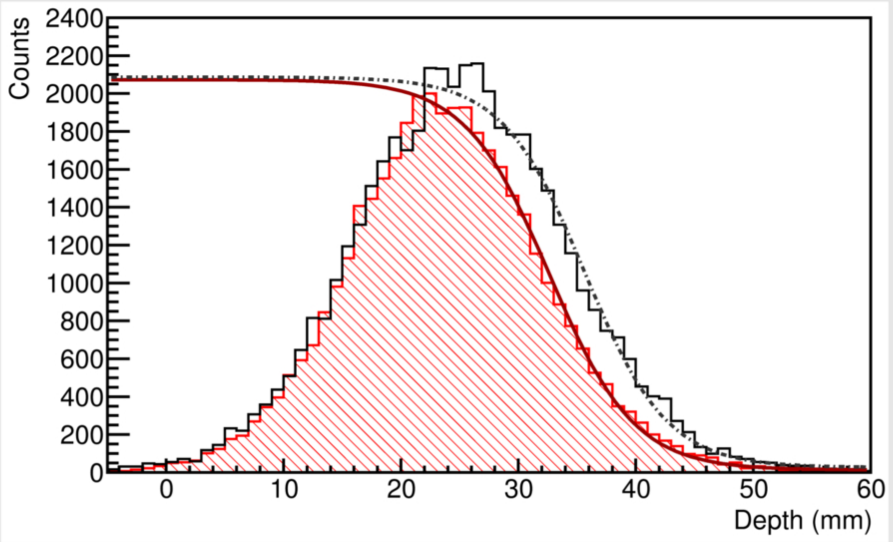

Figure 3: Two interaction vertex distributions reconstructed from a single tracker. Distal edges are fit using a four-parameter logistic function. The black distribution with 29.93(25) mm Bragg peak depth is scaled so fit asymptotes match the red distribution with 27.02(26) mm depth. Depth difference is measured by shifting the black fit in 100 μm steps, and performing a chi-square minimization relative to the red fit. A 2.9 mm depth difference is observed, with no significant difference from the true value of 2.90(36) mm.

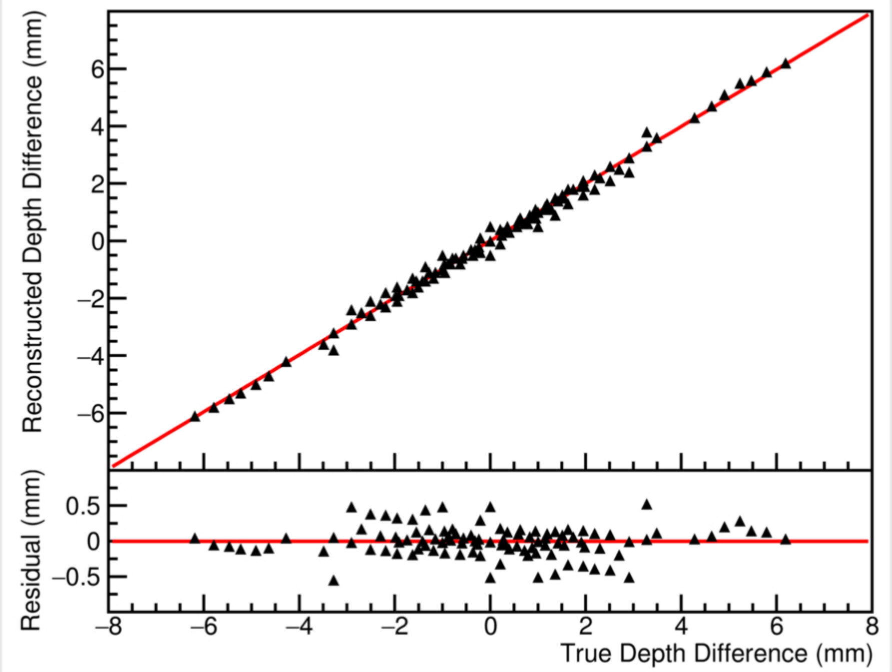

Figure 4: The process from Figure 3, applied to 121 permutations of 11 experimental distributions, each of at least 10^4 interaction vertices, at 10 different Bragg peak depths from 33.21(24) mm to 27.02(26) mm. The linear fit (red) has slope 0.9947(79), and intercept 0.012(18) mm. A consistent direct correspondence exists between the true and reconstructed depth differences.

Discussion

All cases in Figure 4 reproduce true depth differences with sub-millimeter accuracy, verifying simulation results[3]. Unlike other heavy-ion therapy range verification methods, filtered IVI does not require use of implanted markers, and can be performed entirely online. The setup is simple to align and use, facilitating comparison of Bragg peak position between all fractions in a treatment plan. Future studies, using arrays of larger strip-segmented detectors, will characterize filtered IVI for higher beam intensities and shorter irradiations.

Conclusion

Filtered IVI has been successfully validated as a method for verifying consistent Bragg peak position between treatment fractions with sub-millimeter accuracy. This result represents a significant improvement over current range monitoring practices in heavy-ion therapy, allowing high-accuracy range monitoring for all fractions.

Acknowledgements

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