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Fast low-dose pencil beam proton and helium radiographs for motion management

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The HELium Imaging Oncology Scanner (HELIOS) is a novel project to develop helium radiography based on existing proton imaging technologies for mixed carbon and helium beams. Its primary purpose is to enable range-guided particle therapy (RGPT) for non-small-cell lung cancer (NSCLC). One of the challenges in treating NSCLC is dealing with motion-induced changes in patient anatomy that occur on time scales ranging from seconds (intrafractional) to days or weeks (interfractional). Motion management in ion therapy is critical due to the finite range of charged particle beams and their sensitivity to density variations caused by these anatomical changes. The potential of the RGPT system lies in its ability to mitigate toxicity by providing real-time monitoring of the dose delivered to a moving tumor.
The current study aimed to assess the viability of using fast low-dose proton (pRad) and helium (HeRad) radiography to detect anatomical displacements during treatment delivery. The evaluation included proton, helium, or mixed carbon-helium beams using state-of-the-art imaging detectors, reconstruction techniques, and particle beam delivery systems.
Materials and methods involved obtaining 4D computed tomography (4DCT), 4D cone-beam CT as well as experimental pRad scans of a moving phantom. Monte Carlo simulations were performed using open and anonymized patient 4DCT data, modeling pRad and HeRad for helium and mixed beams. Treatment plans for mixed carbon-helium beams were calculated using matRad.
The results showed that experimental pRad achieved a high spatial resolution of 1 mm and a frame rate of 8 fps, while simulated pRad and HeRad showed the same resolution and the ability to detect patient displacements up to 1 mm using 2000 particles per spot for 20 cm × 20 cm full scans. In the case of mixed carbon-helium beams, both integral and single iso-energy, HeRad successfully detected water-equivalent path length differences with sub-millimeter accuracy for different phases of 4DCT data and manual shifts for the same data sets. In addition, HeRad offered potential for respiratory phase determination and beam extraction control in mixed particle therapy.
In conclusion, low-dose proton and helium radiography using pencil beam scanning provides accurate millimeter-level information on inter- and intrafractional (in the case of mixed carbon-helium beams) anatomical displacements in patients. The technique demonstrated sub-second temporal resolution, making it a promising approach for motion management during radiation treatment.

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