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2.5D Imaging: obtaining additional depth information from helium-beam radiographs for applications in ion beam radiotherapy using silicon pixel detectors

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Introduction: Ion beam radiotherapy (IBR) can provide a depth dose distribution with a low dose in the entrance channel and a high dose in the tumor region due to the characteristic peak in the depth-dose curve of ions, called Bragg Peak. This results in a high dose concentration in the tumor and sparing of surrounding organs allowing a more accurate treatment compared to conventional X-ray therapy. IBR is often used for tumors surrounded by critical healthy structures or deeply seated tumor regions. Due to the steep gradients of the dose distribution in the patient, IBR is sensitive to potential uncertainties like anatomical changes of the patient geometry or conversion errors of the CT dataset into stopping power, which is the relevant quantity for IBR treatment planning.
Using the same kind of radiation for imaging and treatment, ion-beam radiography (iRad) provides the potential of frequent treatment-plan verifications by direct and accurate measurements of the integrated stopping power (called water-equivalent thickness (WET)) at low imaging doses. This contrasts with X-ray imaging modalities, which have larger uncertainties due to the error-prone conversion of CT units to stopping power. A daily monitoring based on iRad could help to detect and quantify inter-fractional changes resulting in a shift of the Bragg Peak which could otherwise lead to damage in healthy tissue and a reduced tumor control. Hence, iRad could be a valuable tool to complement conventional X-ray imaging.
Inter-fractional changes occurring within the beam path have a big impact on the dose profile, while changes behind the target are of minor importance. Therefore, not only the detectability of an anatomical change but also its location within the patients'geometry is of high interest. In this contribution, the possibility of using 2D helium-beam radiography to access a third-dimension information is introduced (referred here in the following as 2.5D imaging/radiography).

Material and Methods: An in-house developed detection system was used to perform the experiments at the Heidelberg Ion-beam therapy center using helium ions at low helium ion fluences and fluence rates. The system consists of thin, pixelated silicon detectors (TimePix). They are capable of detecting single ions. Two tracking units measure the position and direction of single ions in front and back of the imaged object. The energy deposition of the ions leaving the imaged object is measured in a third unit –the energy deposition unit. This results in a need of 6 detectors.
To test the feasibility of 2.5D imaging with ions, a homogenous 161mm-thick PMMA block with an air slab of 1mm thickness at different depths was imaged first. The air slab position was estimated with a accuracy of 10 ± 16 mm. To get closer to a clinical situation, a PMMA cylinder with a diameter of 160mm was imaged with air cavities which have diameters of 10 mm. They were positioned in various depths within the phantom.
With the direction and position information of the impinging ions on the front and rear-tracking units, the most-likely path for every single ion is evaluated every 1mm along the depth of the object using the cubic spline algorithm. The energy deposition of each single ion is measured in a single sensitive layer in the energy deposition unit behind the imaged object. Using a calibration curve the energy deposition is translated to WET of the object. In that way, images are reconstructed at planes with 1mm spacing using the most-likely position of each ion and their connected WET.

Results: In the conducted experiment two measurements were performed: one with a completely homogeneous cylindrical phantom and one with an air cavity inserted. In this way, an inter-fractional change should be mimicked. The 2D iRads of the phantom with the air cavity evaluated at different depths already indicate qualitatively its position based on their sharpness. Then, the iRads with the air cavity were each compared to the homogeneous phantom in order to reconstruct the depth of the change in geometry. As a first investigated image quantity, the increase of the SSD indicates already the location of the insert. The average accuracy of this second experiment was determined to be approximately 18 ± 12 mm.

Conclusion: In conclusion, it could be shown that helium-beam radiography based on a detection system using silicon pixel detectors has the potential to not only produce a 2D image to verify the estimated WET values and detect anatomical changes, but also can give an estimation of their position in depth.

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