Quantitative investigation of the potential of ion computed tomography for clinical ion therapy treatment planning

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Abstract

Purpose: To quantitatively evaluate and compare proton, helium- and carbon-ion computed tomography (CT) for ion therapy treatment planning. Thereby, range uncertainties inherent in the conversion of Hounsfield units into relative (to water) stopping power (RSP) in ion-beam therapy treatment planning can be mitigated.
Methods: Different ion-CTs were simulated at 2mGy physical dose using an ideal single-particle tracking detector for an anaplastic astrocytoma and a nasopharyngeal carcinoma case. To this end, the FLUKA Monte-Carlo code was used with dedicated user routines in order to obtain an experimentally validated pencil beam description. The individual RSP maps were reconstructed by an ordered-subset simultaneous algebraic reconstruction technique with incorporated most likely path estimation and coupled total variation superiorization. For each case, proton treatment plans using pencil beam scanning were optimized on the ground truth X-ray CT and recalculated on the ion-CT data sets. Variations of the relative biological effectiveness (RBE) with ion type and energy spectra for the simulated ion-CT scenarios were quantified by coupling the FLUKA-code to the repair-misrepair-fixation model using DNA damage estimations from the Monte-Carlo damage simulation algorithm. This approach allowed accounting for cell survival and DNA complex damage as biological endpoints.

Results: Helium-CT provided the best image quality in terms of overall reduced RSP error, while carbon-CT showed the highest accuracy for bone material and proton-CT for soft/brain tissue. All ion-CTs displayed comparable performances for dose calculation showing only minor variations in obtained dose-volume histograms. For a 0.5%/0.5mm gamma-evaluation, carbon-CT exhibited 91% passing-rate, which increased to 98% for proton- and helium-CT. Using single field uniform dose, the average range variation was 0.34mm, 0.32mm and 0.54mm underestimation for proton-, helium- and carbon-CT, respectively. In anatomical regions with an increased amount of heterogeneities, proton-CT dose calculation resulted

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in over-range up to 0.8mm. Using a diagnostic 130kVp X-ray spectrum as reference, the predicted mean RBE for cell survival was 0.82-0.85, 0.85-0.89 and 0.97-1.03 for proton-, helium- and carbon-CT, respectively (depending on the tissue radiosensitivity parameter combination). The corresponding RBE for DNA double-strand break induction was only 0.82, 0.84 and 0.95.
Conclusion: This study quantitatively underlines the clinical potential of low-dose ion-CT for ion therapy treatment planning with sub-millimeter range accuracy. Furthermore, radiobiological implications are possibly reduced in comparison to conventional X-ray CT imaging. At the investigated dose level and for the considered ideal detector proton- and helium-CT offered superior performance compared to carbon-CT.