Regularised patient-specific stopping power calibration for proton therapy planning based on proton radiographic images

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Abstract

Proton transmission imaging has been proposed and investigated as imaging modality complementary to x-ray based techniques in proton beam therapy. In particular, it addresses the issue of range uncertainties due to the conversion of an x-ray patient computed tomography (CT) image expressed in Hounsfield Units (HU) to relative stopping power (RSP) needed as input to the treatment planning system. One approach to exploit a single proton radiographic projection is to perform a patient-specific calibration of the CT to RSP conversion curve by optimising the match between a measured and a numerically integrated proton radiography.

In this work, we develop the mathematical tools needed to perform such an optimisation in an efficient and robust way. Our main focus lies on set-ups which combine pencil beam scanning with a range telescope detector, although most of our methods can be employed in combination with other set-ups as well. Proton radiographies are simulated in Monte Carlo using an idealised detector and applying the same data processing chain used with experimental data. This approach allows us to have a ground truth CT-RSP curve to compare the optimisation results with.
Our results show that the parameters of the CT-RSP curve are strongly correlated when using a pencil beam based set-up, which leads to unrealistic variation in the optimised CT-RSP curves. To address this issue, we introduce a regularisation procedure which guarantees a plausible degree of smoothness in the optimised CT-RSP curves. We investigate three different methods to perform the numerical projection operation needed to generate a proton digitally reconstructed radiography. We find that the approximate and computationally faster method performs as well as the more accurate but more demanding method. We perform a Monte Carlo experiment based on a head and neck patient to evaluate the range accuracy achievable with the optimised CT-RSP curves and find an agreement with the ground truth expectation of better than 0.5%. Our results further indicate that the region in the patient in which the proton radiography is acquired does not necessarily have to correspond to the treatment volume to achieve this accuracy. This is important as the imaged region could be freely chosen, e.g. in order to spare organs at risk.

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