Four-dimensional dose calculation algorithm using displacement vector fields from deformable image registration for proton therapy as an alternative to robust planning

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Introduction: The dose distributions from proton therapy provides conformal and uniform dose distributions to cover the clinical target volume. However, proton dose distributions are vulnerable to patient setup uncertainties, anatomical variation and respiratory motion. Robust treatment planning is used to account for the previously mentioned uncertainties by setting static margins in different direction without prior knowledge about patient specific setup uncertainties and anatomical variations. Beam gating and breath holding using an external maker are often the techniques employed to manage respiratory motion of cancer patients treated with proton therapy. The goal of this study is to develop an algorithm with 4D-dose optimization and dose calculation that can be used for adaptive proton therapy as an alternative technique for robust treatment planning. The displacement-vector fields (DVF) obtained from deformable image registration using the 4D-CT images are extracted and used in 4D-dose calculation.

Methods: Helical, axial and cone-beam CT image of a mobile thorax phantom that moved with controlled cyclic motion patterns with amplitudes ranging 0-30mm and frequencies 0-0.5Hz. The phantom included three soft-tissue-equivalent target that simulate lesions with different sizes ranging 10-40mm that are inserted in low density foam that mimic lung tissue. The CT images of the mobile phantom were registered to static CT-images and DVF were extracted using different motion patterns. The DVF were employed to calculate the shifts on a voxel-by-voxel based for the whole phantom. An algorithm was developed which used the DVF to reproduce the static CT- number values in the mobile CT-images and regenerate the fluence map to perform 4D-optimization and dose calculation.

Results: The produced CT-number values by remapping the CT images with deformable image registration corrected for anatomical variations and respiratory motion (Fig.1). The volumes for the mobile targets which were elongated in the motion direction were corrected with DVF (Fig.1a). The maximal and minimal DVF correlated linearly with motion amplitude of the mobile targets which was used to extract the shifts of the different voxels particularly in the mobile targets embedded in lung phantom (Fig.1b). This 4D-dose calculation algorithm employed DVF extracted from deformable image registration to obtain conformal 4D-dose distribution considering phantom motion (Fig.1c). The dose distributions were shrunk by optimization which in turn were expanded by phantom motion to produce conformal 4D dose distributions (Fig. 1c).

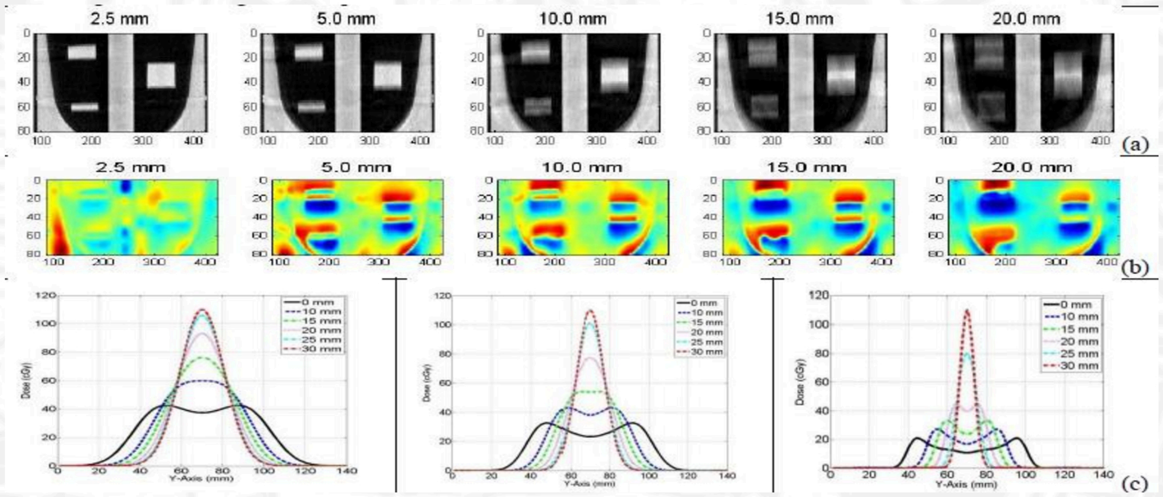

Figure 1: (a) Image artifacts in cone-beam CT images induced by phantom motion with different motion amplitudes as indicated. (b) Displacement-vector-fields maps calculate by the deformable image registration algorithm for the images in (a) with different motion amplitudes (c) The 4D-optimized dose profiles (dotted and dashed curves) corrected for artifacts from cyclic respiratory motion with motion amplitudes 10-30 mm. The dose profiles (solid black) represent 4D-optimized dose profile for stationary targets.

Conclusion: This algorithm provides 4D optimized dose calculation which used DVF from deformable image registration to correct for the mobile target volumes and CT number variations due to motion artifacts. The DFV represent voxel-by-voxel shifts of the phantom that could be used in proton therapy to extract specific shifts induced by actual patient anatomical variation and motion. This approach represented an alternative for robust treatment planning for proton therapy that uses static margins and management of patient motion.

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