Robust 4D-optimized treatment plans in scanned carbon ion beam therapy for intrafractionally moving lung cancer

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Introduction

The treatment of moving tumors with a scanned carbon ion beam is challenging due to interplay effects and range changes. This problem is even more acute for modern hypo- or single fractionated treatment, where averaging effects between fractions are diminished or missing. A technique for conformal treatment is tracking, where the ion beam is deflected to follow the target. This permits to compensate translatory motion components only and needs sophisticated hardware to cope with range changes online. Plans optimized on an entire 4DCT depicting the tumor motion over a breathing cycle inherently include the characteristic motion and also range information. Here, we present a modality that uses this 4DCT information to deliver homogeneous, conformal doses to each motion phase, and as such includes a form of rescanning.

Material and Methods

The treatment plans are generated separately for each motion phase, using the same set of beam energies, though not each plan necessarily has to use all energies. This is similar to single field uniform dose (SFUD) plans commonly generated for static tumors. In contrast to other motion mitigation techniques, a deformable registration between motion phases is not needed during optimization except to propagate the target contours. For delivery, the resulting independently optimized plans are then joined to a 4D plan, which can be irradiated using a 4D control system that was experimentally validated at GSI in 2012 [1]. Plans were computed for a lung cancer patient using 4 fields for a single fraction of 17.7 Gy(RBE). The patient had a complex tumor geometry with a motion amplitude of 12.7mm over the breathing cycle. The fields were both optimized separately (SFUD) and simultaneously (IMPT). DVH results were compared to a static (no motion) and interplay (no motion mitigation) plan on the same patient. We report dose coverage (V95) and the conformity number (CN). Interplay and 4D-optimized plans were calculated on the 4DCT and did not consider residual motion within the discrete motion phases.

Results

Exemplary dose cuts of the patient are shown in figure 1. For SFUD, the static case resulted in V95 of 98.5% and CN of 70.8%, which degraded to V95 of 72.5% and CN of 52.5% for interplay. 4D-optimization could restore V95 to 99.4% and CN to 75.6%. For IMPT, the results of the static case were V95 of 99.3% and CN 83.4% compared to V95 of 76.4% and CN of 56.4% for interplay. Again 4D-optimization maintained excellent coverage with V95 of 100.0% and CN of 82.1%. The IMPT plans indicate that the additional degrees of freedom from 4D-optimization on 10 motion phases as well as from the simultaneous optimization of fields leads to nominally better plan results.

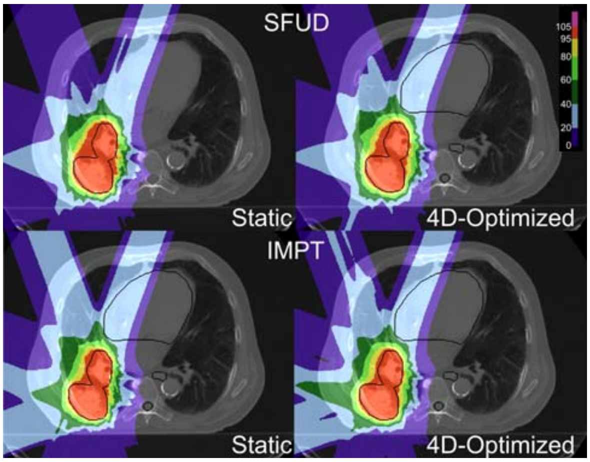

Figure 1: Axial dose cut of the sample patient for static (left panels) and 4D-optimized (right). The top row shows individually optimized fields, the bottom row simultaneous optimization. The static dose coverage could be completely restored.

Discussion

The presented 4D-optimizaton method leads to highly conformal irradiation of moving tumors, restoring or exceeding the results of an irradiation without motion. A major benefit of the proposed method with respect to robustness is the lack of dose gradients between motion phases. This is partially negated through the use of IMPT, which introduces gradient between fields, though not between motion phases. The results presented here will be experimentally tested in the GSI beam times of 2014.

References

[1] C. Graeff, R. Lüchtenborg, J.G. Eley, M. Durante, C. Bert, "A 4D-optimization concept for scanned ion beam therapy", Radiother Oncol. (2013) 109(3):419-24

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