

A VOI-based 4D optimization method for the ion beam therapy of intrafractionally moving tumours

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Introduction

Ion beam therapy permits highly conformal dose delivery. It results in significantly improved therapy outcome in a number of cancer types. The treatment of moving tumour is especially challenging in ion beam therapy due to the high sensitivity to radiological depth which changes with e.g. breathing motion. For scanned beam delivery also interplay effects between pencil beam and tumour motion have to be considered.

Motion mitigation strategies such as tracking inherently use a 3D optimization on a static reference phase of a 4DCT. The treatment plan is then adapted, in part online during delivery, to deliver dose to the moving tumour; especially range-adaptation is challenging [1]. We propose a method that includes the motion information already during optimization, resulting in a 4D treatment plan as conformal as tracking.

Material and Methods

To enable 4D optimization, a correlation between tumour motion and delivery progress has to be defined. This also has to be upheld during delivery. In the present method, the target volume (VOI) is divided into subsections, with each subsection to be irradiated in a specific motion phase. A single treatment plan is prepared for each subsection transformed to the corresponding motion phase. The resulting combined 4D treatment plan is optimized simultaneously for all motion phases. In this way, correct geometrical motion and resulting changes in radiological depth is already factored into the optimization process.

The subsections were chosen as pie slices from beam's eye view, so that each motion phase has similar dose contributions to each iso-energy slice (IES). The pie slices were arranged such that the breathing motion moved them apart during delivery creating a broad, low-dose entry channel.

For delivery, a dedicated treatment control system (TCS) is needed together with precise motion monitoring to keep up the motion correlation assumed during optimization.

At GSI, this 4D-TCS was realized as an addition to the original Cave M TCS. The main control structures of the original TCS were unchanged, but the actual pencil beam to be delivered were determined as a function of motion phase and this motion phase's progress from the external 4D-TCS. The 4D-TCS also controlled the change of IES. If for a given IES a certain motion phase's plan was completely delivered, the beam would be gated using fast KO extraction.

The feasibility of the 4D optimization was investigated in a planning study in a lung cancer patient using a single A-P field with a physical target dose of 1 Gy. The feasibility of the 4D TCS was tested in a simple film experiment in a Ca beam time at Cave M.

Results

The patient study resulted in a conformal dose to the target with $V95=97\%$ in spite of a 22 mm motion amplitude. Figure 1 shows the conformal dose as well as the dose in the entry channel, which is smooth and without hot spots as opposed to tracking which experiences inverse interplay [1].

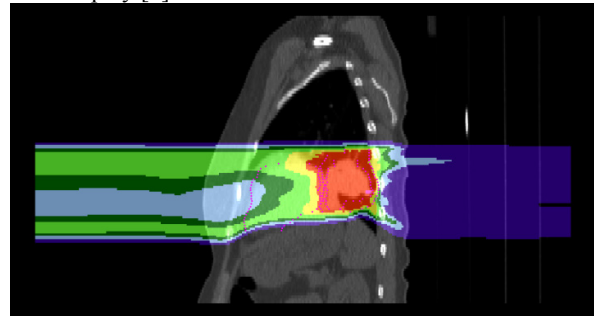


Figure 1: Sagittal dose cut of the patient study, showing conformal dose also in the main S-I motion direction.

The film experiments resulted in a large improvement of dose homogeneity and conformity in comparison to an interplay irradiation (Fig. 2). It also revealed the impact of residual motion of up to 3 mm within the motion phases, which was not considered during the patient study.



Figure 2: Interplay, static and 4D optimized (left to right) dose to a 3cm circular target on a radiographic film.

Conclusion

4D optimization allows conformal dose delivery without additional equipment for online range adaptation. Residual motion within the quasi-static motion phases would have to be countered by re-scanning or fractionation.

References

- [1] C. Bert et al. "Dosimetric precision of an ion beam tracking system," *Radiat Oncol* **5**, 61 (2010).