Layered rescanning spread over full breathing cycle reduces interplay effects in active proton treatments

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Purpose
We investigate four different rescanning techniques in active proton beam therapy of non-small cell lung cancer (NSCLC), and assess their ability to reduce interplay effects. The techniques are (a) volumetric rescanning, (b) layered rescanning, (c) breath-sampled (BS) layered rescanning, and (d) continuous breath-sampled (CBS) layered rescanning (see Figure 1).

Method
The interplay effect was evaluated for robustly optimized treatment plans for seven different NSCLC patients in the treatment planning system RayStation. The optimization and final dose calculation used the Monte Carlo dose engine to fully account for the density heterogeneities in the lung region. A splitting parameter limiting the maximum meteoron per layer was used to determine the number of rescans of the original energy layers. For each rescanning technique, three different splitting parameters were used: 1, 2, or 4 MUs, respectively (referred to as MU1, MU2 and MU4).

We performed interplay evaluation with variation of both starting phase and breathing cycle length. The treatment delivery time structure was retrieved from a direct connection to the IBA ScanArlo simulation tool. Both slow (2.0 s) and fast (0.1 s) energy switching times were simulated.

Results: Motion and delivery metrics

Results: Dose metrics (one patient)

Figure 4: Interplay evaluated doses for patient P110 for different rescanning strategies. The treatment starts in the planning phase in all evaluations above. The splitting parameter is MU1.

Results: Dose metrics (all patients)

Figure 5: Evaluation of the interplay effect with the treatment delivery starting in all different phases. Solid lines represent the mean OAR for the corresponding rescanning strategy. The coloured area represents +/- 1 s. The displayed evaluation is made for the different rescanning strategies, but only for the splitting parameter MU1.

Figure 6: Interplay evaluation for energy switching time 2.0 s (a) and 0.1 s (b) for varying starting phases and for all patients (sorted according to their motion amplitude in ascending order). The splitting parameter is MU1. The dose metrics for the CTV (D50), homogeneity index (HI = D95/D50), and D98 are given relative to the nominal planned plan. Triangles show the mean value and error bars represent standard deviations.

Figure 7: Dose statistics for the CTV assembled over all patients except P111 (excluded from this summary picture, since the large movements resulted in insufficient plan quality for each of the rescanning strategies.) D98 (blue), D50 (red) and D2 (cyan) are shown with error bands (one standard deviation) and with dose values shown on the left axis. The homogeneity index (HI = D95/D50) is shown in black on the right axis. The analysis is made for all different rescanning strategies and the splitting parameters MU1/MU2/MU4.

Conclusions
• Layered rescanning spread over the full breathing cycle (breath-sampled) is superior to normal layered rescanning and volumetric rescanning.
• Breath-sampled rescanning can be used offline and is stable at least for moderate variability in breathing pattern (up to 15% investigated). This can improve the mitigating effect.
• In general, short energy switching times increase the interplay effect (compare Figure 6b to Figure 6a).
• For motion amplitudes above 10 mm, rescanning alone cannot help in mitigating interplay effects.