Parameter vs logfile based 4D proton dose tracking for small movers

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Objective

The motion compensation strategy in particle therapy depends on the anatomic region, motion amplitude and underlying beam delivery technology. The pre-requisite for improving existing particle therapy treatment concepts for moving targets is the quantification of the interplay effect between organ motion and beam delivery and its impact on the dose distribution and hence treatment delivery accuracy. While retrospective logfile-based analysis gives insight into the patient's breathing and beam delivery time structure, a prospective 4D dose prediction allows adaptation on a patient specific basis during the planning process.

Materials and Methods

- 4 pancreas and 3 liver patients treated with curative hypofractionated proton therapy (see Figure 3)
- Pulsed synchrotron accelerated scanned pencil beams
- Prescription
  - Pancreas: 5x7.5 Gy(RBE)
  - Liver: 15x4.68 or 10x5 Gy(RBE)
  - Volumetric rescanning for selected cases
- Imaging
  - Planning CT (Big Bore C, Philips)
  - Phase-based 4DCT (at the time of planning and for some patients also during treatment)
- Breathing data
  - Extracted from the surface scanner during delivery (see Figure 1) or from the 4DCT data (acquired with a surface scanner prior to treatment)
  - Amplitude range: 1.3 - 4mm
- Software environment
  - Clinical treatment plan creation: treatment planning system (TPS) RayStation8B (Monte Carlo dose engine v4.2) (RaySearch, Sweden) employing robust optimisation strategies for mitigating different organ fillings.
  - RayStation 10A for dose tracking
- 4D dose tracking framework [1] (see Figure 2)
  - Delivery time structure: accelerator logfiles for each fraction
  - 4D computed tomography (CT) data
  - Breathing patterns extracted from surface scanner signal during 4DCT (Sentinel, C-Rad) or during irradiation (Catalyst, C-Rad)
  - Deformable image registration between 4DCTs and planning CT → basis for mapping of dose distributions

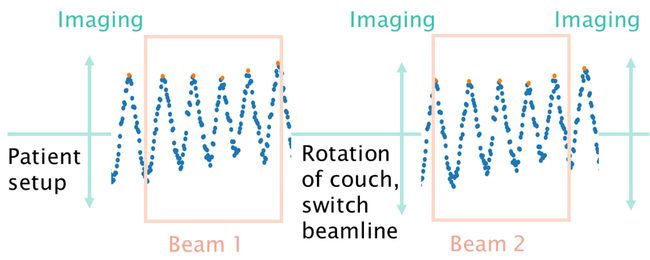

Figure 1: Treatment workflow with breathing curves

Treatment accuracy was determined using: (see Figure 2)

- File-based 4D dose tracking (f-4DDT) considering the time structure from accelerator logfiles and surface scanner breathing patterns (C-Rad) for each fraction;
- Parameter-based 4D dose tracking tool (p-4DDT).
  - Input parameters
    - Averaged dose rate
    - Scanning speed
    - Constant breathing cycle length.

Both methods recalculate the static dose on 8 4DCT phases considering the given time structure input. These 8 dose distributions were mapped onto the planning CT using deformable image registration and accumulated for all fractions.

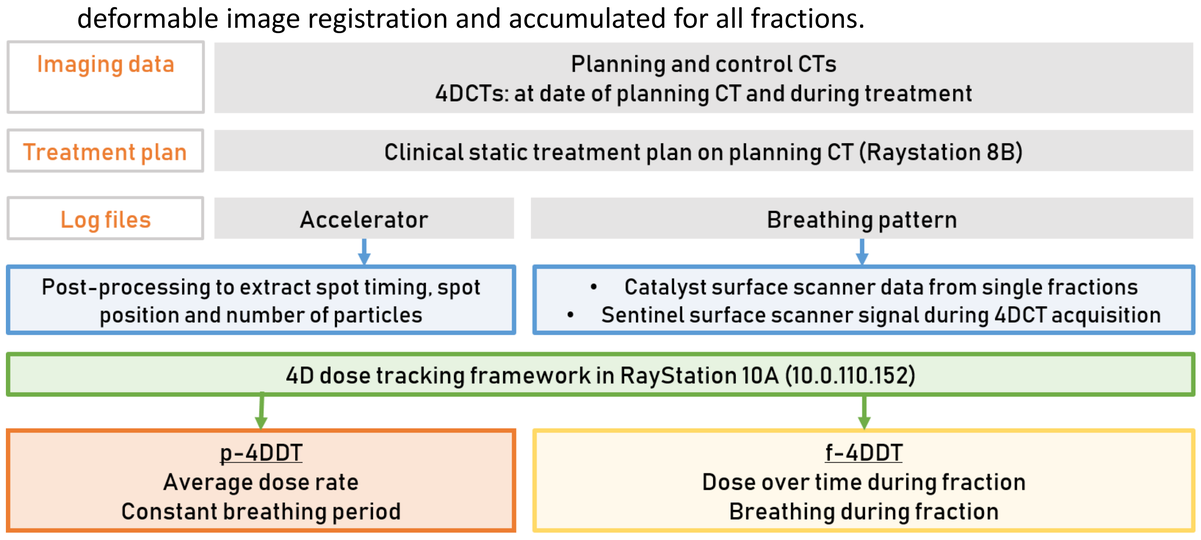

Figure 2: Illustration of 4D dose tracking framework

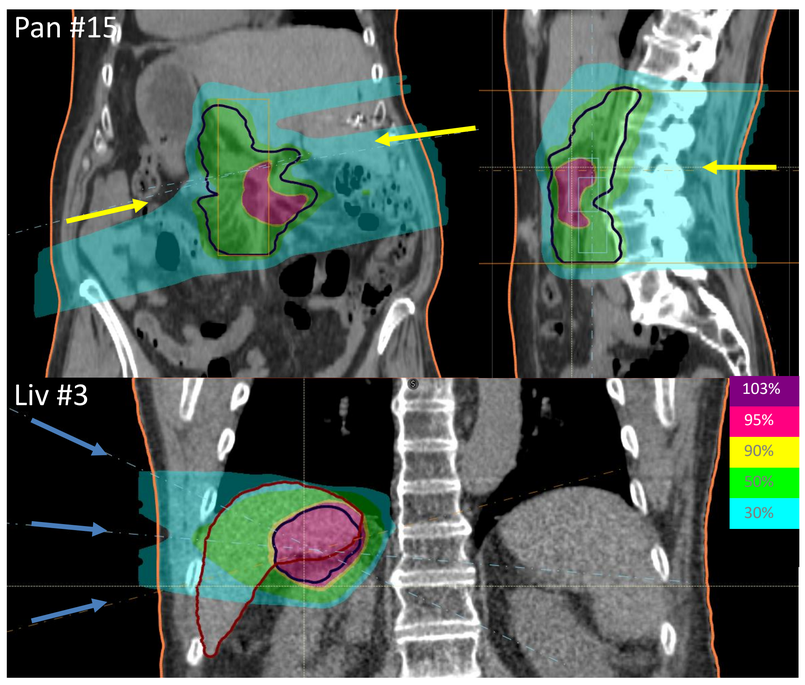

Figure 3: Relative dose distribution pancreas patient #15 (up) and liver patient #3 (down) with the beam directions

Additionally investigated influence parameters

- Starting 4DCT phase: 0%, 25%, 50%, 75%
- Dose rate: min, max and mean dose rate

Dosimetric evaluation

- DVH parameters
- γ-pass rates with a 2%/2mm criteria

Results

Considering the interplay effect $D_{50\%}$ was preserved within 2% for the target structures for both tracking methods. $D_{98\%\_PTV}$ varied up to 15% compared to the static scenario, while the results from the f-4DDT and p-4DDT agreed within 2%. For the liver patients $D_{33\%\_liver}$ deviated up to 35% compared to static and 10% comparing the two 4DDT tools (see Figure 4 for liver patient #3), while for the pancreas patients the $D_{1\%\_stomach}$ varied up to 45% and 11%, respectively.
For all patients, except one, the gamma pass ratio was 98.1%±2.4%. For the outlier patient (liver #3, Figure 4) with the biggest surface motion amplitude up to 1.5 mm and a 4 mm PTV movement the γ-pass rate decreased to 70%.

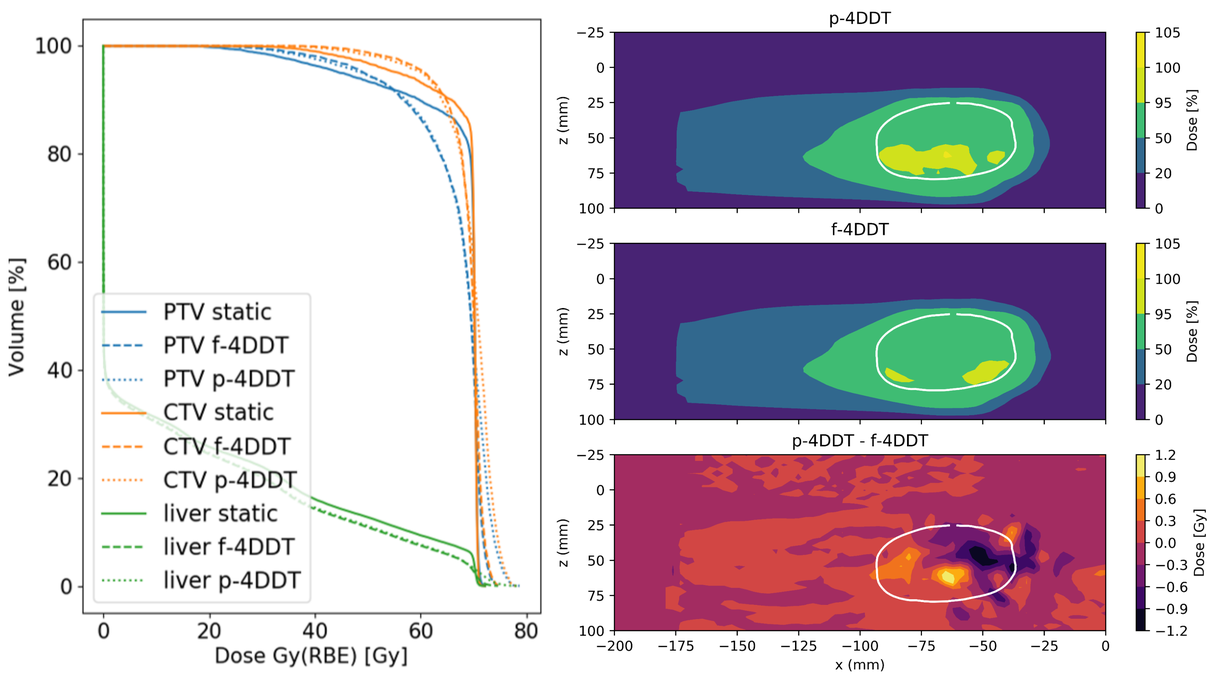

Figure 4: DVH curves for the outlier liver patient #3 for all fractions (left) and the corresponding dose distributions (right)

The 12 different scenarios with varying starting 4DCT phases and dose rates were compared to the reference scenario assuming the mean dose rate and the 0% starting breathing phase. This revealed a variation up to 3% for $D_{33\%\_liver,}$ $D_{98\%\_PTV}$ and $D_{2\%\_PTV}$ for liver and pancreas patients. Since this variation was within the dose prediction accuracy. The mean dose rate and a starting phase of 0% served as basis for all further investigations.

Conclusion

The p-4DDT could be used prospectively to determine the impact of beam and organ motion for pancreatic and liver cases in scanned proton therapy. The systematic uncertainties covered by the PTV margins compensated well for the motion effects of the investigated indications preserving an excellent CTV coverage when motion was considered.

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References:
[1] Knäusl et al doi.org/10.1016/S0167-8140(21)08204-9

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