Experimental methods, using self-gated strategies based on the center of k-space, lack a quantitative signal and have extensive scan times. To overcome these limitations, a new self-sorted 4D-MRI method was developed for treatment planning and MR-guided radiotherapy of the liver.
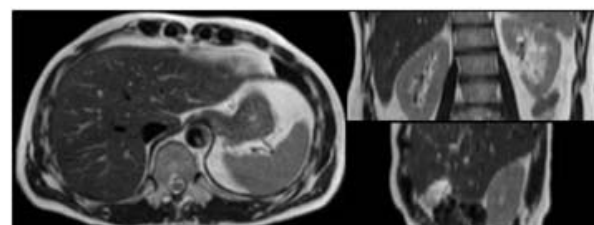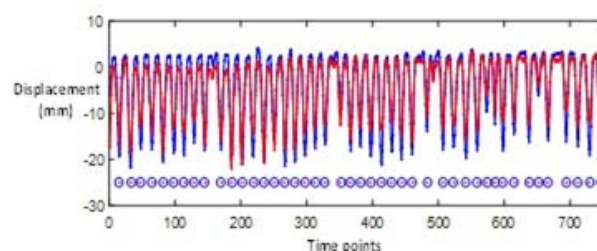
Material and Methods: For 3 volunteers, a 2D multi-slice MRI of the upper-abdomen was acquired 30 times (single-shot TSE, slices=25, voxel size=2x2x5mm3, TR=383ms, TE=80ms, dynamics=30) and resulted in a total of 750 axial slices (scan time 4:50min) in an unknown respiratory state. For comparison, a navigator was acquired, outside the FOV, prior to every slice acquisition.

To extract the respiratory signal from the data, first a 3D exhale reference dataset was constructed. As the anatomy predominantly moves in the SI-direction, the average position of every slice is located below the exhale position. Therefore, for each slice, the dynamic with the highest mean correlation with all dynamics of the slice below was selected for the exhale reference set. The exhale data was then interpolated to slices of 1mm. Then all slices of all dynamics were registered to the exhale reference frame in SI-direction, using correlation as an objective function, resulting in a displacement relative to exhale. To obtain a 4D-MRI reconstruction, the resulting respiratory signal was processed to identify inhale positions and sort the data according to phase. This was compared to the navigator signal and associated sorting.

Results: The self-sorting signal (SsS) and the navigator signal (NavS) correlate very well (mean r=0.86). For all volunteers, the SsS and NavS identified the same number of inhale positions with an average mean absolute difference (MD) of 268ms. This is in good agreement with the slice acquisition time. The 10 phase 4D-MRI was on average under-sampled 7% (NavS) and 14% (SsS) and missing slices were linearly interpolated. After reconstruction, the average MD of the LR, SI and AP motion obtained by local rigid registration were 0.3, 0.6 and 0.3mm, respectively. Reconstruction time was ~20s on a 8 Core Intel CPU, 3.4GzH, 16GB RAM PC.

Figure1 (top): Navigator (blue) and self-sorting signal (red). Blue circles at the bottom represent minima derived from the NavS and red dots represent minima derived from SsS.
Figure2 (bottom): Axial, coronal and sagittal slice from reconstructed 4D-MRI. FOV was lowered for minimal interaction with the navigator channel.

Volunteers		A	B	C
Respiratory signal				
r = corr(NavS,SsS)		0.96	0.74	0.89
Inhale positions				
MD(NavS, SsS)	(ms)	273	284	249
4D reconstruction				
Under-sampling NavS	(%)	2	5	14
Under-sampling SsS	(%)	7	14	15
Motion				
LR: MD(NavS, SsS)	(mm)	0.1	0.3	0.6
SI: MD(NavS, SsS)	(mm)	0.4	0.5	1.0
AP: MD(NavS, SsS)	(mm)	0.2	0.2	0.5

Table1: Comparison between navigator (NavS) and self-sorting signal (SsS) for 3 volunteers

Conclusion: A 4D-MRI dataset could be acquired in ~5min and reconstructed by retrospective sorting using a self-sorting signal. The signal correlated very well with an additionally acquired navigator signal. Differences in motion between the reconstructed data using the self-sorting signal and the navigator were minimal. Before clinical implementation, acquisition and reconstruction parameters should be optimized and the method should be verified in more volunteers as well as in patients.

PV-0326
Respiratory gating guided by internal electromagnetic motion monitoring during liver SBRT
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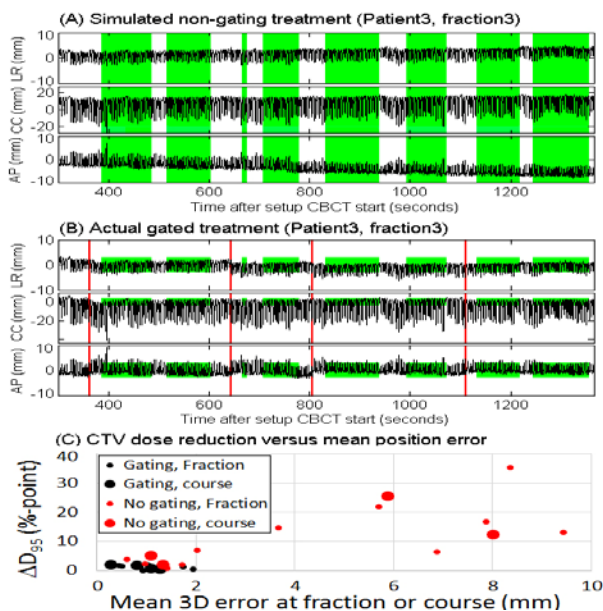[2]Aarhus University Hospital, Department of Medical Physics, Aarhus, Denmark
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Purpose or Objective: Accurate dose delivery is crucial for stereotactic body radiation therapy (SBRT), but the accuracy is challenged by intrafraction motion, which can be several centimeters for the liver. Respiratory gating can improve the treatment delivery, but may be inaccurate if based on external surrogates. This study reports on the geometric and dosimetric accuracy of our first four liver SBRT patients treated with respiratory gating using internal electromagnetic motion monitoring. We expect to include 10-15 patients in this gating protocol with three new patients being recruited at the time of writing.

Material and Methods: Four patients with liver metastases were treated in three fractions with respiratory gated SBRT guided by the position signal of three implanted electromagnetic transponders (Calypso). The CTV was defined in the end exhale phase of a CT scan and extended by 5 mm (LR/AP) and 7-10 mm (CC) to form the PTV. 7-field conformal or IMRT plans were designed to give a mean CTV dose of 18.75Gy or 20.60Gy per fraction (=100% dose level) and minimum target doses of 95% (CTV) and 67% (PTV). The treatment was delivered in free respiration with beam-on in end-exhale when the centroid of the three transponders deviated less than 3mm (LR/AP) and 4mm (CC) from the planned position. The couch was adjusted remotely if intrafraction baseline drift caused the end exhale position to

deviate more than ~2 mm from the gating window center. Log files provided the transponder motion during beam-on in the actual gated treatments and in simulated non-gated treatments with CBCT-guided patient setup. This motion was used to reconstruct the actually delivered CTV dose distribution with gating and the would-be dose distribution without gating. The minimum dose to 95% of the CTV (D95) for each fraction and each course was compared with the planned CTV D95.

Results: Fig. A shows the internal tumor motion at a fraction with large baseline drift of 3mm (LR), 9mm (CC), and 6mm (AP) relative to the pre-treatment CBCT. Fig. B shows the same motion with four drift compensating couch adjustments applied as marked with red lines. The width of the green areas indicates the time of beam delivery. The height indicates the allowed positions for beam-on without (Fig. A) and with (Fig. B) gating. The course mean geometrical error was <1.2mm for all gated treatments, but would have ranged from -2.8mm to 1.2mm (LR), from 0.7mm to 7.1mm (CC), and from -2.6mm to 0.1mm (AP) without gating due to baseline drift. Fig. C shows the CTV D95 reduction relative to the planned D95 versus the 3D mean error for each fraction and course. The mean reduction in D95 for the 12 fractions was 1.1% [range: 0.1-2.1%] with gating and 10.8% [0.9-35%] without gating. The mean duty cycle was 59% [54-70%].

(A) Simulated non-gating treatment (Patient3, fraction3)

(B) Actual gated treatment (Patient3, fraction3)

(C) CTV dose reduction versus mean position error

Conclusion: Respiratory gating based on internal electromagnetic monitoring was performed for four liver SBRT patients. The gating added robustness to the dose delivery and ensured a high CTV dose even in the presence of large intrafraction motion.

PV-0327
Patient-specific motion management and adaptive respiratory gating in Pancreatic SBRT

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Purpose or Objective: Ablative radiotherapy is rapidly emerging as an effective treatment for locally advanced pancreatic adenocarcinoma. However, the pancreas undergoes erratic and unstable respiratory-induced motion, which decreases coverage of the tumor and increases dose to the duodenum. The purpose of this study was to develop and optimize motion management protocols which allow for safe delivery of pancreatic SBRT.

Material and Methods: We analyzed 4DCT and CBCT data from 35 patients who received pancreatic SBRT; the majority were locally advanced tumors receiving 30 Gy in 5 fractions.

In total, the data from 175 treated fractions was analyzed. For each fraction, the daily trajectory of the tumor was reconstructed by calculating a Gaussian probability density function using the location of gold fiducial markers in the CBCT projections. These trajectories represented over 600 samples of the position of the tumor during the course of CBCT acquisition. Using the calculated trajectories, we investigated the dosimetric impact of several respiratory motion management strategies, including gating based on instantaneous kV imaging of implanted fiducial markers.

Results: 4DCT was a poor predictor of pancreatic motion, as the amplitude of daily motion exceeded the predictions of pre-treatment 4DCT by an average of 3.5 mm in the SI direction. In a Fourier-based analysis, these uncertainties were correlated with an increase in low-frequency motion (potentially due to peristalsis of the duodenum). Abdominal compression increased the consistency of motion and reduced the amplitude by 2.7 ± 2.8 mm. On average, respiratory gating decreased the apparent motion even further, with attainable effective motion amplitudes of 2 mm. However, gating based on external surrogates (either phase- or amplitude-based) is greatly hindered in some patients by the inconsistency of pancreatic motion. In these cases, internal gating surrogates are warranted. In a simulated clinical scenario, fiducial-based internal gating using a 2 mm SI window greatly outperformed conventional gating using external surrogates (p<0.001), with a mean target D95 of 99±2%, 95% CI 93-100% (conventional gating – D95 97±7%, 95% CI 68-100%). Additionally, we analyzed the dosimetry of motion by convolving the dose distribution with phase-specific motion information. Using these data, we developed a metric that predicts patient-specific consistency, and in a simulated adaptive protocol which adjusted margins based on this metric, there were significant increases in mean target D95 and minimum dose.

Conclusion: Motion management is essential in reducing the size of target volumes and minimizing dose/side effects to the small bowel. Motion uncertainties and patient-specific differences warrant an adaptive approach to respiratory management. Our data shows that using real-time kV imaging of implanted fiducial markers to adapt the gating protocol based on the instantaneous position of the tumor outperforms conventional approaches.
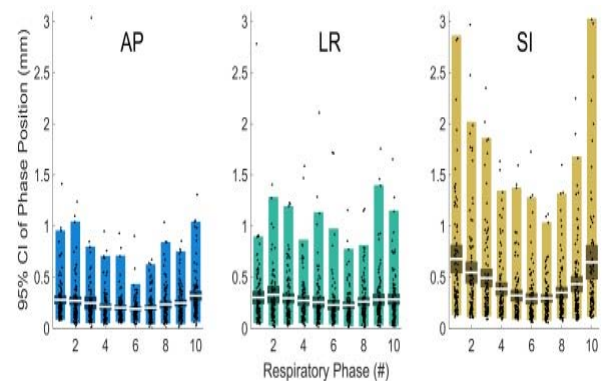
PV-0328
Rectal immobilisation device in stereotactic prostate treatment: intrafraction motion and dosimetry

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Purpose or Objective: PROMETHEUS (UTN: U1111-1167-2997) is a multicentre clinical trial investigating the feasibility of stereotactic radiotherapy (SBRT) as a boost technique for