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Full Abdominal Motion Interplay in Pencil Beam Scanning Proton Therapy: Integrating Respiratory and Gastrointestinal Dynamics

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ABSTRACT

Purpose: To implement a full abdominal motion model that combines respiration with gastrointestinal (GI) motility and quantify its interplay impact in pencil-beam scanning (PBS) proton therapy.
Methods: We compared full-motion (GI motility with respiratory superposition) against GI motility-only simulations in six abdominal cases (three pancreas and three liver). Respiratory deformation vector fields (DVFs) were derived from 4DCT via deformable registration. GI motility (peristalsis, rhythmic segmentation, and high-amplitude propagated contractions) was generated along stomach/duodenum/small-bowel centerlines using traveling/standing waveforms, with local radius modulations mapped to 3D DVFs via boundary-aware kernels. For full-motion modeling, the respiratory DVF and GI-DVF were composed at spot time to perform realistic 4D dose replay. Endpoints were interplay-induced deviance (Δ) vs static for clinical-target-volume (CTV) D95% and organ-at-risk (OAR) D2%, and distribution width (the width of CTV-D95% or OAR-D2% between two extreme scenarios). Both are reported as mean [min, max] (Gy) for single fraction (1-fx) and full course (30-fx) replay.
Results: Full-motion modeling produced larger interplay-induced dosimetric deviations and wider dose distributions than GI-only. For CTV D95% (1-fx), dose deviations Δ was −3.3 [−5.2, 0] Gy with full motion vs −1.4 [−4.4, 0.1] Gy for GI-only. The distribution width was likewise greater for full motion: 4.3 [0.3, 9.9] Gy vs GI-only: 1.8 [0.1, 7.0] Gy. The same results of larger mean shifts and wider spreads in full-motion were also observed across OAR D2% metrics in both pancreas and liver cases. Multiple fractions (full-fx) tightened deviations and narrowed widths in both models but did not fully restore static-like distributions.
Conclusion: A delivery-accurate, respiratory-plus-GI model shows that full abdominal motion produces stronger interplay than GI-only in abdominal PBS. These results support incorporating combined respiratory and GI dynamics in motion-robust planning and evaluation, and using distribution-aware endpoints (Δ and width) when assessing interplay risk.

INTRODUCTION

Pencil beam scanning (PBS) proton therapy offers a favorable therapeutic ratio for abdominal cancers, including pancreas and liver, with reduced toxicity and high disease control. However, the pancreas and upper abdomen lie adjacent to highly motile stomach, duodenum, and small bowel, so gastrointestinal (GI) motility can perturb dose near the distal fall-off on delivery timescales.

Currently, most interplay analyses emphasize respiration via 4D-CT/4D-MRI and under-sample aperiodic, localized GI motility, which can further perturb dose. To address this gap, we explicitly simulate GI motility using physiology-informed models of peristalsis, rhythmic segmentations, and high-amplitude propagated contractions (HAPCs), and replay clinical PBS deliveries in abdominal PBS cases to quantify target coverage degradation and organ-at-risk (OAR) tail-risk. Interplay effects were quantitatively evaluated at two scenarios: the combined effect of full abdominal motion (respiration plus GI tract motility) versus GI motility only, for pancreas and liver cases. Two fractionations (single-fraction (1-fx) versus full-course (full-fx) accumulation) were also compared.

MOTION MODELING

Respiratory motion

- estimated from the 4DCT
- deformable image registration between phases
- phase-resolved deformation vector fields (DVFs)
- interpolated over time of a 5-s breathing cycle.

GI motility

- GI contours used to reconstruct patient's GI tract
- modeled as a stochastic sequence of physiological events (peristalsis, rhythmic segmentation, and high-amplitude propagated contraction)
- tract-aligned deviations along the GI tract
- population-based simulation parameters-Table 1.

Table 1. GI tract motion simulation parameters.

Mode	Amplitude (mm)	Speed (mm/s)	Wavelength (mm)	Bolus Size (mm)	Nodal Points (n)
Peristalsis	6	11	200	-	-
Rhythmic Segmentations	6	5	-	-	5
HAPC	9	19	-	180	-

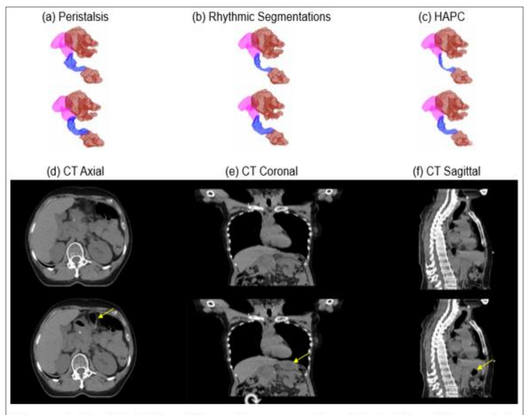

Figure 1. Simulated GI motility and corresponding CT at different time points.

Full motion

- respiratory + GI DVFs at each time point to
- total DVFs for time-resolved deformed anatomy
- downstream GI interplay.

INTERPLAY ANALYSIS

PBS redelivery (spot order + energy-layer sequencing) with an in-house 4D dose accumulation –

- dynamic spot timing: for each spot timestamp, dose was computed on motion deformed frames and accumulated to the reference via invertible deformations.
- MCsquare (A Monte Carlo dose engine) - 108 initial protons of statistical uncertainty targeted ≤1%.
- Plans spot-sorted into phase-specific subplans of random start phases over the full-motion or GI-only cycle phases (Figure 2, Panel A).

Single fraction (1-fx) vs full treatment (full-tx)

- 1-fx interplay were derived across start phases (Figure 2, Panel B)
- full-tx (30 fxs) accumulation was estimated by sampling one 1-fx realization per fraction and then accumulate all fractions. We repeat this process 100 times (100 scenarios) for uncertainty evaluation phases (Figure 2, Panel C).
- ***Endpoints:*** Interplay-static differences (Δ) and dose ranges for CTV D95% and OAR D2%, with DVHs and violin plots for single- vs. full-tx (30 fxs).

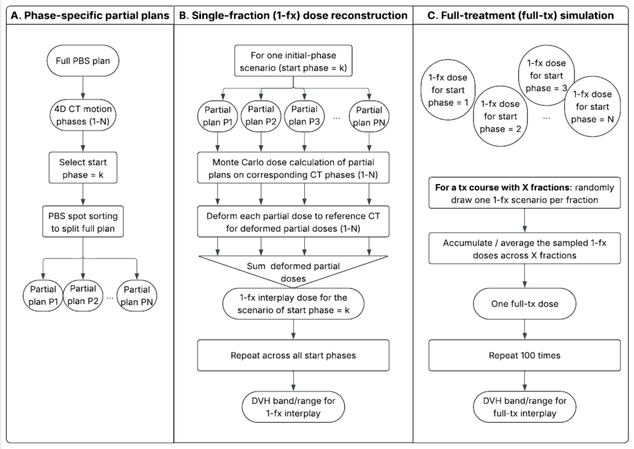

Figure 2. Schematic workflow of the 1-fx and full-tx PBS interplay.

RESULTS

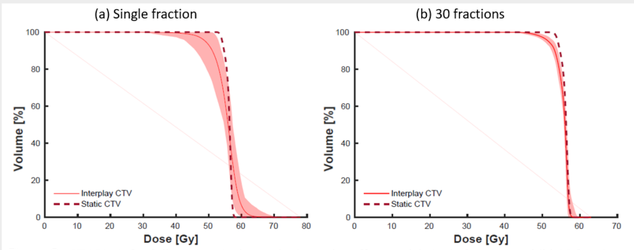

Figure 3. CTV DVHs for full motion. It shows the interplay effect on (a) single fraction and (b) 30 fractions.

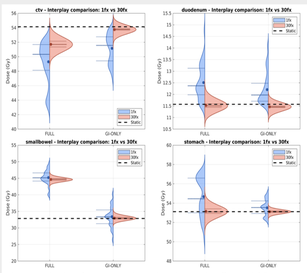

Figure 4. Violin plots of a PANCREAS plan to show the interplay effects with full motion (respiratory and GI motility) versus GI-only motion simulation.

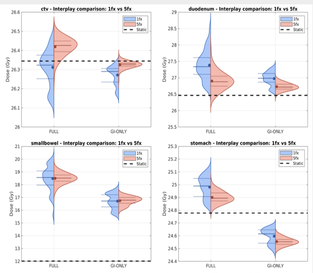

Figure 5. Violin plots of a LIVER plan to show the interplay effects with full versus GI-only motion simulation.

Table 2. Cohort summaries of Δ (dosimetric differences relative to the static plan) and dose distributions (the differences of CTV D95% or OAR D2% between 2 extreme scenarios) across all six cases. Both Δ and distribution are reported in mean [min, max] Gy.

	Metric	Full-motion 1fx	Full-motion full-fx	GI-only 1fx	GI-only full-fx
Δ	CTV D95%	-3.3 [-5.2, 0.0]	-2.6 [-4.3, 0.1]	-1.4 [-4.4, 0.1]	-0.8 [-4.3, 0.2]
	Duodenum D2%	0.8 [-0.3, 1.5]	0.3 [-0.8, 0.9]	0.6 [-0.6, 1.4]	0.3 [-0.8, 1.3]
	Smallbowel D2%	2.4 [-2.5, 12.1]	2.3 [-2.5, 11.6]	-0.1 [-3.8, 3.1]	0.5 [-0.5, 3.2]
	Stomach D2%	-1.4 [-12.0, 1.9]	-1.9 [-12.5, 1.4]	0.3 [-0.0, 0.8]	0.1 [-0.1, 0.3]
Distribution	CTV D95%	4.3 [0.3, 9.9]	1.8 [0.2, 3.9]	1.8 [0.1, 7.0]	0.5 [0.1, 1.1]
	Duodenum D2%	2.8 [1.8, 4.3]	1.1 [0.6, 1.5]	1.7 [0.7, 2.6]	0.7 [0.3, 1.2]
	Smallbowel D2%	4.0 [0.0, 9.8]	1.3 [0.0, 2.1]	3.4 [0.0, 13.8]	1.1 [0.0, 2.1]
	Stomach D2%	4.5 [0.0, 15.2]	1.3 [0.0, 3.1]	1.9 [0.0, 3.8]	0.7 [0.0, 2.4]

RESULTS

Six patients with pancreatic (n = 3) and liver (n = 3) cancer were included, prescribed of 25/30/5 fxs for pancreas and 5 fxs for all liver patients.

A first patient-specific, delivery-accurate evaluation of full (respiratory + GI motion) abdominal motion interplay effect on PBS, at spot time resolution.

The framework produces distribution-aware metrics (Δ and dose range) that directly inform motion-robust planning and evaluation:

- Figure 3 (a pancreas patient, 30 fxs) illustrates the CTV DVHs under full abdominal motion. DVH shows a left-shifted fall-off and a substantially broadened scenario band relative to the static plan for 1-fx. For 30-fx accumulation it recenters and narrows the DVH.
- Figure 4 shows scenario-wise violin plots for the same pancreas patient. Comparing *full versus GI-only motions*, full motion shows larger shifts from static plan and wider dose ranges than GI-only, in all metric (CTV D95%, Duodenum D2%, Stomach D2%, Small-bowel D2%).
- Comparing *1-fx (left half, blue) versus 30-fx (right half, red)* scenario distributions, fractionation narrowing but not eliminating the distributions.
- Figure 5 is a liver case with hypofractionation (5 fxs). Full motion again yields greater dose deviation and ranges than GI-only, while 5-fx partially tightens the distributions.
- Table 2 shows Cohort summaries Δ and dose distributions across all patients. Consistent with the representative cases, overall, interplay is more pronounced in full-motion than GI-only, reflected by larger Δ-deviance and wider distribution widths. Comparing the 1fx and full-tx values, fractionation narrows but not eliminates deviance and spreads.

CONCLUSIONS

Three consistent patterns stand out.

- Full-motion produces larger interplay effects than GI-only: across targets and OARs, the Δ and the spread between extreme scenarios are generally bigger in full-motion than GI-only, indicating full-motion amplifies variability.
- Fractionation reduces, though does not eliminate motion-induced variability: moving from 1fx to full-tx, both the mean deviance Δ and the dose ranges shrink markedly, but residual Δ and spread remain.
- Dosimetric endpoints are mostly disturbed under full motion: full motion shows the largest deviations/ranges for D2% of small bowel and stomach, and more negative Δ for CTV D95% compared with GI-only – suggesting free breathing can both increase OAR hotspots and degrade target coverage more than breath hold.

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