Impact of Interplay Effects In Lung SBRT for Intensity-Modulated Proton Therapy and Spot-Scanning Proton Arc Therapy

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Purpose

- This study assessed the impact of machine-specific delivery sequence in quantifying interplay effects for lung stereotactic body radiotherapy (SBRT) between two proton therapy modalities, intensity-modulated proton therapy (IMPT) and spot-scanning proton arc therapy (SPArc®).

Methods

- We used two published proton therapy system (PTS) delivery sequencemodels in this study:
  - IBA Proteus®ONE
  - IBA Proteus®PLUS.
- Interplay effects were retrospectively evaluated in ten proton lung SBRT patients (4-5 fractions) using 4D dynamic dose accumulation.
- Two-field IMPT and SPArc® treatment delivery were simulated on each PTS.
- We used a single-fraction approach where every fraction of a patient's treatment course is assumed to start on the same breathing phase.
- We evaluated data across ten possible starting phases. Reported dose volume histogram metrics for the GTV, as contoured on the 50% phase image, include:
  - $D_{99\%}$
  - $D_{1\%}$
  - Mean dose
  - Heterogeneity index (HI)
  - Quality of coverage (QC).
  - These are given as percent change from the planned distribution.
- We also reported estimated total delivery time and beam-on time.

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Table 1. Statistical summary table. Values are presented as: **mean** ± std. dev. [minimum – maximum]. Statistics are averaged first over all ten possible single-fraction simulations for each patient and subsequently summarized across patients.

Metric		IMPT		SPArc®	
		Proteus®One	Proteus®Plus	Proteus®One	Proteus®Plus
Change from Planned Distribution (%)	$D_{99\%}$	**-2.4** ± 1.8 [-6.4—0.1]	**-4.0** ± 2.3 [-8.0—0.2]	**-2.7** ± 2.1 [-7.1—0.3]	**-2.7** ± 1.8 [-6.4—0.6]
	$D_{1\%}$	**2.4** ± 1.8 [0.6–6.9]	**4.2** ± 2.8 [0.6–11.2]	**2.1** ± 2.4 [-0.3–7.4]	**2.1** ± 2.2 [0.2–7.1]
	Mean Dose	**-0.1** ± 0.2 [-0.3–0.3]	**-0.1** ± 0.2 [-0.3–0.3]	**-0.3** ± 0.6 [-1.8–0.5]	**-0.3** ± 0.6 [-1.8–0.5]
	HI	**2.6** ± 2.3 [0.5–8.0]	**4.7** ± 3.6 [0.2–13.5]	**2.9** ± 2.7 [-0.6–8.7]	**3.0** ± 2.5 [0.3–8.6]
	QC	**-3.5** ± 2.6 [-9.4–0.2]	**-5.2** ± 2.7 [-9.9—0.3]	**-3.8** ± 4.3 [-13.1–0.6]	**-4.0** ± 4.3 [-13.5–0.1]
Total Time (seconds)		**59.8** ± 17.4 [28.8–85.6]	**37.1** ± 10.3 [17.6–54.8]	**200.3** ± 49.4 [109.8–275.6]	**98.7** ± 22.0 [62.7–131.5]
Beam-On Time (seconds)		**38.3** ± 12.5 [16.8–52.6]	**11.6** ± 3.5 [5.3–15.8]	**83.5** ± 22.4 [49.2–116.0]	**13.4** ± 4.6 [5.1–20.7]

Figure 1. Violin plots showing the distribution of change in A) $D_{99\%}$ and B) $D_{1\%}$ for each patient across their ten single-fraction simulations as compared with the original planned dose distribution. Black circular markers indicate each single-fraction result and the distribution of results is displayed as a kernel density estimate. The semi-transparent, dashed, black line indicates 0% change.

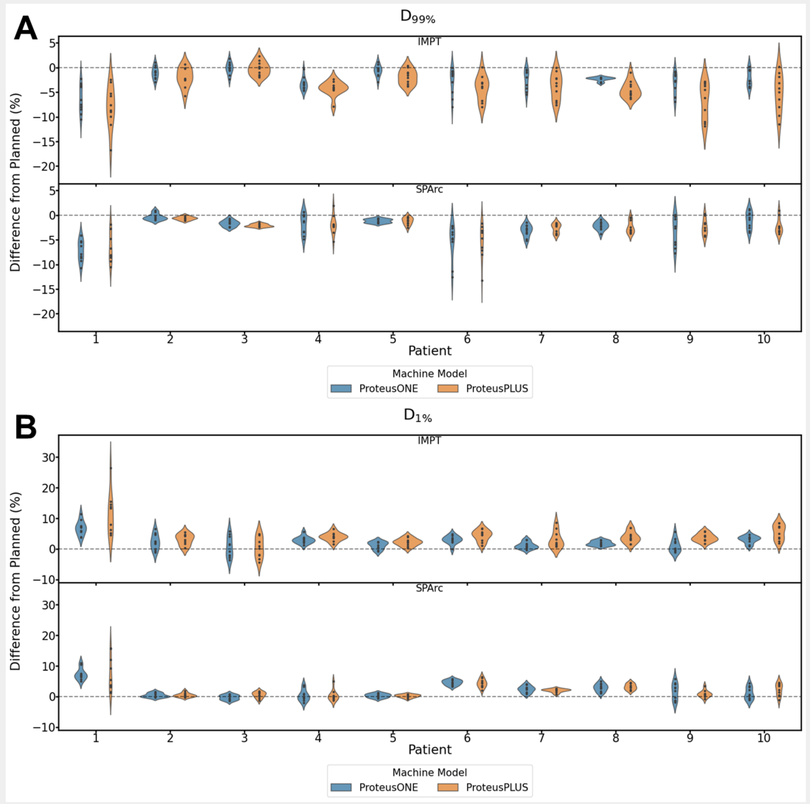


Figure 2. Box plots indicating the estimated A) total delivery time and B) beam-on time in seconds.

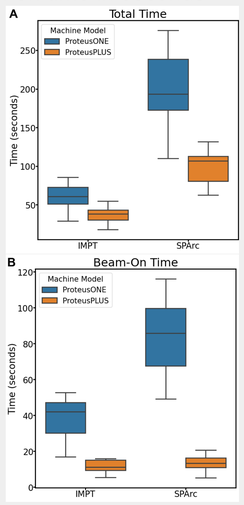
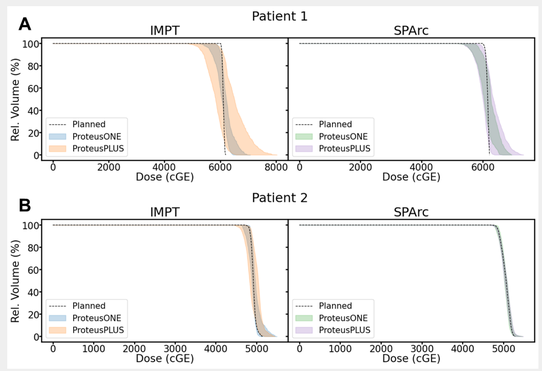


Figure 3. Example DVHs for two patients. Dashed curves indicate the planned DVH, shaded areas indicate the range of single-fraction DVHs.



Results

- Averaging across all possible single-fraction dose distributions and all patients (see Table 1) for $IMPT_{ProteusONE}$/$IMPT_{ProteusPLUS}$/$SPArc_{ProteusONE}$/$SPArc_{ProteusPLUS}$:
  - $D_{99\%}$ decreased 2.4%/4.0%/2.7%/2.7%
  - $D_{1\%}$ increased 2.4%/4.2%/2.1%/2.1%.
  - Mean dose decreased by 0.1%/0.1%/0.3%/0.3%.
  - HI increased 2.6%/4.7%/2.9%/3.0%.
  - QC decreased 3.5%/5.2%/3.8%/4.0%.
  - Average total delivery times were 59.8/37.1/200.3/98.7 seconds.
  - Beam-on times were 38.3/11.6/83.5/13.4 seconds.

Conclusion

- Synchrocyclotron-based Proteus®ONE treatment delivery was more robust to interplay effects than cyclotron-based Proteus®PLUS, likely due to the burst delivery mechanism, allowing time-average smoothing of the delivered dose distribution. The disparity between the two PTS is reduced in SPArc® plans, where delivery is spread over the arc trajectory. The magnitude of the decrease in $D_{99\%}$ and QC of the target and the increase in HI is larger for both SPArc® plans than for IMPT plans. Thus, interplay effect evaluation is critical for the implementation of the proton arc modality.