Preliminary Monte Carlo Benchmarking of the First U.S. Carbon TPS: Range, Voxel-Wise Differences, and Microdosimetry

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ABSTRACT

We report preliminary validation results for the first carbon treatment planning system (TPS) in the United States using an independent Monte Carlo reference.

METHODS

Gamma pass rates and integral-dose agreement can remain high even when disagreement is spatially structured (e.g., concentrated in distal fall-off or near high-Z interfaces). VWD is designed to highlight localized disagreement patterns while retaining a clear depth association.

$VWD_i = \frac{\varepsilon_i^{TPS} - \varepsilon_i^{Ref}}{\sum_{j \in slab(z)} \varepsilon_j^{Ref}}$, where ε_i^{TPS} and ε_i^{Ref} are the voxel energy depositions from the TPS engine and the independent reference, and $\sum_{j \in slab(z)} \varepsilon_j^{Ref}$ denotes the total reference energy deposition within the entire axial slab at Bragg peak depth. This normalization yields a dimensionless "relative contribution error" that supports comparisons across depths and materials and helps avoid over-weighting isolated low-dose voxels

To make VWD actionable for commissioning decisions, maxima are reported separately for three clinically interpretable depth regions: (1) Proximal plateau (P), (2) Bragg-peak region (B) defined as proximal 80% to R80, and (3) Distal tail (D) beyond R80.

RESULTS

Integral dose differences and VWD differences were reported in Table1. Range and LETd differences were reported in Figure 1. Figure 2 shows two examples of the depth physical dose, RBE, RBE-weighted dose, and microdosimetric result (yD values) comparison for uniform phantom of dense oxygen and dense calcium.

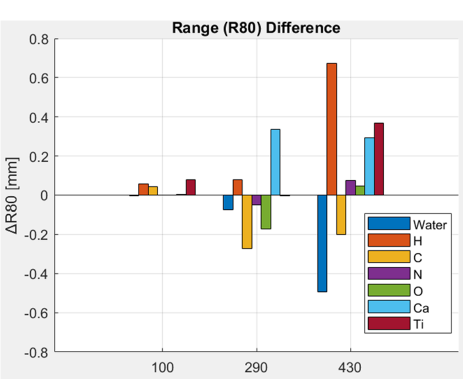

Figure 1. R80 differences.

Table 1. for each material and beam energy, the integral dose difference (ΔIntDose) and the maximum slab-normalized VWD in three depth regions (P: proximal plateau; B: Bragg-peak region from proximal 80% to R80; D: distal tail). This regional decomposition helps distinguish (i) low-level baseline disagreement in the plateau from (ii) high-gradient sensitivity near the Bragg peak and distal tail.

Material	E [MeV]	ΔIntDose [%]	VWDmax_P [%]	VWDmax_B [%]	VWDmax_D [%]
water	100	-0.36	0.07	0.09	0.07
	290	-0.97	0.08	1.33	1.25
	430	-3.14	0.16	0.38	0.11
hydrogen	100	-0.73	0.16	0.82	0.16
	290	-1.85	0.24	1.73	0.47
	430	-3.50	0.30	1.03	0.32
carbon	100	-0.34	0.08	0.52	0.08
	290	-1.19	0.17	0.92	2.10
	430	-2.63	0.31	0.71	0.48
nitrogen	100	-0.23	0.06	0.12	0.10
	290	-0.56	0.09	0.41	0.11
	430	-2.83	0.19	0.30	0.08
oxygen	100	-0.18	0.07	0.18	0.06
	290	-0.42	0.10	0.59	0.90
	430	-2.05	0.19	0.42	0.15
calcium	100	-0.07	0.08	1.06	0.03
	290	-1.04	0.11	0.99	0.05
	430	-2.85	0.16	0.33	0.07
titanium	100	-0.18	0.04	0.85	0.15
	290	-1.93	0.24	0.79	0.15
	430	-4.33	0.42	1.63	0.26

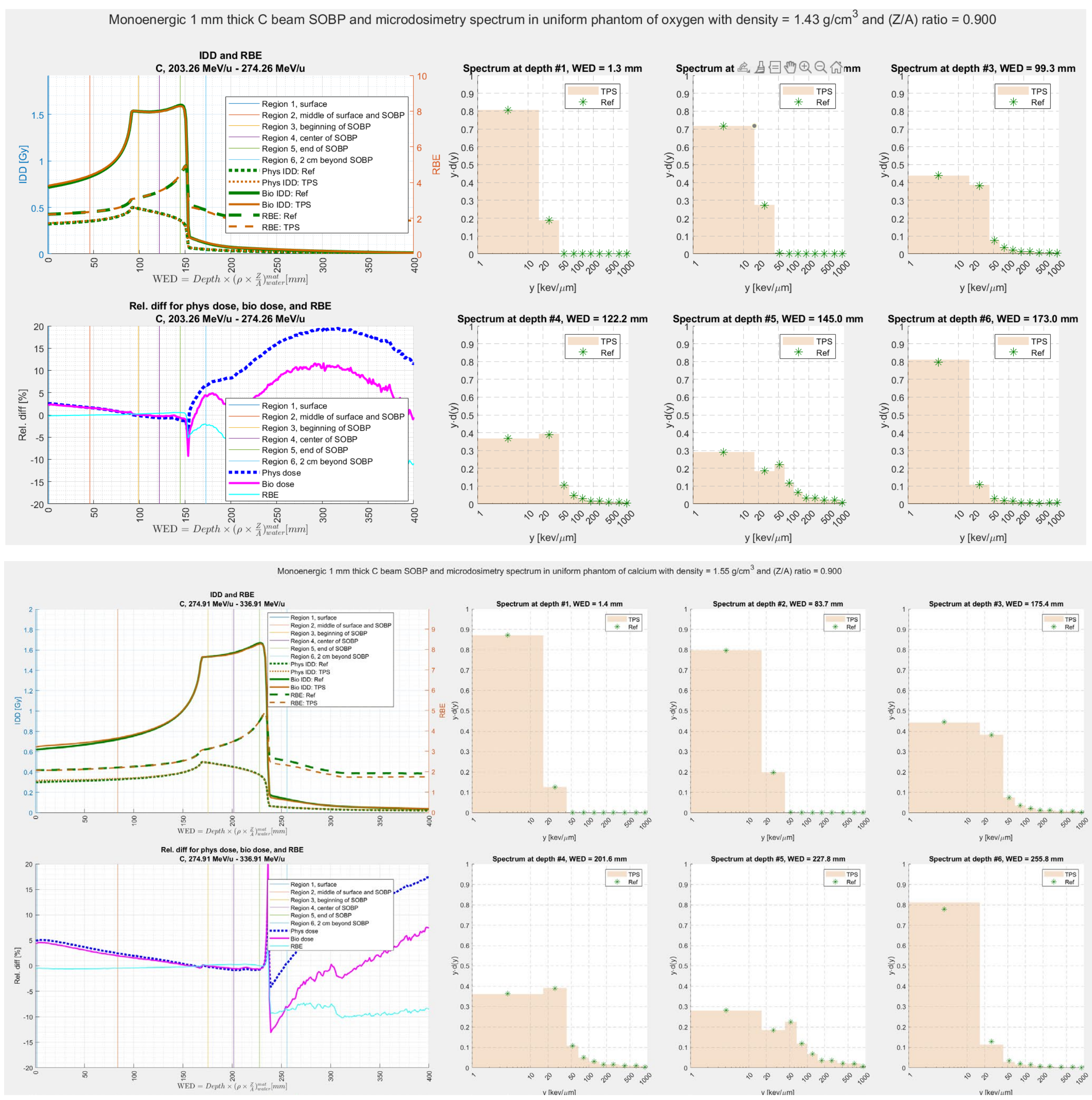

Figure 2. Normalized microdosimetric spectra at six SOBP depths (entrance to distal tail) with distal-tail inset for uniform phantoms of dense oxygen and dense calcium.