Upright Image-Guided Proton Therapy for Pediatric CNS, Peri-Cranial, and Ocular Tumors: Early Clinical Outcomes and Medical Physics Experience

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Introduction

Clinical challenge: Pediatric CNS, pericranial, and ocular tumors lie beside developing neural, endocrine, auditory, and visual structures, making durable control and late-effect reduction equally important.

Why protons: The Bragg peak limits exit dose and integral exposure, an important advantage for children with long expected survival.

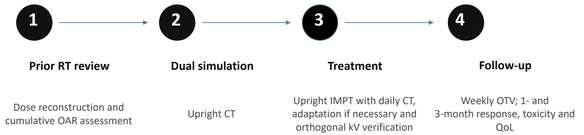
Access problem: Conventional rotating gantries are large, complex, and expensive. Fixed-beam treatment with upright robotic positioning offers a compact alternative.

Evidence gap: Pediatric experience is scarce for CSI, ocular gating, re-irradiation, very young children, and monitored anesthesia care.

Objective: Assess feasibility, setup reproducibility, prescription-compliant dosimetry, acute toxicity, and early local control with gantry-less upright IGPT.

Population	Intervention	Study Endpoints
10 patients	**Upright IMPT**	**3-month LC and Adverse Events (CTCAE V5)**
Pediatric CNS, pericranial, and ocular tumors	Fixed horizontal beamline, robotic chair, daily image guidance	Setup reproducibility, dosimetry comparison, QoL using QLQ-LC13

Study Design



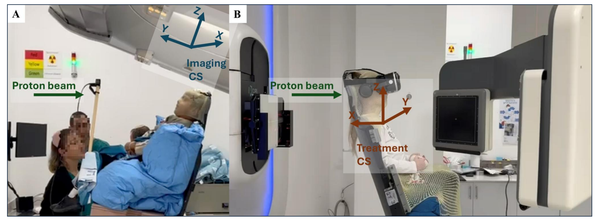


Figure 1. Upright pediatric positioning at imaging and treatment isocenters; ocular gating and CSI setup are shown.

Patient Cohort

Patient #	Performance Status	Age	Histology	Irradiated Area	Prescribed Dose, Gy(RBE)	Dose per Fraction, Gy(RBE)
1	1	4	Retinoblastoma	Eye	45	1.8
2	1	18	Rhabdomyosarcoma	Oropharynx	41.4/18	1.8
3	0	18	Chordoma	Clivus	70	2
4	1	4	Relapsed Neuroblastoma	CSI-Brainboost	18/30.6	1.8
5	0	16	Craniopharyngioma	Suprasellar region	54	1.8
6	0	2	Craniopharyngioma	Suprasellar region	52.2	1.8
7	0	7	Medulloblastoma	Posterior fossa resection bed	23.4/54	1.8
8	0	9	Craniopharyngioma	Suprasellar region	54	1.8
9	1	10	Medulloblastoma	Posterior fossa resection bed	36/54	1.8
10	1	5	Primary CNS: Neuroblastoma	CSI-Brainboost	23.4/54	1.8

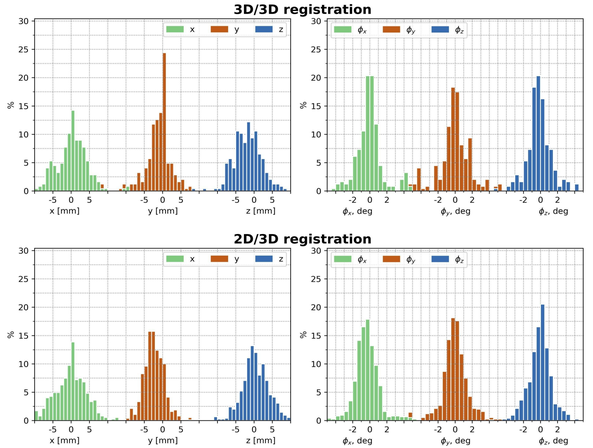


Figure 2. Distribution of translational and rotational corrections for pre-irradiation 3D/3D and intra-irradiation 2D/3D registration.

Methods and Materials

Design: Single-institution retrospective observational study using prospectively collected data from 10 patients ≤18 years treated January 2024–December 2025.

System: Fixed horizontal pencil-beam scanning with a robotic 6-DoF chair, dedicated upright immobilization, and a vertical CT scanner angled 20° from room vertical.

Planning: Upright CT simulation, RayStation 2023B, Monte Carlo dose calculation, robust optimization, and DVH review of CTV and serial OAR metrics.

Image guidance: Daily low-dose 3D/3D CT registration before irradiation and orthogonal kV 2D/3D verification at treatment isocenter; 246 and 750 registrations were analyzed.

Results

Completion: All 10 patients completed upright IGPT without interruption, re-immobilization, manual repositioning, or anesthesia-related complications.

3D/3D setup: Mean translations were −0.1±4.8, −1.1±3.5, and −1.8±3.7 mm; mean rotations were 0.0±1.9°, −0.2±2.2°, and −0.2±1.4°.

2D/3D setup: Mean translations were −0.4±4.6, −2.3±3.0, and 0.5±4.0 mm; mean rotations remained within ±2°.

Workflow evidence: 246 volumetric and 750 planar registrations; no positioning-related treatment interruption.

Dosimetry: CTV D95% followed prescription intent across focal and multi-phase plans; serial OAR doses remained constrained relative to prescription.

Early outcomes: Local control was 100% at ~3 months: 5 complete responses, 1 partial response, and 4 stable disease; one grade ≥3 acute toxicity occurred.

Metric	Metric	#1	#2**	#3	#4**	#5	#6	#7**	#8	#9**	#10**
CTV	$D_{95\%}$, GY_{RBE}	43.52	40.62	53.90	17.29	53.55	53.10	22.46	50.31	35.64	23.33
	$D_{2\%}$, GY_{RBE}	47.22	43.32	76.47	21.95	56.22	55.99	24.60	55.78	37.28	24.28
Brainstem	D_{max}, GY_{RBE}	NA*	9.94	70.23	18.93	39.83	55.78	NA*	48.14	37.82	24.39
Spinal cord	D_{max}, GY_{RBE}	NA*	15.7	27.43	NA*	0.00	NA*	NA*	NA*	NA*	NA*
Optic chiasm	D_{max}, GY_{RBE}	0.37	1.42	54.73	18.92	54.77	53.77	NA*	52.60	37.55	24.09
Optic nerve L	D_{max}, GY_{RBE}	NA*	2.38	47.13	NA	54.51	NA*	NA*	43.08	37.58	NA*
Optic nerve R	D_{max}, GY_{RBE}	45.67	1.21	47.29	NA	54.82	NA*	NA*	45.68	37.66	NA*
Lens L	D_{max}, GY_{RBE}	NA*	0.13	NA	1.53	0.00	0.02	13.00	0.00	NA*	NA*
Lens R	D_{max}, GY_{RBE}	31.74	0.01	NA	1.91	0.00	0.10	15.80	0.00	NA*	NA*
Cochlea L	D_{mean}, GY_{RBE}	NA*	0.26	29.60	13.70	NA*	NA*	22.12	0.20	35.76	21.93
Cochlea R	D_{mean}, GY_{RBE}	NA*	29.29	29.66	13.26	NA*	NA*	18.58	0.23	36.16	23.25
Brain	D_{mean}, GY_{RBE}	0.14	0.53	6.83	18.37	1.56	7.67	23.95	2.56	35.24	23.82

*NA indicates structure not contoured/applicable in that plan.
**For patients with multi-phase treatments, metrics were shown for the 1st phase

Early Outcomes: Local Control and AEs

100%	5 CR	1 PR	4 SD
local control within the re-irradiated volume at 3 months	complete metabolic responses on PET/CT using PERCIST criteria	partial metabolic responses on PET/CT using PERCIST criteria	stable disease on CT, PET not available

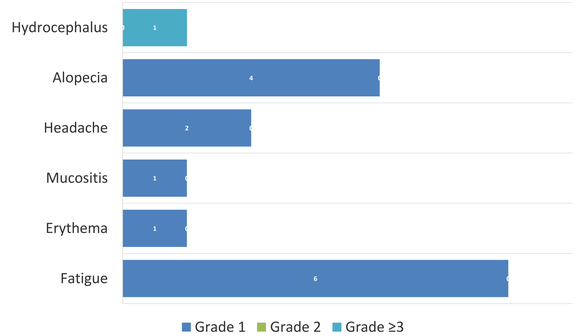


Figure 3. CTCAE v5.0 AEs (n=10)

Discussion

Interpretation: Millimeter- and degree-scale setup corrections support high-precision PBS in complex pediatric indications, including CSI, ocular gating, re-irradiation, and anesthesia-assisted care.

Clinical meaning: A fixed-beam upright workflow can retain proton-level targeting while reducing dependence on a rotating gantry.

Limitations: The cohort is small and follow-up is short; late tumor control and neurocognitive, endocrine, auditory, visual, growth, and second-cancer outcomes remain under study.

Conclusions

Take-home message: Upright gantry-less IGPT delivered uninterrupted treatment, reproducible positioning, prescription-consistent dosimetry, and favorable early control.

Next step: Prospective expansion and longer follow-up are needed.

Contact

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