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Under the Patronage and Honoring of HRH Prince Saud bin Nayef bin Abdulaziz, Governor of the Eastern Province: Saudi Cancer Foundation Successfully Launches "AlSharqia Wardiyah 18"

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Review Article

Craniospinal Irradiation (CSI) Techniques: A Systematic Review of Comparative Dosimetric Outcomes, Organ–at–Risk Sparing, and Treatment Efficiency

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Abstract:

Background: Craniospinal irradiation (CSI) is technically demanding because the treatment volume extends along the entire neuraxis. Adequate coverage has to be maintained over a long target while limiting junction–related uncertainties and unnecessary irradiation of normal tissues. Although several techniques are now used for CSI, their relative dosimetric strengths and limitations are not fully established.

Methods: We performed a systematic review based on a registered PROSPERO protocol. PubMed/MEDLINE, Embase, and Scopus were searched for comparative, patient–based CSI studies published between January 2000 and February 2026. The review focused on target coverage, conformity index (CI), homogeneity index (HI), junction characteristics, organ–at–risk (OAR) doses, integral dose and low–dose exposure, monitor units (MU), and beam–on time (BoT). Risk of bias was assessed using domains adapted for comparative dosimetric studies.

Results: Twenty–two (22) comparative studies were included. Contemporary IMRT, VMAT, and helical techniques generally achieved at least 95% target coverage. In a multicentre comparison, PTV V95 ranged from 97.8% to 99.8%, while CI improved from 0.6 with 3DCRT to 0.9 with VMAT. Proton therapy produced substantially lower low–dose exposure; esophageal V20 was 3.89% versus 65.87% and heart V20 was 0.03% versus 2.80% compared with photon therapy. In the comparison of TrueBeam 6–MV FFF, Halcyon 6–MV FFF, and IMPT, CTV D95 was 2367, 2375, and 2360 cGy, respectively, while total normal–tissue V1 Gy was 57.3%, 55.8%, and 17.8%. Mean heart dose was 291, 378, and 27 cGy, and mean lung dose was 505, 481, and 160 cGy, respectively. Halcyon reduced beam–on time to 6.1 minutes compared with 12.1 minutes for TrueBeam, while IMPT required 4.2 minutes.

Conclusion: Modern photon techniques can achieve reliable CSI coverage while making junction management and treatment delivery more practical. Proton therapy offers a clear advantage in reducing low–dose and integral–dose exposure. In practice, the choice of technique should take into account the patient's anatomy and age, the treatment goal, available equipment, and the resources and expertise of the treating centre.

Key Words: Craniospinal irradiation; Dosimetric comparison; Photon radiotherapy; Proton therapy; Organ–at–risk sparing

Introduction

Craniospinal irradiation (CSI) remains an important part of treatment for tumours with a high risk of leptomeningeal spread, particularly medulloblastoma and other embryonal central nervous system tumours. Unlike irradiation of a single anatomical site, CSI covers both the brain and spinal neuraxis over a considerable longitudinal

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distance [1]. Achieving a uniform dose throughout this volume while protecting radiosensitive organs makes CSI one of the more demanding radiotherapy techniques [2].

Traditionally, CSI was delivered with opposed lateral cranial fields and posterior spinal fields, with junctions between adjacent fields. Feathering and field shifts were used to distribute dose variation and reduce hot or cold spots. However, these methods are affected by setup errors, field matching, and changes in patient geometry during the treatment course [3]. Helical tomotherapy offered a different approach by providing continuous longitudinal delivery and avoiding conventional junction lines. Planning studies subsequently showed favourable OAR distributions, although this could be accompanied by a modest increase in whole–body integral dose [4].

The introduction of IMRT and VMAT made it easier to shape the dose around the craniospinal target and reduce irradiation of critical structures. Several comparative studies have reported better conformity and homogeneity, with similar or improved target coverage, compared with conventional 3DCRT. The trade–off is that highly modulated photon plans can increase monitor units and expose larger volumes of normal tissue to low doses [5,6]. More recent VMAT techniques use overlapping isocentres, automated junction management, and flattening–filter–free beams [7]. Comparisons of TrueBeam and Halcyon 6–MV FFF platforms suggest that similar target coverage can be achieved with shorter delivery times on ring–gantry systems [8].

Proton therapy, especially pencil–beam scanning and intensity–modulated proton therapy (IMPT), is attractive for CSI because there is no exit dose beyond the Bragg peak [9]. Planning studies have therefore shown lower integral and low–dose exposure to several organs, including the heart, lungs, liver, thyroid, and kidneys, without a major loss of target coverage [10]. Proton CSI is nevertheless more resource–intensive, and the plan can be affected by range uncertainty and changes in anatomy. Thus, a dosimetric advantage alone does not determine the best treatment for every patient; age, anatomy, disease extent, available technology, and institutional experience also need to be considered.

A large number of individual planning studies have been published, but they differ considerably in treatment technique, target definition, CI and HI calculation, OAR endpoints, junction strategy, and treatment–efficiency measures. Newer approaches such as FFF VMAT, Halcyon–based delivery, and contemporary proton planning have also appeared more recently. We therefore undertook this systematic review to compare current photon and proton CSI techniques, with particular attention to target coverage, conformity, homogeneity, junction dose, OAR sparing, integral and low–dose exposure, and treatment efficiency.

Methods

This systematic review followed a prospectively registered PROSPERO protocol (CRD420261333696) and was reported in accordance with PRISMA recommendations. The review was designed to identify comparative patient–based studies that evaluated the dosimetric performance of different CSI techniques. The main outcomes of interest were target coverage, conformity, homogeneity, OAR sparing, low–dose bath, junction management, and treatment efficiency.

PubMed/MEDLINE, Embase, Scopus, and the Cochrane Central Register of Controlled Trials (CENTRAL) were searched for English–language studies published from January 2000 through February 2026. The search combined controlled vocabulary and free–text terms covering craniospinal irradiation and the major delivery techniques, including CSI, IMRT, VMAT, 3DCRT, helical tomotherapy, proton therapy, IMPT, and flattening–filter–free delivery. Reference lists of eligible papers and relevant systematic reviews were also screened for additional studies.

Studies were eligible when patients receiving CSI were included and at least two radiotherapy techniques were directly compared using patient–specific plans. Eligible techniques included 3DCRT, field–in–field methods, IMRT, VMAT, helical tomotherapy, proton therapy, IMPT, and hybrid approaches. Both paediatric and adult populations were considered, regardless of the underlying CNS malignancy. Retrospective, prospective, and randomized comparative studies were eligible. Phantom–only or simulation–only studies, noncomparative reports, clinical studies without a dosimetric comparison, reviews, editorials, letters, conference abstracts without adequate full–text data, duplicate publications, and studies excluded during the predefined screening process were not included (Figure 1).

Screening was performed in two stages, followed by standardized data extraction using a predefined data sheet. We recorded publication year, country, study design, sample size, disease, prescription and fractionation, treatment position, planning system, beam energy, technique, number of isocentres, and junction strategy. Dosimetric data included target D98, D95, D50, D2, Dmax, Dmean, V95, V100, CI, HI, junction dose variation, and other reported dose–volume parameters. For OARs, mean, maximum, and volume–based doses were collected when available. Integral dose, total normal–tissue volume, low–dose volumes, MU, beam–

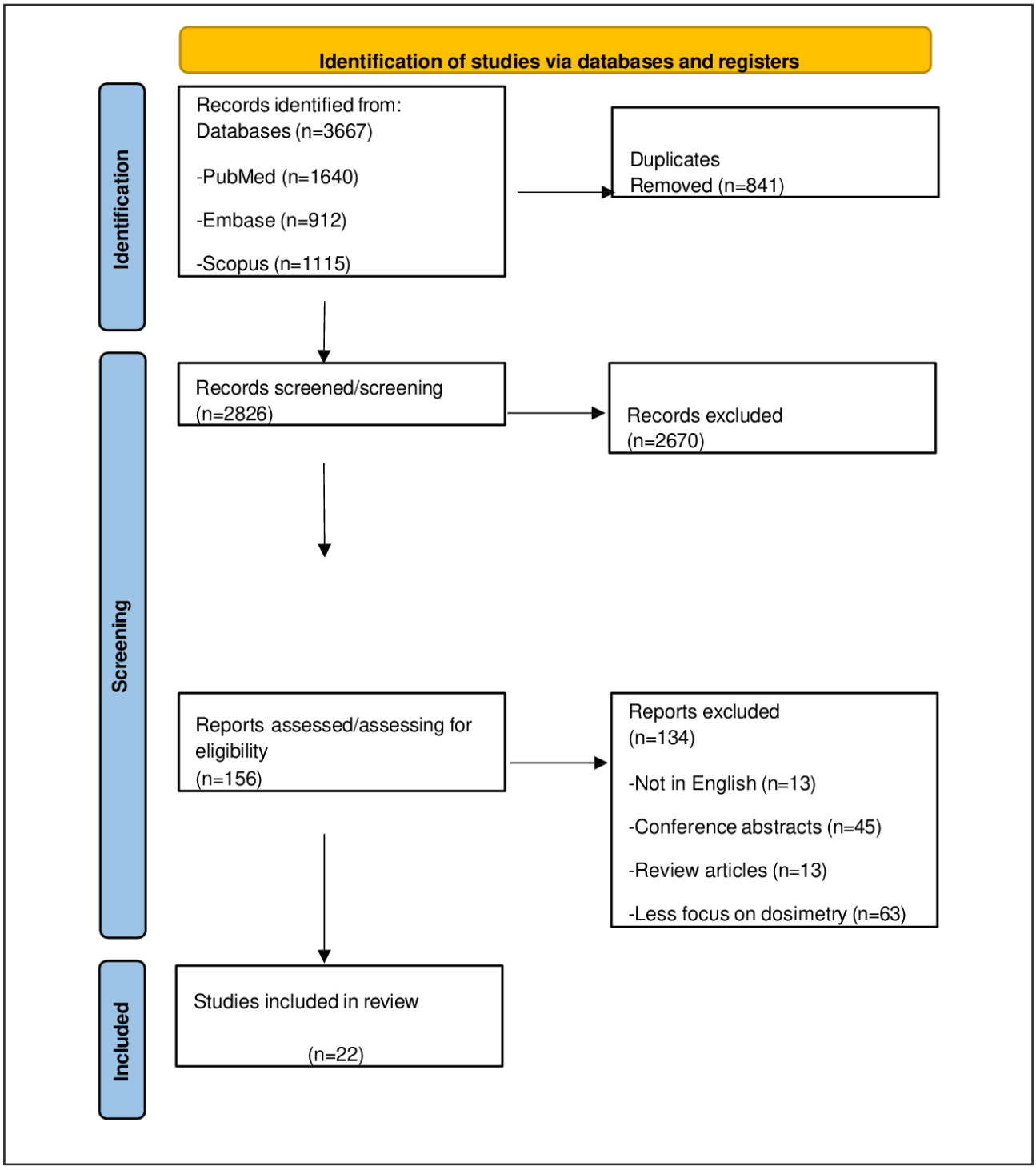


Figure 1. PRISMA Flow Diagram of the Study Collection

Abbreviations:

CSI– Craniospinal irradiation
3DCRT– Three–dimensional conformal radiotherapy
IMRT– Intensity–modulated radiotherapy
VMAT– Volumetric–modulated arc therapy
HT– Helical tomotherapy
IMPT– Intensity–modulated proton therapy
PSPT– Passive–scattered proton therapy
CI– Conformity index
HI– Homogeneity index
FIF– Field–in–field
FFF– Flattening–filter–free
MU– Monitor units
OAR– Organ at risk
AAA– Anisotropic analytical algorithm
PBS– Pencil–beam scanning
PTV– Planning target volume
TPS– Treatment–planning system
VBS– Vertebral–body sparing
WVB– Whole–vertebral–body

on time, total treatment time, and QA results were also recorded where reported.

Methodological quality was assessed using domains adapted to comparative dosimetric studies, including patient selection, comparability of treatment plans, planning methods, completeness of reported outcomes, and other potential sources of bias. Quantitative synthesis was considered only when studies reported sufficiently comparable endpoints with appropriate measures of dispersion. Because the studies varied substantially in patient populations, prescriptions, planning techniques, CI/HI definitions, OAR constraints, and reporting formats, most results were summarized narratively. Numerical findings were presented descriptively when pooling was not appropriate, and missing values were not imputed.

Results

The final evidence base included comparative dosimetric studies covering 3DCRT, IMRT, VMAT, helical techniques, and proton therapy (Table 1). Across the studies, modern techniques generally maintained good target coverage (Table 2). The main differences between techniques were seen in conformity, homogeneity, junction control, normal–tissue dose, and treatment efficiency (Table 3). Differences in dose prescriptions, planning systems, reported indices, and study design made direct quantitative pooling difficult.

Conventional 3DCRT could provide acceptable CSI plans when the junctions were carefully planned. Sharma et al. reported V95 values of 99.40% and 99.33% for two– and three–isocentre 3DCRT, respectively; CI was 0.57±0.08 and 0.58±0.07, while DHI was 0.91±0.02 and 0.89±0.03. With supine positioning, V107 decreased from 243.50 to 141.83 cc and the minimum PTV dose increased from 14.49 to 29.68 Gy [23]. Athiyaman et al. achieved 95% PTV coverage with maximum hotspots of 110–111%. Their junction measurements showed less than 3% dose deviation with exact matching, whereas a 2–mm overlap and a 2–mm gap produced doses of 122% and 66%, respectively [14]. Prabhakar et al. reported a mean junction variation of about 3%, with median whole–cord doses of 31.4–32.6 Gy [27].

In the photon–versus–electron comparison, photon plans gave slightly more favourable spinal dose uniformity. Chojnacka et al. reported a spinal PTV dose SD of 3.3% for both techniques, while CTV SD was 2.5% with photons and 2.9% with electrons. Forward–planned segmented photon fields reduced PTV and CTV SD further, to 2.9% and 2.2%, respectively. Photon treatment resulted in lower thyroid, lung, and kidney doses, whereas electrons had lower heart and liver doses [13].

Among the intensity–modulated photon techniques, VMAT generally maintained coverage while offering better conformity and faster delivery. Al–Wassia et al. found similar PTV coverage with VMAT and IMRT, with a small advantage for VMAT in conformity and homogeneity. VMAT used fewer monitor units and required less treatment time, but it exposed a larger volume of normal tissue to low doses [30]. In the study by Thakur et al., V95 was 99.51% versus 99.99%, CI was 0.86±0.063 versus 0.85±0.045, and HI was 0.095±0.003 versus 0.099±0.004 for avoidance–sector and partial–arc VMAT, respectively. Lung mean dose was 8.84 versus 10.62 Gy and lung V20 was 2.45% versus 9.00%; MU values were 1340 and 1377 [21].

Helical and other continuous–delivery approaches produced comparable plan quality while avoiding a conventional junction line. Bedford et al. reported normalized objective values of 100±13% for separate arcs, 104.0±14.8% for continuous delivery, 102.3±13.5% for ALT10, and 101.5±15.8% for ALT15. ALT10 treatment times ranged from 14.1 to 23.8 minutes, and gamma pass rates were 94.9–99.2% [31].

The clearest and most consistent reduction in normal–tissue dose was seen with proton therapy. Yoon et al. reported CI values of 1.62±0.21, 1.25±0.07, and 1.23±0.07 for 3DCRT, tomotherapy, and proton therapy, respectively; the corresponding HI values were 28.7±5.9, 16.8±5.1, and 12.8±2.3 [26]. Howell et al. found similar V23.4 coverage with photons and protons (99.36% versus 99.23%), but V25 was much lower with proton therapy (1.72% versus 12.01%). Overall, proton therapy reduced 20 of 24 evaluated OAR DVH parameters, including esophageal V20 (3.89% versus 65.87%) and heart V20 (0.03% versus 2.80%) [29].

More recent planning work has focused on reducing doses to selected normal tissues without sacrificing target coverage. In the study by Perlow et al., vertebral–body mean dose fell from 91.7% to 61.5% of the prescription, while mean doses to the small bowel and esophagus decreased from 720.3 to 386.0 cGy and from 1741.1 to 570.4 cGy, respectively, with vertebral–body–sparing VMAT [19].

In the comparison by Buranavanitvong et al., total normal–tissue V1 Gy was 57.3%, 55.8%, and 17.8% with TrueBeam, Halcyon, and IMPT, respectively. Beam–on time was 12.1, 6.1, and 4.2 minutes. Mean heart dose was 291, 378, and 27 cGy, and mean lung dose was 505, 481, and 160 cGy, respectively [32]. These results illustrate the different strengths of the techniques: modern photon platforms can deliver CSI efficiently, whereas IMPT markedly reduces the volume of normal tissue receiving low doses (Table 4).

S.No	Study	N	Technique(s)	Prescription	Target coverage	CI	HI	Junction / planning feature
1	Panandiker et al., 2007 [11]	12 IMRT + 16 conventional comparator	Spinal IMRT + lateral cranial fields	~36 Gy	NR	NR	NR	Spinal IMRT gradient/junction modulation
2	Sharma et al., 2009 [12]	4	3DCRT vs IMRT–LA vs HT	35 Gy/21 fx	Brain/spine coverage improved with IMRT/HT	Brain: 0.93, 0.93, 0.96; spine: 0.84, 0.91, 0.96	Brain/spine: 0.93/0.84, 0.93/0.91, 0.96/0.96	HT eliminates conventional junction problem
3	Chojnacka et al., 2010 [13]	11; 9 comparative plans	Photon vs electron spinal irradiation	25.05–35.07 Gy/15–21 fx + boost 54–55 Gy	NR	NR	Photon SD ~2.2–2.9% vs electron ~2.9–3.3%	Two–isocenter photon + oblique cervical fields + feathering
4	Athiyaman et al., 2014 [14]	6	3DCRT + FiF + Eclipse field alignment	36 Gy/20 fx	95% PTV	NR	mHI D5/Dp 1.034; (D5–D95)/Dp 0.10	Two isocenters; automated junction matching
5	Seravalli et al., 2018 [15]	1 common dataset / 15 centers	3DCRT vs IMRT vs VMAT vs HT vs PBS	36 Gy/20 fx	PTV V95: 97.8, 98.3, 98.8, 98.2, 99.8%	0.6, 0.7, 0.9, 0.8, 0.8	~0.1 for modern techniques; ~0.2 spine with 3DCRT	Three centers per technique; real–world multicentre planning
6	Rao et al., 2022 [16]	3	RapidArc VMAT	36 Gy/1.8 Gy/fx; boost 54 Gy	NR	0.95 (0.91–1.00)	0.11 (0.06–0.15)	Multi–isocenter VMAT
7	Barsing et al., 2022 [17]	NR	Halcyon VMAT, 6 MV FFF	36 Gy/20 fx + 18 Gy/9–fx boost	CI >0.95	>0.95	≤0.10	Multi–isocenter arcs + auto–feathering; no junction shift
8	Patel et al., 2024 [18]	12	Complete VMAT vs hybrid conventional brain + VMAT spine	36 Gy/20 fx	95% PTV coverage in both	NR	NR	2.5–3.5 cm brain–spine overlap + base–plan optimization
9	Perlow et al., 2024 [19]	10	Standard VMAT/IMRT vs vertebral–body–sparing VMAT	30 Gy/10 fx	Maintained; quantitative D95 not reported	NR	NR	3 isocenters; robust optimization + autofeathering; 5–10–cm overlap
10	Devi et al., 2025 [20]	20	HIMRT vs H3DCRT vs VMAT	36 Gy/20 fx + 18–Gy boost/10 fx	Brain V95 98.70/99.42/97.69%; spine 99.98/99.95/99.83%	Brain 1.02/1.04/1.11; spine 1.00/1.01/1.07	Brain 0.73/0.39/0.43; spine 0.07/0.06/0.23	HIMRT has no junction; helical treatment up to 135 cm
11	Thakur et al., 2024 [21]	8	VMAT avoidance–sector vs partial–arc VMAT	36 Gy/20 fx	V95 99.51 vs 99.99%; V107 0.73 vs 0.74%	0.86 ±0.063 vs 0.85 ±0.045	0.095 ±0.003 vs 0.099 ±0.004	2–4–cm overlap; multi–isocenter
12	Fukumitsu et al., 2023 [22]	24	PSPT vs IMPT; WVB vs VBS	18–36 Gy(RBE), median 23.4 Gy	IMPT Dmax 103.6 ±0.6%; Dmin 94.9%	0.46 ±0.08 vs 0.48 ±0.08	0.10 ±0.03 vs 0.07 ±0.01	Proton–only comparative study; VBS/WVB

S.No	Study	N	Technique(s)	Prescription	Target coverage	CI	HI	Junction / planning feature
13	Sharma et al., [2022 23]	6; 12 plans	2–isocenter vs 3–isocenter 3DCRT; supine vs prone	36 Gy/20 fx	2–isocenter V95 99.40%; 3–isocenter 99.33%	0.57 ±0.08 vs 0.58 ±0.07	DHI ≈ 0.91 vs 0.89	Feathering every 5 fractions; 1–cm junction shift
14	Smyth et al., 2022 [24]	20	Robust multi–isocenter VMAT	23.4–39.6 Gy/13–22 fx	PTV D99 96.1–97.9%, median 96.5%	NR	NR	±5–mm setup–error robust optimization; 27 scenarios
15	Peterson et al., 2013 [25]	1	Supine 3DCRT + FIF	NR	Qualitatively homogeneous	NR	NR	Perfect match + daily intrafractional feathering; total 2–cm feathering
16	Yoon et al., 2011 [26]	10	3DCRT vs HT vs passive–scattering proton	36 Gy/20 fx	V30 100%; V60 100%; V90 ~99–100%	1.62 ±0.21 / 1.25 ±0.07 / 1.23 ±0.07	28.7 ±5.9 / 16.8 ±5.1 / 12.8 ±2.3	Moving–junction 3DCRT vs seamless HT/proton
17	Prabhakar et al., 2009 [27]	10	Half–beam blocked 3DCRT + FiF	Cranial 36 Gy/20 fx; spine 30 Gy/20 fx + boost	Whole cord 31.4–32.6 Gy	NR	NR	Mean junction variation ~3%
18	Parker et al., 2006 [28]	Technical	Supine CT–based 3DCRT	NR	NR	NR	NR	Asymmetric jaws; junction feathering; supine setup
19	Howell et al., 2012 [29]	18	Photon FIF vs passively scattered proton	23.4 Gy/13 fx	V23.4 99.36 ±1.04 vs 99.23 ±0.88%; V25 12.01 ±9.87 vs 1.72 ±4.01%	0.99 ±0.01 vs 0.99 ±0.009	1.05 ±0.009 vs 1.04 ±0.012	Proton age–dependent target volumes
20	Al–Wassia et al., 2015 [30]	10	VMAT vs IMRT	23.4 Gy/13 fx + boost 55.8 Gy	CNS V95 98.97 ±0.83 vs 99.19 ±0.78%; boost V95 98.77 ±1.12 vs 97.89 ±1.61%	CNS 0.94 ±0.03 vs 0.95 ±0.04; boost 0.80 ±0.08 vs 0.68 ±0.12	CNS 1.09 ±0.02 vs 1.12 ±0.02; boost 1.07 ±0.02 vs 1.10 ±0.01	Two isocenters; 2 full arcs/ isocenter vs 5 beams/ isocenter
21	Bedford et al., 2012 [31]	5	Separate VMAT vs continuous/alternating helical VMAT	23.4 Gy/13 fx	Objective function: SEP 100 ±13, CONT 104.0 ±14.8, ALT5 118.9 ±9.8, ALT10 102.3 ±13.5, ALT15 101.5 ±15.8	NR	NR	Helical couch translation eliminates conventional junction
22	Buranavanitvong 2026 [32]	15	TrueBeam FFF / Halcyon FFF / IMPT	23.4 Gy/13 fx	D95 CTV	0.69 ±0.04, 0.69 ±0.04, 0.74 ±0.05	0.06 ±0.01, 0.05 ±0.01, 0.06 ±0.01	

Table 1. Study characteristics, target dosimetry and planning parameters

S.No	Study	Organ / endpoint	Technique 1	Technique 2	Technique 3 / Proton	Key numerical finding
1	Sharma 2009 [12]	Heart Dmean	17.8 ±2.1 Gy	7.5 ±1.0	5.0 ±1.0	HT lowest
		Thyroid Dmean	30.5 ±2.5	12.2 ±4.8	8.3 ±2.9	HT lowest
		Liver Dmean	7.2 ±1.4	5.3 ±0.6	3.9 ±0.6	HT lowest
		Esophagus Dmean	32.7 ±2.3	18.7 ±1.8	9.1 ±0.3	HT lowest
		L/R lung Dmean	5.3/4.8	5.7/5.2	6.7/6.7	Photon differences less consistent
2	Seravalli 2018 [15]	TNTV V1 Gy	52.6%	66.1%	15.4%	PBS lowest
		TNTV V2 Gy	35.9%	57.2%	14.1%	PBS lowest
		TNTV V5 Gy	22.9%	41.7%	12.2%	PBS lowest
		TNTV V34.2 Gy	5.1%	3.4%	1.3%	Modern photon/PBS lower
		TNTV V36 Gy	3.7%	0.9%	0.4%	Modern techniques lower
		Thyroid Dmean range	—	VMAT 5.6–24.6 Gy	PBS 0.3–10.1 Gy	Large inter–centre variability
3	Patel 2024 [18]	Right lens Dmean	10.23 Gy	5.67 Gy	—	Hybrid ↓44.6%
		Right lens Dmax	12.49 Gy	8.25 Gy	—	Hybrid ↓34.0%
		Left lens Dmean	9.49 Gy	5.48 Gy	—	Hybrid ↓42.3%
		Left lens Dmax	11.96 Gy	8.02 Gy	—	Hybrid ↓32.9%
4	Perlow 2024 [19]	Vertebral–body Dmean	91.7% Rx	61.5% Rx	—	VBS ↓33%
		Small bowel Dmean	720.3 cGy	386.0 cGy	—	↓46%
		Small bowel Dmax	2415.4 cGy	2106.6 cGy	—	↓13%
		Esophagus Dmean	1741.1 cGy	570.4 cGy	—	↓67%
		Esophagus Dmax	2699.8 cGy	1757.0 cGy	—	↓35%
5	Athiyaman 2014 [14]	Right/left eye Dmean	12.03/13.20 Gy	—	—	Conventional technique
		Heart Dmean	14.81 Gy	—	—	—
		R/L lung Dmean	4.96/3.75 Gy	—	—	—
		Liver Dmean	7.37 Gy	—	—	—
		R/L kidney Dmean	4.63/3.96 Gy	—	—	—
		R/L lens Dmean	4.12/4.45 Gy	—	—	—
		Max spinal cord	38.56 ±0.41 Gy	—	—	—
		Max lens	5.16 ±2.7 Gy	—	—	—
6	Thakur 2024 [21]	Heart Dmean	10.42 Gy	9.03 Gy	—	Partial arcs lower, p=.005
		Thyroid Dmean	16.10 Gy	16.37 Gy	—	Avoidance–sector lower, p=.030
		Lung Dmean	8.84 Gy	10.62 Gy	—	Avoidance–sector lower
		Lung V5	69.72%	84.22%	—	↓ with avoidance sectors
		Lung V10	27.48%	42.89%	—	↓
		Lung V20	2.45%	9.00%	—	↓
		R/L kidney Dmean	11.36/11.99 Gy	12.72/12.56 Gy	—	Avoidance–sector lower
7	Yoon 2011 [26]	Esophagus Dmean	34.6 Gy	22.9 Gy	19.4 Gy	PBT lowest
		Stomach Dmean	3.6	4.5	0.6 Gy	PBT lowest
		Liver Dmean	8.0	6.1	0.3 Gy	PBT lowest
		Lung Dmean	4.6	4.0	2.5 Gy	PBT lowest
		Pancreas Dmean	22.9	13.3	0.2 Gy	PBT lowest
		Kidney Dmean	4.3	4.9	2.2 Gy	PBT lowest

S.No	Study	Organ / endpoint	Technique 1	Technique 2	Technique 3 / Proton	Key numerical finding
8	Howell 2012 [29]	Esophagus V20	65.87%	—	3.89%	Proton significantly lower
		Esophagus V15	96.68%	—	8.73%	Proton significantly lower
		Esophagus V10	98.09%	—	14.76%	Proton significantly lower
		Esophagus V5	99.61%	—	24.67%	Proton significantly lower
		Heart V20	2.80%	—	0.03%	Proton significantly lower
		Heart V15	42.49%	—	0.15%	Proton significantly lower
		Heart V10	56.77%	—	0.53%	Proton significantly lower
		Heart V5	60.68%	—	1.31%	Proton significantly lower
		Thyroid V20	11.91%	—	0%	Proton
		Thyroid V15	66.16%	—	0%	Proton
		Thyroid V10	80.97%	—	0%	Proton
		Thyroid V5	92.50%	—	0.51%	Proton
		Lung V20	3.07%	—	2.27%	Proton significantly lower
		Lung V15	6.03%	—	4.87%	Proton significantly lower
		Lung V10	8.35%	—	7.66%	NS
		Lung V5	11.69%	—	11.31%	NS
9	Al–Wassia 2015 [30]	Eyes Dmean	16.10 ±2.15	16.88 ±1.55 Gy	—	VMAT lower
		Lens Dmax	11.38 ±1.54	12.14 ±1.41 Gy	—	VMAT lower
		Optic nerve Dmax	30.46 ±3.14	31.91 ±4.63 Gy	—	NS
		Optic chiasm Dmax	36.93 ±5.92	36.77 ±4.81 Gy	—	NS
		Cochlea Dmean	41.81 ±3.72	42.09 ±2.32 Gy	—	NS
		Heart Dmean	3.24 ±0.24	3.22 ±0.24 Gy	—	NS
		Liver Dmean	4.48 ±0.78	3.48 ±0.40 Gy	—	IMRT lower, p<.001
		Thyroid Dmean	5.38 ±0.24	5.56 ±0.60 Gy	—	NS
		Brain Dmean	32.08 ±1.46	32.44 ±1.48 Gy	—	NS/minimal
		Testis Dmean	0.09 ±0.05	0.10 ±0.05 Gy	—	Very low
		Ovary Dmean	0.39 ±0.11	0.37 ±0.11 Gy	—	Very low
		Uterus Dmean	0.49 ±0.18	0.50 ±0.18 Gy	—	Very low
		Kidney Dmean	8.43 ±1.57	8.70 ±1.87 Gy	—	NS
		Lung Dmean	7.41 ±1.11	7.39 ±1.42 Gy	—	NS
		Nontarget Dmean	5.75 ±0.97	5.94 ±1.15 Gy	—	NS
		Nontarget V5	37.37 ±7.23%	40.69 ±8.33%	—	p=.006

Table 2. Detailed numerical OAR dosimetry

Taken together, the studies suggest that modern techniques seldom compromise target coverage. The more meaningful differences are in conformity, dose homogeneity, junction behaviour, low–dose exposure, and delivery time. These factors, rather than coverage alone, should guide selection of a CSI technique for an individual patient.

Discussion

Across the available comparative studies, modern CSI techniques consistently achieved high target coverage. The main advantages of one technique over another were instead related to conformity, homogeneity, junction control, normal–tissue exposure, and treatment time. Overall, the literature supports moving beyond

S.No	Study	Technique	MU / delivery	Beam–on / treatment time	QA / junction
1	Rao 2022 [16]	VMAT	NR	~5–7 min	—
2	Sharma 2009 [12]	3DCRT / IMRT–LA / HT	NR	1.56 / 2.17 / 21.8 min	—
3	Athiyaman 2014 [14]	3DCRT–FiF	NR	Reduced planning/delivery time; quantitative time NR	Junction measurement deviation <3%
4	Patel 2024 [18]	Full VMAT / Hybrid	934 ±54.5 / 698 ±56.6 MU	Quantitative BOT NR	2.5–3.5–cm optimized overlap
5	Devi 2025 [20]	HIMRT / H3DCRT / VMAT	VMAT lower MU	Phase 1 17.77/14.83/9.72 min; phase 2 1.99/1.68/3.39 min	No conventional junction for HIMRT
6	Thakur 2024 [21]	VMAT–as / VMAT–pa	1340 / 1377 MU, p=.455	NR	2–4–cm overlap
7	Smyth 2022 [24]	Robust VMAT	NR	NR	Gamma 95.2–100%; median 99.8% at 3%/3 mm; ±5–mm robustness
8	Peterson 2013 [25]	3DCRT–FIF	NR	~25–30 min	Daily 2–cm feathering
9	Prabhakar 2009 [27]	3DCRT	NR	Setup reduction 3–5 min	Junction variation ~3%
10	Parker 2006 [28]	Supine 3DCRT	NR	~15 min	Asymmetric–jaw matching + feathering
11	Howell 2012 [29]	Photon vs PSPT	NR	NR	No quantitative junction metric
12	Al–Wassia 2015 [30]	VMAT / IMRT	1823 ±174.5 / 1282.3 ±85.2 MU	VMAT shorter; exact BOT NR	V5 nontarget 37.4 vs 40.7%, p=.006
13	Bedford 2012 [31]	SEP / CONT / ALT5 / ALT10 / ALT15	ALT10 examples 478.3–714.5 MU	23:48 / 15:38 / 14:07 min for ALT10A/B/C	Gamma 94.9–99.2%
14	Buranavanitvong 2026 [32]	TrueBeam FFF / Halcyon FFF / IMPT	1407.4 ±116.8 / 1517.7 ±315.3 / 15822.3 ±21172.9 MU	12.1 ±0.5 / 6.1 ±0.8 / 4.2 ±0.1 min	Gamma 100 / 100 / 99.3% at 3%/2 mm

Table 3. Treatment efficiency, MU and QA

conventional field–matched 3DCRT when more advanced technology is available and appropriate.

3DCRT remains a practical option, particularly when resources are limited, but its main weakness is the dependence on accurate junction geometry. Even small gaps or overlaps can create clinically important hot and cold regions, so reproducible positioning and junction QA are essential. Studenski et al. also emphasized the importance of junction quality assurance for IMRT–based CSI. In their comparison, IMRT improved OAR sparing, whereas VMAT offered greater efficiency but could increase mean doses to some spinal–field organs [33]. The studies included in our review show a similar balance: photon techniques can maintain excellent coverage, but improvements in efficiency or conformity may come with additional low–dose exposure.

Helical tomotherapy avoids the conventional junction by delivering the treatment continuously along the craniospinal axis. Zhang et al. reported similar PTV coverage across tomotherapy approaches, while dynamic jaws reduced doses to organs near the field edge and improved delivery efficiency. Narrower jaw widths provided better OAR sparing and homogeneity, but approximately doubled beam–on time [34]. Other comparative planning studies have also reported favourable CI and HI with helical techniques compared with IMRT or VMAT, suggesting that this approach is useful when continuity across the junction region is a major concern [35].

VMAT provides a useful middle ground between plan quality and treatment speed. Noncoplanar IMRT has shown better OAR sparing than conventional coplanar IMRT and VMAT, although it requires more monitor units [36]. In the studies reviewed here, VMAT maintained high V95 with favourable CI and HI, but the larger low–dose bath remains a concern. This issue is especially relevant in children, in whom reducing unnecessary low–dose

Parameter	TrueBeam 6–MV FFF	Halcyon 6–MV FFF	ProBeam IMPT
Patients	15	15	15
Prescription	23.4 Gy/13 fx	23.4 Gy/13 fx	23.4 Gy/13 fx
D95 CTV (cGy)	2367.1 ±9.4	2375.1 ±8.9	2359.5 ±4.9
D50 CTV (cGy)	2422.8 ±11.6	2427.1 ±9.3	2417.3 ±8.9
D2 CTV (cGy)	2489.9 ±12.6	2489.8 ±10.8	2480.2 ±16.8
CI	0.69 ±0.04	0.69 ±0.04	0.74 ±0.05
HI	0.06 ±0.01	0.05 ±0.01	0.06 ±0.01
TNTV V1 Gy	57.3 ±3.4%	55.8 ±3.8%	17.8 ±4.9%
TNTV V2 Gy	48.4 ±3.7%	46.2 ±3.9%	16.1 ±4.5%
TNTV V5 Gy	26.9 ±3.4%	26.0 ±3.8%	13.5 ±3.7%
TNTV V22.23 Gy	1.1 ±0.4%	1.2 ±0.4%	3.1 ±1.2%
TNTV V23.4 Gy	0.4 ±0.2%	0.4 ±0.1%	1.7 ±0.7%
Heart Dmean	291.4 ±39.2 cGy	377.5 ±183.5 cGy	27.0 ±26.5 cGy
Lung Dmean	505.2 ±41.9 cGy	480.5 ±39.7 cGy	160.2 ±62.3 cGy
Liver Dmean	358.5 ±29.3 cGy	364.2 ±31.3 cGy	14.2 ±7.4 cGy
Kidney Dmean	359.4 ±94.6 cGy	336.7 ±84.6 cGy	155.4 ±97.2 cGy
Thyroid Dmean	464.6 ±46.8 cGy	533.2 ±120.6 cGy	469.2 ±238.4 cGy
Esophagus Dmean	589.5 ±70.5 cGy	693.1 ±152.5 cGy	673.4 ±216.5 cGy
Eye L Dmean	1052.6 ±101.6 cGy	1041.5 ±102.7 cGy	348.7 ±78.2 cGy
Eye R Dmean	1079.1 ±128.4 cGy	1066.8 ±137.1 cGy	362.1 ±79.8 cGy
Brainstem D0.2cc	2417.6 ±16.1 cGy	2423.6 ±14.6 cGy	2429.9 ±41.1 cGy
Cochlea L D0.2cc	2345.1 ±17.8 cGy	2364.1 ±24.0 cGy	2362.1 ±37.8 cGy
Cochlea R D0.2cc	2341.1 ±28.0 cGy	2367.8 ±22.8 cGy	2352.4 ±38.5 cGy
Lens L D0.2cc	349.9 ±56.7 cGy	343.1 ±47.7 cGy	78.8 ±21.1 cGy
Lens R D0.2cc	340.8 ±58.5 cGy	343.3 ±57.2 cGy	77.0 ±17.4 cGy
Optic nerve L D0.2cc	2360.2 ±68.7 cGy	2390.3 ±20.1 cGy	1941.3 ±520.5 cGy
Optic nerve R D0.2cc	2361.5 ±55.2 cGy	2395.7 ±20.6 cGy	2055.0 ±389.4 cGy
MU	1407.4 ±116.8	1517.7 ±315.3	15822.3 ±21172.9
Beam–on time	12.1 ±0.5 min	6.1 ±0.8 min	4.2 ±0.1 min
Gamma 3%/2 mm	100%	100%	99.3%

Table 4. Buranavanitvong 2026 [32] — detailed FFF/IMPT comparison

exposure is important because of the long–term risk of treatment–related toxicity and second malignancies.

Proton therapy showed the most consistent reduction in integral and low–dose exposure. Howell et al. reported lower dose–volume exposure for several OARs while maintaining similar target coverage. At the same time, proton comparisons are sensitive to differences in target definition and range assumptions, making consistent planning methodology important [37]. Clinical data in adults with medulloblastoma have also reported lower organ doses and less acute dysphagia and weight loss with proton CSI. However, differences in follow–up duration make it difficult to draw firm conclusions about late effects [38].

The available evidence does not support one CSI technique as universally superior. Recent comparisons of Halcyon and TrueBeam showed similar target coverage, with differences mainly in monitor units and delivery characteristics, indicating that FFF photon platforms

can be efficient alternatives [39]. In contrast, paediatric planning studies using NTCP modelling have suggested lower predicted thoracic toxicity with proton PBS [40]. The practical decision should therefore consider the patient's anatomy, age, disease extent, treatment objectives, local expertise, and access to technology.

The main limitation of this review is the heterogeneity of the available studies. Most cohorts were small and retrospective, and studies used different CI and HI definitions, prescriptions, margins, junction strategies, and OAR constraints. For several outcomes, these differences prevented meaningful quantitative pooling. Future multicentre work would benefit from agreed dosimetric definitions and longer clinical follow–up, particularly for late toxicity and survivorship outcomes.

Conclusion

Modern CSI techniques can all provide high target coverage, but they differ in how they manage junctions, shape the dose, spare normal tissues, and deliver treatment. IMRT and VMAT are effective photon–based options and can reduce treatment time, while helical techniques provide continuous delivery without a conventional junction. Proton therapy offers the greatest reduction in integral and low–dose exposure in most comparative studies, with target coverage generally maintained. Because the evidence is based largely on small and methodologically heterogeneous planning studies, these findings should not be interpreted as proof that one technique is best for every patient. In clinical practice, technique selection should be individualized according to anatomy, age, disease characteristics, available technology, treatment efficiency, and institutional experience.

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ii. If any scientific Body approved it/ if it is part of an approved student thesis

– None. Being a Systematic review, this study reported only already published data.

iii. Any conflict of interest

–None

iv. Ethical declaration

–This study reported only already published data. We had no direct access to the original data used in the included studies for the review. Therefore, no ethical approval was needed.

v. Authors' contribution

KAK proposed the initial concept idea, conceived, and designed the systematic review protocol. KAK, AKR, CR and KSB designed search strategies. TM, KAK, KND and PN undertook the searches and retrieved articles. KAK, VSB, YA and KSAR performed the study selection, data extraction, and study quality assessment. KAK wrote the first draft of the manuscript. All authors discussed, advised, and revised the manuscript. All authors read and accepted the final version.

vi. Availability of data

–The data that supports the findings of this study are available on request from the corresponding author.

vii. Registration:

The study was prospectively registered with PROSPERO (CRD420261333696).

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