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REVIEW

Is survival in primary spinal osteosarcoma determined by surgical margins or tumour biology? A systematic review

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Abstract

Study design Systematic review.

Objective To synthesise evidence on surgical management, reconstruction strategies, adjuvant therapies, survival outcomes, local recurrence, and prognostic factors in primary spinal osteosarcoma, with emphasis on margin status and multimodal therapy.

Methods A PRISMA 2020-compliant systematic review was performed. PubMed/ MEDLINE, Scopus, Web of Science and Cochrane Library were searched through January 2026. Studies reporting outcomes in histologically confirmed primary spinal osteosarcoma were included. Institutional series and registry-based analyses were eligible. Extracted variables included surgical approach (en-bloc versus intralesional), reconstruction, chemotherapy, radiotherapy, survival, recurrence and prognostic factors. Owing to heterogeneity, qualitative synthesis was undertaken.

Results Eighteen studies comprising 2,239 patients were included. Registry cohorts reported median overall survival of 15–23 months and 5-year survival below 20%. In contrast, selected Institutional surgical series demonstrated median survival exceeding 4–6 years in patients undergoing aggressive resection. En bloc or Enneking-appropriate resection was associated with improved local control and superior unadjusted survival; however, multivariable analyses did not consistently confirm an independent survival benefit. Local recurrence ranged from approximately 10% following en-bloc resection to more than 40% after intralesional resection. Multimodal chemotherapy remained standard. Modern radiotherapy techniques, including intensity-modulated radiation therapy (IMRT), stereotactic body radiotherapy (SBRT), proton-beam therapy and carbon-ion therapy, were increasingly utilised, especially in anatomically unresectable disease.

Conclusions Primary spinal osteosarcoma carries poor population-level survival. Margin-negative resection improves local control, but outcomes are strongly influenced by tumour biology and stage. Multidisciplinary management at specialised centres is essential to optimise survival.

Keywords Primary spinal osteosarcoma · En-bloc resection · Surgical margins · Local recurrence · Multimodal therapy · Proton beam therapy · Carbon-ion therapy · Prognostic factors · Systematic review

Introduction

Primary osteosarcoma of the spine is a rare and aggressive malignant bone tumour that accounts for a small proportion of all osteosarcomas, but is associated with disproportionately poor outcomes compared with appendicular disease [1, 2]. Population-based analyses from the Surveillance, Epidemiology and End Results (SEER) database have reported median overall survival as low as 15 months, with 5-year survival rates below 20% [1]. These outcomes are markedly inferior to those observed in extremity osteosarcoma, underscoring the unique biological and anatomical challenges posed by spinal involvement. Unlike appendicular osteosarcoma, where wide resection margins can often be achieved, spinal osteosarcoma is anatomically constrained by the proximity of the spinal cord, major vascular structures and thoracic or abdominal viscera [3, 4]. Tumours frequently present with extraosseous extension and epidural

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involvement, limiting the feasibility of Enneking-appropriate resection [5]. As a result, surgical management must balance oncologic margins against preservation of neurological function. En-bloc resection and total en-bloc spondylectomy (TES) have been advocated as strategies to improve local control in selected patients [3, 4]. Several Institutional series have demonstrated improved survival and mitigated recurrence rates following en-bloc or margin-appropriate resections [6, 7]. However, multivariate analyses have not consistently confirmed margin status as an independent predictor of survival [6], raising questions regarding the relative contribution of tumour biology versus surgical technique.

Multimodal therapy remains the standard of care. Systemic chemotherapy regimens, typically high-dose methotrexate, doxorubicin and cisplatin, are routinely incorporated into treatment algorithms [3, 8]. Historically, osteosarcoma has been considered relatively radioresistant, and conventional photon radiotherapy demonstrated limited efficacy [9]. However, modern radiotherapy modalities, including intensity-modulated radiation therapy (IMRT), stereotactic body radiotherapy (SBRT), proton-beam therapy (PBT) and carbon-ion therapy (CIT), have expanded the therapeutic landscape, particularly for anatomically unresectable disease [10]. Despite advances in surgical technique, instrumentation and radiation delivery, management strategies remain heterogeneous, and no consensus exists regarding optimal surgical margins, the role of radiotherapy, or the survival impact of en bloc resection in the spine. Moreover, existing literature consists mainly of small Institutional series and registry-based retrospective analyses, each with inherent limitations [1, 4].

Given the rarity of primary spinal osteosarcoma and the evolving treatment paradigm, a comprehensive synthesis of available evidence is warranted. The objective of the systematic review is to evaluate surgical approaches, reconstruction strategies, adjuvant therapies, survival outcomes, local recurrence patterns, and prognostic factors in patients with primary spinal osteosarcoma, with particular emphasis on the role of margin status and multimodal therapy.

Methods

Protocol

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [11]. The protocol was developed prospectively and defined a priori, ensuring methodological transparency and reproducibility. The research question was structured using the PICO framework: ***Population*** – patients diagnosed with primary osteosarcoma of the spine; ***Intervention*** – surgical resection and/or multimodal therapy (chemotherapy, radiotherapy, reconstruction techniques); ***Comparator*** – not consistently available across studies, but when reported included different surgical approaches or treatment regimens; ***Outcomes*** – survival (overall, disease-free, median), neurological improvement or deterioration, pain relief, complication rates, and treatment-related morbidity and mortality.

Eligibility criteria

We included all published clinical studies that reported on patients with primary spinal osteosarcoma. To ensure robustness, only studies with a minimum of five cases were considered. Studies reporting fewer than five patients were excluded a priori to limit the disproportionate influence of isolated case reports and very small series, which are particularly susceptible to selective outcome reporting and publication bias and seldom provide stratified, cohort-level data suitable for extraction; this minimum-cohort threshold is consistent with the approach adopted in previous systematic reviews of rare primary bone sarcomas. Studies were required to provide extractable data on at least one of the following outcomes: histological subtype, tumour characteristics, neurological status, reconstruction methods, chemotherapy or radiotherapy regimens, survival outcomes, neurological improvement or deterioration, pain relief, and complications. Exclusion criteria were case reports or series with fewer than five patients, studies on metastatic osteosarcoma, and reports that did not provide outcome data specific to spinal osteosarcoma.

Information sources

A comprehensive search was performed across PubMed/MEDLINE, Scopus, Web of Science, and the Cochrane Library, covering all records from database inception until January 2026. The search terms combined controlled vocabulary and free-text keywords, including “spinal osteosarcoma,” “primary osteosarcoma of the spine,” “vertebral osteosarcoma,” “osteogenic sarcoma spine,” and “spinal bone tumour.” Boolean operators were used to refine the search, and truncation was applied where appropriate. A representative search string combined the concepts (“spinal” OR “vertebral” OR “spine”) AND (“osteosarcoma” OR “osteogenic sarcoma”), using both controlled vocabulary (MeSH / Emtree) and title–abstract free-text terms adapted to the syntax of each database; the search was last executed in January 2026, with outputs exported as complete bibliographic records to permit reproducible de-duplication. The search strategy was peer-reviewed by a medical librarian to maximise sensitivity and specificity. The reference lists of

included studies and relevant reviews were hand-searched to identify additional eligible articles. Grey literature was explored through Google Scholar and ProQuest Dissertations. These grey-literature sources were screened against the same eligibility criteria applied to the primary databases and assessed at full text where potentially relevant; however, none met the minimum cohort-size and outcome-reporting requirements, and consequently no grey-literature source was included in the final synthesis. No language restrictions were applied during the initial search, but only English-language full texts were included in the final synthesis.

Study selection

All retrieved records were imported into EndNote for de-duplication. Two reviewers independently screened titles and abstracts for relevance. Prior to formal screening, the two reviewers completed a calibration exercise on a random subset of records, and inter-reviewer agreement at the title-and-abstract stage was high. Reasons for exclusion at the full-text stage were documented and are reflected in the PRISMA flow diagram. Full texts of potentially eligible studies were then assessed against the inclusion criteria. Disagreements were resolved through discussion or consultation with a third reviewer. The study selection process was documented using a PRISMA flow diagram, detailing the number of records identified, screened, excluded, and included.

Data extraction

Data extraction was performed independently by two reviewers using a standardised form developed a priori. Extracted variables included study characteristics (author, year, country, sample size, sex distribution), histological subtype, tumour characteristics (size, vertebral level, extra-osseous extension), preoperative neurological status, reconstruction methods, chemotherapy and radiotherapy regimens, follow-up duration, survival outcomes (disease-free survival, overall survival, median survival), 30-day mortality, neurological improvement or deterioration, pain relief, and complications. Where data were incomplete or unclear, attempts were made to contact study authors. Extracted data were cross-checked for accuracy, and discrepancies were resolved by consensus. The final dataset was tabulated to facilitate synthesis and meta-analysis.

Outcome measures

The primary outcomes of interest were overall survival, disease-free survival, and median survival. Secondary outcomes included neurological improvement or deterioration, pain relief, complication rates (overall and surgical), 30-day mortality, and treatment-related morbidity.

Risk of bias assessment

The methodological quality of included studies was assessed using validated tools appropriate to the study design. For cohort and case-control studies, the Newcastle–Ottawa Scale (NOS) [12] was applied, evaluating selection, comparability, and outcome domains. For case series, the Joanna Briggs Institute (JBI) checklist [13] was used, assessing clarity of inclusion criteria, consecutive recruitment, completeness of follow-up, and reliability of outcome measurement. Each study was independently evaluated by two reviewers, with disagreements resolved by consensus. Studies were categorised as low, moderate, or high risk of bias.

Data synthesis

Because of the considerable heterogeneity in treatment modalities, patient cohorts, and follow-up time points across the included studies, only qualitative synthesis was undertaken. No pooled quantitative meta-analysis was performed. Instead, outcomes such as survival, neurological improvement or deterioration, pain relief, and complication rates were summarised descriptively, highlighting patterns and variations across studies. This approach allowed for meaningful comparison of results while respecting the methodological differences between reports. The qualitative analysis focused on identifying consistent trends, reporting ranges of outcomes, and contextualising findings within the diversity of clinical practices and study designs.

Results

Study selection The literature search identified 1,314 records. After removal of duplicates, ***847 studies*** underwent title and abstract screening. Thirty-nine full-text articles were assessed for eligibility. ***Eighteen studies*** comprising a total of ***2,239 patients*** with primary spinal osteosarcoma were finally included in the qualitative synthesis [1–10, 14–23]. The PRISMA flow diagram is shown in Fig. 1.

Study characteristics The study designs were heterogeneous and included single-institution retrospective surgical series (e.g., Schoenfeld et al. [20], 2010; Feng et al. [3], 2013; Gasho et al. [6], 2025), multicentre ambispective cohorts (e.g., Dekutoski et al. [4], 2016), extensive population-based registry analyses [Surveillance, Epidemiology, and End Results (SEER) and National Cancer Database

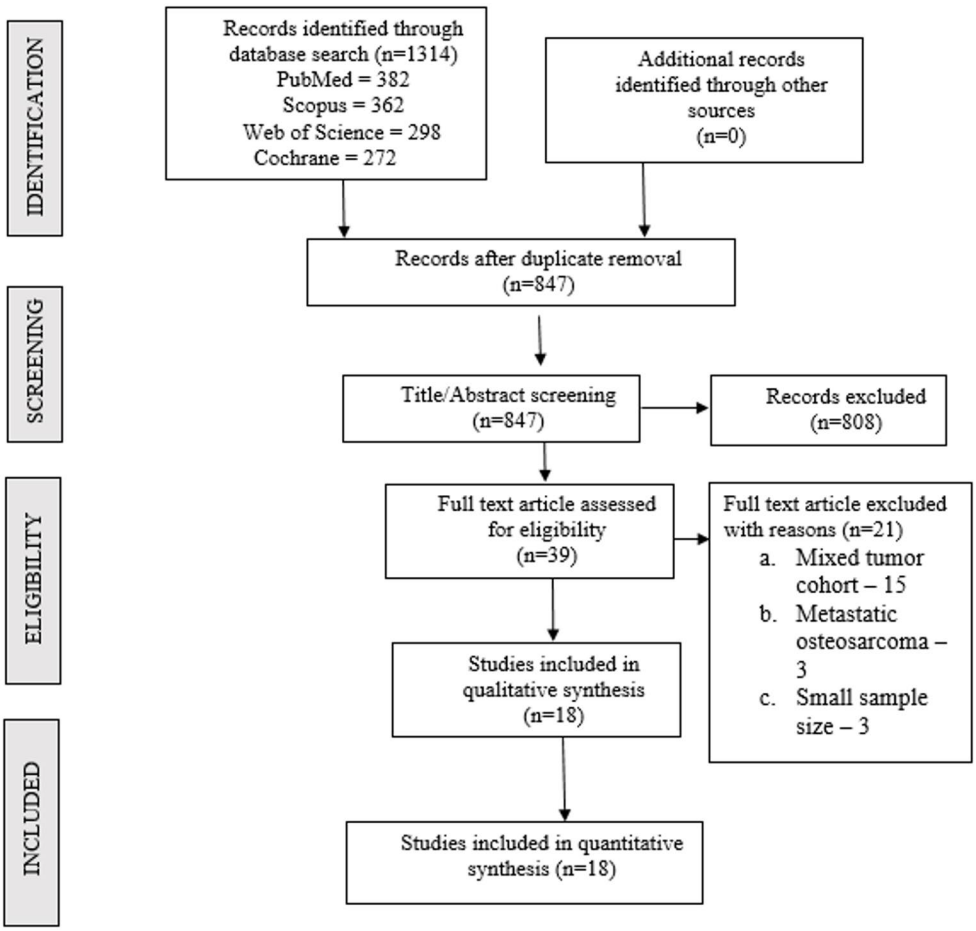


Fig. 1 PRISMA flow diagram of inclusion of studies in the analysis

(NCDB); Tang et al. [2], 2022; J Wang [1] et al., 2023; Huang et al. [16], 2024; Jagtiani et al. [17], 2024)]; and radiation-focused or multimodal therapy cohorts (e.g., Evangelisti et al. [10], 2024). Institutional surgical series included sample sizes between 5 and 58 patients [3, 6, 15, 20]; while the largest registry (SEER)-based cohort included a sample size of 727 patients [1, 2, 16, 22]. Geographically, the studies originated from North America, Europe and Asia. The follow-up duration ranged from a median of 15.7 months in modern particle therapy cohorts [10] to long-term follow-up exceeding 10 years in extended en bloc resection series [15].

Patient and tumour characteristics Across studies, a slight male (53–55%) predominance was observed in registry cohorts [1, 2]. The mean age at diagnosis in surgical series [6, 20] ranged from the third to fifth decades. At the same time, the registry-based data involved paediatric cohorts (e.g., Jagtiani et al. [17]) as well as older adults (mean 45.2 years in SEER analyses – J Wang et al. [1], 2023). The thoracic and lumbar levels were most frequently involved [5, 8]. Extraosseous extension was commonly reported in the Institutional series [3], while the incidence of metastatic disease at presentation ranged between 15 and 32% in registry cohorts [1, 2]. The histological subtypes were variably reported, with osteoblastic and chondroblastic subtypes being the most common. Extensive registry studies demonstrated that advanced stage at diagnosis, metastatic disease and high tumour grade were independently associated with worse survival [1, 2] (Table 1).

Surgical management

A. Extent of resection: Among the Institutional surgical cohorts (n = 265 across 10 surgical series), en-bloc resection was performed in approximately 40–70% in high-volume centres; while intralesional or piecemeal resection was carried out when en-bloc or Enneking-appropriate margins were not technically feasible [3, 4, 6–10, 14, 15, 18–20, 22, 23]. In the 58-patient multicentre cohort [4], Enneking-appropriate resection was achieved in 53% of patients; and was associated with improved mean survival (6.8 versus 3.7 years; p = 0.048) and significantly lower local recurrence (p = 0.001). In a 32-patient modern surgical series, en bloc resection was associated with improved unadjusted median survival (81.5 months vs. 12.4 months, p = 0.006); although

Table 1 Patient demographics and tumour characteristics

Study (Year)	Country	Sample size	Gender (M: F)	Histological Subtype	Tumor characteristics	Extraosseous extension	Neurological status
Schoenfeld et al. (2010)	USA	26	15:11	Osteoblastic (9), Chondroblastic (9), Fibroblastic (2), Small-cell (1), Giant-cell-rich (1), Telangiectatic (0), Not specified (4)	10 patients – tumours > 8 cm 4 - Paget osteosarcoma; 4 - radiation-associated osteosarcoma	NR	NR
Feng et al. (2013)	China	16	10:6	NR	Location: 6 cervical, 6 thoracic, 4 lumbar 13 cases - limited to 1 vertebra 2 cases - involved 3 vertebrae 12 cases - invaded epidural space	Yes	Frankel: Grade B (2), Grade C (3), Grade D (4), Grade E (7)
Dekutoski et al. (2016)	USA	58	26:32	NR	Mean size 7.9 ± 4.8 cm; Vertebral levels spanned: 1 (17%), 2–3 (52%), ≥ 4 (31%)	Yes	ASIA grades (n = 52): A 1 (2%), B 1 (2%), C 6 (12%), D 14 (27%), E 30 (58%)
Gasho et al. (2025)	USA	32	15:17	Osteoblastic (5), Chondroblastic (16), Other or Unknown (11)	Cervical (5), Thoracic (18), Lumbar (7), Multiple levels (2). Resection of 1 level (14), Resection of 2 or 3 levels (18)	NR	NR
Bhatia et al. (2014)	UK	26	12:14	Osteoblastic (18), Chondroblastic (6), Low-grade parosteal (1), Giant cell rich (1)	NR	Yes	NR
Ozaki et al. (2002)	International	22	9:13	Osteoblastic (6), Chondroblastic (6), Small-cell (2), Teleangiectatic (2), Fibroblastic (1), Not specified (5)	Median size 8 cm (range 3–18 cm)	Yes	Frankel grading (12 patients had a deficit: A: 1, B: 2, C: 1, D1: 1, D2: 3, D3: 4)
Zils et al. (2013)	International	20	11:9	Osteoblastic, Telangiectatic, Chondroblastic, Small cell, Unclassified	Most frequent sites: thoracic and lumbar spine Tumour volume: median 120 cm^3 (range 3–576)	Yes	9/20 experienced neurological dysfunction
Harimaya et al. (2021)	Japan	10	6:4	Chondrosarcoma (4), Osteosarcoma (1), PNET (1), Malignant phyllodes tumour (1), Leiomyosarcoma (1), NSCLC (2)	Malignant tumours involving the spinal column and posterior chest wall Mean resected vertebrae: 3.1 ± 1.3 (range, 1–5); Mean resected ribs: 4.1 ± 2.1 (range, 1–7)	Yes	NR
Evangelisti et al. (2024)	Italy	20	12:08	NR	Spinal localization (C2-C5, T4, T9, T12, L1, L3, L4, L5); Median tumor volume 14 cm^3 to 54 cm^3	Yes	NR
Jing Wang et al. (2023; SEER)	USA	668	355:313	Osteosarcoma NOS (68.7%), Chondroblastic (18.7%), Fibroblastic (4.5%), Osteosarcoma with Paget disease (4.3%), Telangiectatic (1.6%), Small cell (1.0%), Central (0.7%), Intraosseous well differentiated (0.3%), Periosteal (0.1%), High grade surface (0.1%)	Size (mm): ≤ 50 (51 cases), 50–100 (109 cases), ≥ 100 (165 cases) Stage: Localise (104), Regional (197), Metastasis (159). Unknown size (343), Unknown stage (208)	NR	NR
Tang et al. (2022)	USA	727	392:335	NR	NR	NR	NR

Table 1 (continued)

Study (Year)	Country	Sample size	Gender (M: F)	Histological Subtype	Tumor characteristics	Extraosseous extension	Neurological status
Huang et al. (2024; SEER)	USA	230	121:109	NOS, Chondroblastic, Other	NR	NR	NR
Wang et al. (2023; Pelvis/Spine model)	International	90	55:3	NR	Median Size: 58.5 mm (IQR 44.25–79.25 mm) Involving segments: Single (61, 68%), Multiple (29, 32%)	NR	Frankel A-C: 42 (47%); Frankel D-E: 48 (53%)
Ilaslan et al. (2004)	USA	198	95:103	Osteoblastic, Chondroblastic, Telangiectatic, Fibroblastic, Small-cell, Epithelioid	Location: Cervical (13.6%), Thoracic (33.3%), Lumbar (32.3%), Sacral (20.7%) In the nonsacral spine, 79% arose from posterior elements with partial involvement of the vertebral body. Matrix mineralisation observed in 55 cases (80%), purely lytic pattern in 14 cases (20%)	Yes	NR
Jagtiani et al. (2025)	USA	32	12:20	NR	Maximum Tumour Dimension: <8 cm: 20 (64.5%), > 8 cm: 11 (35.5%)	NR	NR
Schairer et al. (2014)	USA	33	15:18	NR	Cord compression reported in 97.0% (32/33)	Yes	Normal ambulation 72.7% (24/33)
Lefebvre et al. (2013)	France	5	2:3	Osteoblastic (3), Fibroblastic (1), Chondroblastic (1)	Vertebral body predominance; Frequent extension to posterior arch (2/5); Vertebral collapse (2/5); Involvement of several contiguous vertebrae (3/5) Locations: T1, T6, L1, L4, S1	Yes	Radicular irradiation (4/5) One case presented with paraparesis
Wang et al. (2017)	China	26	15:11	Osteoblastic, Chondroblastic, Telangiectatic, Small-cell	Sacral osteosarcoma Mean diameter 11 cm (range, 9–21 cm)	NR	73.1% symptoms in lower limbs, 37.5% bladder/bowel dysfunction

this was not significant in multivariate regression analysis [6]. Similarly, in a 16-patient surgical cohort, none of the patients undergoing wide en bloc resection developed local recurrence or died from disease, while 60% of intralesional resections recurred and 50% resulted in mortality [3]. An earlier-published, 26-patient series reported an overall poor prognosis despite multimodal therapy, with a median survival of 29.5 months [20]. Broadly, multivariate modelling in several cohorts has not consistently confirmed en bloc resection as an independent predictor of survival (Table 2).

B. Reconstruction strategies: The reconstruction techniques varied widely across the reviewed studies (based on the type or extent of tumour clearance, tumour characteristics and location; and quality of the bone); and included posterior instrumented fixations (especially with pedicle screw anchors), combined anteroposterior reconstructions (with titanium mesh cages, carbon fibre-reinforced PEEK implants etc.); and chest wall reconstruction for extensive tumour resections [15]. The mean number of vertebral levels resected ranged from 1 to > 3 levels, depending on tumour extent.

Adjuvant therapy

A. Chemotherapy: Multimodal chemotherapy was reported in all Institutional cohorts, typically including combinations of high-dose methotrexate, doxorubicin, cisplatin and ifosfamide [3, 8]. In registry-based analyses, the administration of chemotherapy was associated with improved survival in some models. Where reported, the histological response to neoadjuvant chemotherapy—the degree of tumour necrosis in the resected specimen—was associated with improved survival, although such response data were inconsistently documented across the included studies.

B. Radiotherapy: Radiotherapy (RT) utilisation varied among the reviewed studies, ranging from 21 to 32% in registry cohorts [1, 2] to near-universal use in Institutional cohorts [20]. The modalities included conventional photon radiotherapy, IMRT, SBRT, proton-beam therapy and carbon-ion therapy. In a 20-patient cohort evaluating particle therapy after intralesional gross-total resection [10], 3-year disease-specific survival (DSS) was 100% in the small subgroup receiving high-energy particle therapy. Registry studies also reported radiotherapy as an independent predictor of disease-specific survival in some analyses [1, 2].

Survival outcomes The reporting of survival outcomes was heterogeneous. The median overall survival was reported as 15 months in a 668-patient SEER cohort [1], 23 months in a 22-patient international study [9], 29.5 months in a 26-patient Institutional series [20], 45.5 months in a modern 32-patient cohort, and 6.7 years in a multicentre ambispective cohort [4]. On the other hand, the 5-year survival was reported to be 10.8%, 16.8%, 38.7%, 43–60% and 53–60% in an Institutional study [7], SEER-based data [1], sacral-focused study, selected surgical cohorts [8], and 20-patient cooperative group analysis (5- to 10-year survival reporting), respectively. Overall, registry-based cohorts consistently demonstrated lower long-term survival, as compared with high-volume surgical series [1, 2].

Local recurrence The local recurrence rates ranged from 10% (in en bloc resection cohorts) to around 44% after intralesional resections [4, 6]. In the multicentre, ambispective cohort, Enneking-inappropriate resection was associated with significantly enhanced local recurrence ($p = 0.001$) [4] (Table 3).

Neurological outcomes Whenever reported, 50% of patients demonstrated postoperative neurological improvement (especially in smaller surgical cohorts) [3], while certain studies have reported new-onset neurological deficits in 4–10% of individuals [20]. Neurological deterioration following treatment was largely uncommon and inconsistently reported. Registry-based studies did not consistently report neurological outcomes.

Complications Overall complication rates in Institutional surgical series ranged from 20% to 50% [6, 15]. The common complications included wound infection, durotomy, respiratory complications, instrumentation failure and neurological deficits [15, 20]. The 30-day mortality was low in modern surgical cohorts (0–2%), while in registry-based studies, 30-day mortality ranged between 0 and 6% [2]. Among the paediatric cohort, unplanned readmissions were reported in 14% of cases [17].

Prognostic factors Across studies, independent adverse prognostic factors included advanced age (> 60 years) [1], high tumour grade, regional staging, presence of distant metastasis [1, 2], and absence of surgical treatment [2]. In the large SEER cohort of 727 patients, surgery was independently associated with improved overall and cancer-specific survival after propensity score matching [2]. Although en bloc resection demonstrated a survival advantage in unadjusted analyses, multivariate models did not consistently confirm margin status as independently predictive [6].

Discussion

Primary spinal osteosarcoma remains one of the most challenging malignancies in spine oncology. Unlike appendicular osteosarcoma, where wide resection margins are

Table 2 Treatment strategies in spinal osteosarcoma

Study (Year)	Resection Type	Margin Status Reported	Reconstruction Strategy	Chemotherapy	Radiotherapy
Schoenfeld et al. (2010)	20 surgical; 7 en bloc	Yes (margins analysed)	Instrumented stabilisation; vertebral reconstruction	25/26 received (ADM-based regimens)	24/26; mean 62.2 Gy (photon ± proton)
Feng et al. (2013)	TES (7) vs. piecemeal (9)	Yes (wide vs. contaminated)	Occipitocervical fusion upper cervical; anterior titanium plate + mesh – subaxial cervical; posterior pedicle screw fixation plus mesh cage filled with cement - thoracolumbar	Cisplatin, Doxorubicin, HD-MTX	14/16; photon RT (35–65 Gy)
Dekutoski et al. (2016)	En bloc (53%) vs. intralesional	Enneking appropriate vs. inappropriate	Autograft (17), allograft (9), titanium cage (11), carbon fibre cage (12), vascular autograft (2), cement (1)	Variable (multimodal)	Not uniformly reported
Gasho et al. (2025)	En bloc (22) vs. intralesional (10)	Yes	Multilevel posterior fixation; vertebral reconstruction	Multimodal; variable	27/32; mean adjuvant 55.9 Gy; some intraoperative RT
Bhatia et al. (2014)	En bloc vs. non–en bloc	Yes	Instrumentation	Standard OS regimens	Reported: multimodal era
Ozaki et al. (2002)	Surgical resection (mixed)	Not detailed	Bone graft, spacer implantation, posterior fusion	HD-MTX + ADM + cisplatin ± IFO	8/22; 30–56 Gy (conventional; neutron in 1)
Zils et al. (2013)	Complete vs. incomplete remission	Yes (complete vs. incomplete)	Surgical stabilisation (details limited)	COSS cisplatin-based protocols	13/20; median 50 Gy
Harimaya et al. (2021)	En bloc (thoracic spine + chest wall)	Wide (7), marginal (2)	Combined anterior/posterior; chest wall mesh; soft tissue flap; long posterior constructs.	Cisplatin + doxorubicin	IMRT (select cases)
Evangelisti et al. (2024)	En bloc vs. intralesional GTR	Intentional Enneking-inappropriate subgroup	Carbon fibre–reinforced PEEK implants	MTX + doxorubicin + cisplatin (80%)	High-energy particle therapy (PBT/CIT); SBRT/photon
Jing Wang et al. (2023; SEER, $n = 668$)	Surgery vs. no surgery	No	Not available (registry)	Registry variable	RT associated with DSS
Tang et al. (2022; SEER, $n = 727$)	Surgery vs. no surgery	No	Not available	Registry variable	Noted; surgery is independently associated with OS.
Huang et al. (2024; SEER, $n = 230$)	Registry	No	Not available	Registry variable	Registry variable
Wang et al. (2023; Pelvis/ Spine model)	Surgery analyzed	No	Not detailed	Chemotherapy is significant in the model	Not consistently reported
Ilaslan et al. (2004)	Imaging study	N/A	N/A	N/A	N/A
Jagtiani et al. (2024; NCDB pediatric)	Resection vs. no resection	No	Registry data	Multimodal	RT associated with improved survival in sacral/pelvic
Schairer et al. (2014)	Tumour surgery cohort	No	Fusion constructs	Not detailed	Not the primary focus
Lefebvre et al. (2013)	Decompression surgery	No	NA	Methotrexate and Cisplatin-Adriblastine	NR
Wang et al. (2017)			Instrumentation (Posterior instrumentation with cages for total sacrectomy)	Doxorubicin, cisplatin, high-dose methotrexate, and ifosfamide	Used post-recurrence/salvage; dose up to 98.2 Gy

Table 3 Outcome measures and survival rates in spinal osteosarcoma

Study (Year)	Median Overall Survival	1-Year OS	3-Year OS	5-Year OS	10-Year OS	Local Recurrence	Complications	Key Survival Findings
Schoenfeld et al. (2010)	29.5 months	69%	NR	NR	NR	27%	OC: 8/26 Durotomy (4), Postoperative infection (2), Neurodeficit (1), Deep venous thrombosis (1)	Paget-associated OS is worse. High metastasis rate (62%)
Feng et al. (2013)	NR	NR	NR	NR	NR	37.5%	Anaphylactic shock (1); 3 Transient CSF leak (2 subsequent infection: S. aureus, S. epidermidis); Nerve root ligation (3 - dull pain reported); Unilateral vertebral artery ligation (1 - no post-op complication)	Wide en-bloc: 0% recurrence vs. intralesional: 60% When en-bloc resection is not possible, total piecemeal spondylectomy (in combination with adjuvant therapy) can be an appropriate choice.
Dekutoski et al. (2016)	6.7 years	NR	NR	NR	NR	30%	NR	Enneking-appropriate resection improved survival (6.8 vs. 3.7 yrs) En-bloc resection resulted in significantly lower local recurrence (10% vs. 44%, $p=0.001$)
Gasho et al. (2025)	45.5 months	8%	NR	NR	NR	38%	OC: 16/32 8/32 required revision surgery. Reasons for revision: Infection/wound (2), Recurrence (2), Mechanical failure (2), Infection/wound and Recurrence (2)	En-bloc median OS 81.5 vs. 12.4 months ($p=0.006$; unadjusted) Multivariable regression: En-bloc resection ◊ not predictive of better outcomes ($p=0.21$) Younger age (<21) and resection of >1 level ◊ worse survival ($p=0.04$)
Bhatia et al. (2014)	NR	69.5%	NR	10.8%	NR	NR	DVT (2); respiratory compromise (2); wound infection (1); neurological deficits (2)	En-bloc associated with improved survival ($p=0.009$)
Ozaki et al. (2002)	23 months	NR	NR	NR	NR	NR	2/22 (Died of complications)	Wide/marginal excision improved survival Large lesion, sacral tumour and metastasis – poor prognosis Chemotherapy plus surgery+/-postop radiotherapy
Zils et al. (2013)	NR	NR	NR	60%	53%	15%	NR	Complete remission predicted improved OS
Harimaya 2021	NR	NR	NR	NR	90% (13-yr)	10%	OC: 6/10 Atelectasis (3), Hemopneumothorax (1), Pleural effusion (2), CSF leakage (2), Dural tear (2), Transient leg paralysis (2), CMV infection (1), Spinal instrument failure (1 late)	Long-term disease-free survival in the selected en bloc cohort
Evangelisti et al. (2024)	NR	NR	58.3%	NR	NR	38%	OC: 8/20 4 intraoperative complications (2 incidental durotomies, 1 visceral injury (pleural tear), 1 massive blood loss/hypovolemic shock) 2 early postoperative complications (1 spontaneous CSF leak, 1 unexpected neurological deterioration/ incomplete paraplegia); 2 late postoperative complications (1 superficial wound infection, 1 death due to uncontrolled haemorrhage)	3-year DSS 100% in particle therapy subgroup

Table 3 (continued)

Study (Year)	Median Overall Survival	1-Year OS	3-Year OS	5-Year OS	10-Year OS	Local Recurrence	Complications	Key Survival Findings
Jing Wang et al. (2023; SEER)	15 months	NR	NR	16.8%	NR	NR	NR	Surgery independently improved OS
Tang et al. (2022; SEER)	NR	NR	NR	NR	NR	NR	NR	Surgery improved OS & CSS after PSM
Huang et al. (2024; SEER)	18 months	NR	NR	NR	NR	NR	NR	Nomogram; C-index 0.737
Wang et al. (2023; Pelvis/ Spine model)	NR	1-, 3-, 5-yr predicted	—	—	—	NR	NR	Lung metastasis, ECOG performance score, alkaline phosphatase (ALP) level, and en-bloc resection: independent prognostic factors for OS ($p<0.05$)
Jagtiani et al. (2024; NCDB pediatric)	NR	NR	NR	56.4%	NR	NR	Unplanned readmissions: 4 / 28 (14.3%)	Metastasis strongly predicted mortality
Schairer et al. (2014)	NR	93.9%	NR	NR	NR	NR	Wound dehiscence: 2; Pseudarthrosis: 1	NR
Lfebvre et al. (2013)	NR	NR	NR	NR	NR	NR	NR	NR
Wang et al. (2017)	NR	92.3%	38.7%	NR	NR	NR	OC: 8/26 8 (Wound infection and delayed healing)	Low survival Adequate margins: Improves survival recurrence

routinely achievable, spinal disease is constrained by proximity to the spinal cord, major vessels, thoracic and abdominal viscera, and critical neural structures. This anatomical limitation fundamentally shapes both surgical strategy and long-term oncologic outcomes [3, 4].

Survival disparity between registry and Institutional series A significant finding of this review is the pronounced survival discrepancy between population-based registry studies and high-volume Institutional series. Large SEER-based cohorts consistently report median survival of approximately 15–23 months and 5-year overall survival below 20% [1, 9]. In contrast, selected Institutional surgical cohorts demonstrate markedly improved outcomes, with median survival exceeding 4–6 years and 5-year survival approaching 50–60% in patients undergoing aggressive resection [4, 6]. Registry analyses show that surgery is independently associated with improved overall and cancer-specific survival [1, 2]. However, these datasets lack margin classification and surgical granularity. This divergence likely reflects selection bias towards resectable disease in Institutional cohorts, referral bias to tertiary centres, and incomplete reporting of chemotherapy and radiation details in registry data. These registry cohorts likely represent the actual population-level burden, whereas the Institutional series reflects optimised, multidisciplinary care environments.

Surgical techniques and reconstruction strategies Across Institutional surgical series, the operative strategy was primarily dictated by tumour location (cervical vs. thoracolumbar vs. sacral), epidural extension/ cord compression, and the ***feasibility of achieving oncologic margins*** [3, 4, 20]. Several cohorts specifically ***compared total en-bloc spondylectomy (TES)/ Enneking-appropriate resection*** versus ***intralesional/ total piecemeal spondylectomy/ Enneking-inappropriate resections*** [4, 10]. Reconstruction strategies varied according to the location and extent of the lesions. Reconstruction options reported across cohorts included ***autograft/ allograft constructs***, ***titanium cages/ mesh constructs***, cement augmentation of the vertebral body, and carbon-fibre implant technology (including carbon fibre-reinforced PEEK composite implants to mitigate imaging artefact and facilitate postoperative surveillance or RT planning) [3]. A smaller but essential subgroup included tumours requiring ***combined spinal column and posterior chest wall resections***. These surgeries used a combined anteroposterior strategy and incorporated ***chest wall reconstruction*** (e.g., mesh-based reconstruction and soft-tissue flap coverage), reflecting the complexity of achieving local control when disease extends beyond the vertebra into the thoracic cage [15] (Table 4).

Adjuvant and neoadjuvant therapies

Chemotherapy regimens and timing: Most Institutional cohorts employed multimodal chemotherapy broadly consistent with osteosarcoma standards, with common regimens including combinations of: ***high-dose methotrexate***, ***doxorubicin***, ***cisplatin ± ifosfamide*** and/or ***etoposide*** [3, 8]. The key variation across studies was not whether chemotherapy was used (often it was), but rather ***sequencing (neoadjuvant vs. adjuvant)***, ***regimen heterogeneity***, ***and incomplete reporting*** in some datasets. Histological response, conventionally quantified as the percentage of tumour necrosis in the resected specimen (Huvos / Salzer-Kuntschik grading), is among the most powerful determinants of outcome in osteosarcoma: a good response (≥ 90% necrosis) is consistently associated with superior overall survival, whereas a poor response identifies patients at high risk of both systemic relapse and local failure. Because effective cytoreduction can downstage the tumour and sharpen the tumour–tissue interface, chemotherapy response is mechanistically linked to the feasibility of achieving adequate surgical margins; a poor histological response should therefore be regarded as an adverse prognostic signal warranting intensification or modification of systemic therapy rather than reliance on margin status alone. In keeping with established protocols for high-grade osteosarcoma at all anatomical sites, neoadjuvant chemotherapy is generally administered first in fit patients with resectable high-grade disease, and the proposed framework (Table 7) should accordingly be read as positioning resection within a multimodal sequence rather than as advocating upfront surgery.

An important unresolved issue is defining the optimal surgical margin following neoadjuvant chemotherapy. Tumour regression may alter the radiographic appearance of the lesion while leaving microscopic disease beyond the residual mass. Consequently, surgeons must decide whether resection should encompass the original pre-treatment tumour volume or the post-chemotherapy residual lesion. In spinal osteosarcoma, extending the resection to include the original tumour boundaries may substantially increase neurological and vascular morbidity, whereas limiting resection to the residual lesion risks leaving occult microscopic disease [3, 4, 10]. The current evidence provides little guidance regarding this complex balance, highlighting an important area for future prospective investigation [3, 4, 10].

Radiotherapy utilisation and modality: Radiotherapy use varied widely across the cohorts, reflecting both historic practice and evolving technology. ***Conventional photon RT*** was frequently delivered in older cohorts and

Table 4 Margin status and local recurrence across Institutional cohorts

Study	Resection Strategy	Margin Classification	Local Recurrence Rate	Survival Trend
Dekutoski 2016	En bloc vs. intralesional	Enneking appropriate vs. inappropriate	10% vs. 44%	Median OS 6.8 vs. 3.7 yrs
Feng 2013	TES vs. piecemeal	Wide vs. contaminated	0% (wide) vs. 60% (intralesional)	Wide resection improved survival
Gasho 2025	En bloc vs. intralesional	Margin status reported	Lower recurrence in en bloc	Median OS 81.5 vs. 12.4 months (unadjusted)
Zils 2013	Complete vs. incomplete remission	Complete macroscopic remission	15% recurrence	Complete remission predicted OS
Harimaya 2021	En bloc (thoracic + chest wall)	Wide/ marginal	10% recurrence	Long-term disease-free survival

mixed-modality series, with reported total doses historically in the region of 50–60 Gy—a ceiling imposed largely by the radiation tolerance of the spinal cord (approximately 45–50 Gy) and widely considered subtherapeutic for an intrinsically radioresistant tumour. A meaningful tumouricidal effect is thought to require substantially higher biologically effective doses (on the order of 70 GyRBE or more), which modern proton-beam and carbon-ion techniques can deliver while respecting cord and visceral tolerances through steep dose gradients. ***Modern high-energy particle therapy*** (proton-beam therapy and/or carbon-ion therapy) was emphasised in contemporary series, particularly as a strategy to complement ***intralesional gross-total resection*** in anatomically resectable cases [10]. Some modern cohorts also incorporated ***SBRT*** or highly conformal photon techniques when particle therapy was not used or as part of multimodal salvage/ local control approaches [10] The associated morbidity is not negligible and includes radiation-induced myelopathy, vertebral compression fracture and impaired bone healing, oesophagitis and dermatitis, and the long-term risk of radiation-associated secondary malignancy, which is particularly relevant in younger patients. (Table 5).

En-bloc paradox: biology vs. technique Across multiple Institutional cohorts, en-bloc resection demonstrates improved survival in unadjusted analyses [6, 7]. In the multicentre, ambispective cohort, Enneking-appropriate resection was associated with significantly improved median survival and lower recurrence rates [4]. Similarly, total en-bloc spondylectomy was related to the absence of recurrence in selected patients, as compared with intralesional resection [3]. However, multivariate modelling often attenuates this benefit. This apparent contradiction warrants careful interpretation [6].

Although several institutional series reported improved local control and survival following Enneking-appropriate resection, these findings should be interpreted cautiously [4, 6, 7]. In particular, the available retrospective studies, including the multicentre ambispective cohort [4], do not provide sufficient granularity to determine whether improved outcomes resulted from the oncologic benefit of margin-negative surgery itself, preferential selection of technically resectable tumours, greater institutional expertise, or a willingness to accept higher operative morbidity in pursuit of wider margins [4, 6].

En-bloc resection may not appear independently protective because patients selected for Enneking-appropriate surgery may have had more favourable tumour anatomy, whereas surgeons may also have accepted substantially greater operative morbidity in selected patients to achieve oncologically appropriate margins. Furthermore, multilevel

Table 5 Evolution of radiotherapy strategies in primary spinal osteosarcoma

Radiotherapy Modality	Physical Principle	Clinical Rationale in Spine	Supporting Study	Key Observations
Conventional External Beam Radiotherapy (Photon-based)	Uniform photon dose with exit radiation	Historically used when margins are positive or unresectable Limited by spinal cord tolerance	Ozaki 2002; Schoenfeld 2010	Limited dose escalation Modest impact on local control of Osteosarcoma – historically considered radioresistant.
Intensity-Modulated Radiation Therapy (IMRT)	Conformal photon beam shaping with intensity modulation	Improved spinal cord sparing Better dose conformality around complex spinal anatomy	Harimaya 2021	Enhanced target conformity compared to conventional RT Improved safety in thoracic/chest wall resections
Stereotactic Body Radiotherapy (SBRT)	Hypo-fractionated high-dose focused photon delivery.	Escalated biologically effective dose; precise targeting in localised disease	Evangelisti 2024	Allows high-dose delivery with improved tumour targeting; limited by photon exit dose
Proton-Beam Therapy (PBT)	Bragg peak phenomenon (no exit dose beyond target)	Reduced radiation exposure to the spinal cord and adjacent viscera Advantageous in anatomically constrained tumours	Evangelisti 2024	Enables higher tumour dose with reduced collateral damage Promising local control in unresectable cases
Carbon-Ion Therapy (CIT)	Bragg peak + higher relative biological effectiveness (RBE)	Potential to overcome the relative radioresistance of osteosarcoma Induces complex DNA damage	Evangelisti 2024	Early evidence of improved short-term disease-specific survival in selected cohorts
Multimodal Surgery + Particle Therapy	Cytoreduction + high-energy particle RT	Strategy for intralesional or unresectable disease	Evangelisti 2024	Encouraging 3-year DSS in selected patients Long-term data limited
Radiotherapy in Registry Analyses	Variable modality (registry-level data)	Evaluated as a prognostic factor	J Wang 2023	Radiotherapy is associated with improved disease-specific survival in specific subgroups

Table 6 Outcome-based management in spinal osteosarcoma

Clinical Scenario	Expected Local Control	Survival Outlook	Recommended Strategy
En bloc, localized	Low recurrence (≈0–15%)	Improved median survival	Aggressive resection + chemotherapy
Intralesional, localized	Higher recurrence (30–44%)	Moderate survival	Cytoreduction + advanced Radiotherapy
Metastatic disease at diagnosis	High systemic risk	Poor median survival (~15–23 months)	Systemic therapy first
Unresectable tumor	Variable	Depends on response	Cytoreduction + particle therapy

disease and sacral involvement remain adverse prognostic factors, and margin status may correlate with tumour stage rather than independently determine survival. These important confounders cannot be adequately evaluated using the available retrospective data [4, 6].

Nevertheless, recurrence data consistently show higher failure rates after intralesional resection. This suggests that while en bloc resection may not fully overcome aggressive tumour biology, it likely mitigates local recurrence [4, 6]. This suggests that local control remains central even if systemic disease load ultimately dictates long-term survival (Table 6).

The role of multimodal therapy in spine Unlike appendicular osteosarcoma, the spine frequently requires a compromise between oncologic margin and neurological preservation. Consequently, spinal osteosarcoma is inherently a multimodal disease. Chemotherapy remains foundational, mirroring extremity osteosarcoma regimens (methotrexate, doxorubicin, cisplatin±ifosfamide) [3, 8]. Registry analyses also confirm chemotherapy as an important survival-associated variable [1]. However, the spine differs in its frequent reliance on radiotherapy.

Historically, osteosarcoma has been considered radioresistant [9, 20]. However, modern techniques, including IMRT, SBRT, proton-beam therapy and carbon-ion therapy, challenge the paradigm [10]. In a contemporary 20-patient cohort, high-energy particle therapy following intralesional gross-total resection demonstrated promising short-term disease-specific survival (DSS) – 100% 3-year DSS in a small subgroup [10]. These findings suggest that, in anatomically constrained tumours where en bloc resection is infeasible, intentional cytoreductive surgery combined with precision high-dose particle therapy (in combination with systemic chemotherapy) may represent a biologically rational alternative. This multimodal escalation may represent

the most realistic paradigm for anatomically constrained spinal tumours.

Anatomical and biological distinctiveness of spinal osteosarcoma Spinal osteosarcoma differs from appendicular disease in several ways: (a) higher rates of advanced stage at diagnosis, (b) greater frequency of extraosseous extension, (c) frequent epidural involvement, and difficulty in achieving wide margins. These features partly explain the inferior survival in comparison with extremity osteosarcomas [1, 5]. Thoracic and lumbar predominance of the disease has been consistently reported, and it has been speculated that the spinal venous plexus may facilitate early metastatic disease dissemination [5, 8]. Registry analyses have identified advanced age, high tumour grade, regional/metastatic staging and absence of surgery as independent adverse prognostic variables [1, 2].

Intentional "Enneking-inappropriate" surgery plus high-energy particle therapy A notable contemporary paradigm in the reviewed literature is ***intentional intralesional GTR*** (gross total resection; when en bloc is not feasible) followed by high-energy particle therapy as a local control strategy for unresectable spinal osteosarcoma [10] (Table 7; Fig. 2).

Local recurrence as a central driver Local recurrence rates remain substantial across Institutional series, particularly following intralesional resection [4, 6]. Even in en bloc resection cohorts, recurrence rates are not negligible. This emphasises two issues: (a) local control remains central to survival, (b) margin status alone may be insufficient without optimal systemic therapy. Future research must focus on integrating local control strategies with improved systemic and biological targeting [8]. Based on our analysis, we have herewith put forth the clinical guidelines and an algorithm depicting the practical framework in the management of primary spinal osteosarcoma (shown in Table 7; Fig. 2, respectively).

Biologic considerations in primary spinal osteosarcoma Beyond anatomical constraints, the aggressive clinical course of spinal osteosarcoma likely reflects intrinsic tumour biology [1, 2]. Compared with appendicular osteosarcoma, spinal tumours frequently present at a more advanced stage and with greater extraosseous extension [1, 5]. Molecular profiling specific to spinal osteosarcoma remains limited. Most available data extrapolate from extremity disease, which is characterised by complex karyotyping abnormalities, chromosomal instability, TP53 and RB pathway alterations, and high genomic heterogeneity [24–28]. Whether spinal osteosarcoma exhibits distinct molecular signatures or therapeutic vulnerabilities remains largely unknown. No spine-specific targeted therapy trials have been conducted. These biologic realities help contextualise the en bloc ***paradox***: even technically optimal resections may not overcome aggressive systemic disease biology. Margin status influences local recurrence, while tumour grade, metastatic potential and host factors ultimately determine survival. Future investigations incorporating molecular stratification and biological risk modelling are essential to refine patient selection and personalise treatment strategies.

Limitations of the evidence base The current literature is limited by retrospective design, small Institutional cohorts, heterogeneous margin reporting, inconsistent survival endpoints, and a lack of standardised neurological outcome measures. Registry analyses lack surgical details, while Institutional series lack external validity. No prospective comparative trial of en bloc versus intralesional resection exists, and such a study may be infeasible due to disease rarity. Furthermore, none of the included studies adequately reported how neoadjuvant chemotherapy influenced surgical margin planning or whether resections were planned according to the original pre-treatment tumour extent or the post-treatment residual lesion, limiting interpretation of the true oncologic significance of Enneking-appropriate resection.

Beyond these constraints, the included studies exhibit pronounced clinical and methodological heterogeneity—spanning different treatment eras, surgical philosophies, chemotherapy and radiotherapy protocols, margin definitions and follow-up durations—which precludes direct cross-study comparison and was the principal reason a quantitative meta-analysis was not undertaken. There is also likely to be differential selection bias between the two dominant cohort types: institutional surgical series preferentially capture younger patients with localised, resectable disease managed at tertiary referral centres, whereas population-based registry cohorts capture an unselected, real-world population that includes patients with metastatic, unresectable or untreated disease. This structural difference, rather than surgical technique alone, may account for much of the apparent survival advantage observed in institutional series and should temper the interpretation of margin-related outcomes.

Future directions Future research must focus on standardised Enneking margin reporting, prospective multicentre spine sarcoma registries, comparative evaluation of particle therapy versus photon-based RT, and integration of molecular and biological markers into prognostic models. Modern management should be individualised based on

Table 7 Proposed clinical guidelines for primary spinal osteosarcoma. (Evidence level: predominantly level III–IV; recommendations consensus-based)

Initial Evaluation and Staging	***Recommendation 1: All patients with suspected primary spinal osteosarcoma must undergo:*** • MRI of the entire involved spinal segment • CT chest for pulmonary metastasis • Whole-body staging (PET-CT / bone scan) • Image-guided biopsy before definitive surgery	***Rationale: Metastatic disease and tumour stage are the strongest predictors of survival (registry-based analyses)***
Multidisciplinary management	***Recommendation 2: Management should occur in a high-volume sarcoma centre with:*** • Spine oncology surgeon • Musculoskeletal oncologist • Radiation oncologist (including particle therapy capability if available) • Medical oncologist • Thoracic / vascular surgeon if required	***Rationale: Outcomes are superior in institutional series compared to population datasets***
Surgical Strategy	***Recommendation 3 A – Localised***, ***Resectable***, ***High-Grade Disease***: *Administer neoadjuvant (induction) chemotherapy first in fit patientsRestage and reassess resectability after induction chemotherapy* *When technically and neurologically feasible, perform Enneking-appropriate (en bloc) resection with margin-negative intent* *Plan reconstruction preoperatively* *Resume adjuvant chemotherapy after surgery, guided by histological response* *Consider adjuvant RT selectively* *(Upfront surgery without prior chemotherapy is reserved for low-grade [e.g., parosteal] histology, urgent instability, or contraindications to systemic therapy)*	***Strength: Moderate for local control; low–moderate for survival benefit***
Surgical Strategy	***Recommendation 3B – Margin-Constrained Disease***: *If en-bloc resection would cause unacceptable neurologic or vascular morbidity: Perform maximal safe cytoreductive resection* *Combine with high-dose conformal radiotherapy (IMRT / SBRT)* *Consider proton or carbon-ion therapy when available*	***Strength: Low–moderate (emerging evidence)***
Surgical Strategy	***Recommendation 3 C – Multilevel Extensive Disease***: *If > 3 vertebral levels involved: Balance morbidity vs. oncologic gain* *Consider staged or palliative stabilisation when necessary* *Integrate advanced radiotherapy*	
Metastatic Disease at Presentation	***Recommendation 4***: *Initiate systemic chemotherapy first* *Consider surgery for*: *Mechanical instability* *Progressive neurologic deficit* *Refractory pain* *Oligometastatic disease in selected patients*	*Surgery in widely metastatic disease should be individualised.*
Reconstruction Principles	• *Long-segment posterior fixation for multilevel resection* • *Anterior column support using cages or structural grafts* • *Consider carbon fibre–reinforced implants to reduce imaging artefact and facilitate radiation planning* • *Thoracic tumours may require chest wall reconstruction*	
Radiotherapy Recommendations	**Modern RT should be considered in**: • *Intralesional resections* • *Positive margins* • *Unresectable tumours* • *Recurrent disease*	**Preferred modalities**: • *IMRT for conformal dose shaping* • *SBRT for focal high-dose delivery* • *Proton-beam therapy (Bragg peak advantage)* • *Carbon-ion therapy (higher relative biological effectiveness)*

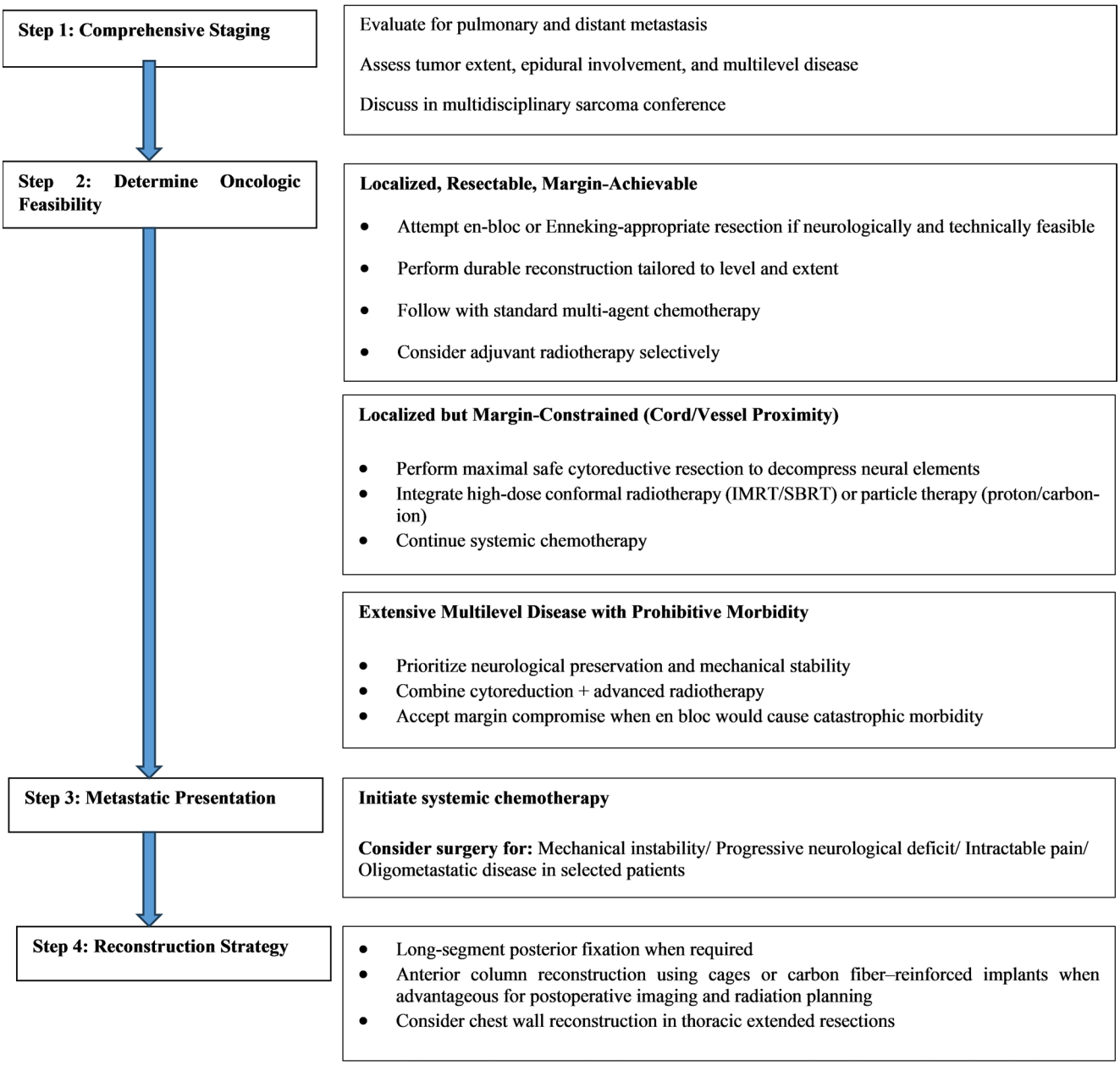


Fig. 2 Algorithm describing the practical treatment framework in spinal osteosarcoma

metastatic status, resectability, and the patient's functional status.

Conclusion

Spinal osteosarcoma remains associated with poor population-level survival. However, selected patients treated at specialised multidisciplinary centres may achieve substantially improved outcomes. When feasible, ***en bloc resection*** appears to offer the most excellent chance of durable local control. When margins are anatomically constrained, ***cytoreductive (intentional "Enneking-inappropriate") surgery*** combined with high-energy particle therapy represents a promising contemporary alternative. Centralisation of care in high-volume sarcoma centres with access to advanced surgical and radiation modalities is likely essential.

Author contributions Author's Contributions CRediT roles: VK - Conceptualization, literature search, manuscript writing and editing. DVKP, SKRC, KS – data retrieval, manuscript writing and editing. SM - conceptualization, statistical analysis, literature search, manuscript writing. LH, ST - literature search, manuscript writing, references, editing and supervision. All have approved the final draft.

Data availability No datasets were generated or analysed during the

current study.

Declarations

Competing interests The authors declare no competing interests.

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