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ORIGINAL PAPER

Sacral chordoma: do the width of surgical margin and the use of photon/proton radiotherapy affect local disease control?

Tomohiro Fujiwara[1,2] · Yusuke Tsuda[1] · Jonathan Stevenson[1] · Michael Parry[1] · Lee Jeys[1]

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Abstract

Purpose Chordoma is a rare but highly aggressive primary bone sarcoma that arises commonly from the sacrum. While en bloc resection has been the mainstay of the treatment, the role of resection margin in millimetres with/without adjuvant radiotherapy (RT) has been unknown. We investigated the prognostic impact of surgical margin width, adjuvant RT, and their combined factor for sacral chordoma.

Methods Forty-eight patients who underwent surgical treatment between 1996 and 2016 were studied. Of these, 11 patients (23%) received adjuvant RT; photon RT in 7 (15%) and proton RT in 4 (8%). Margins were microscopically measured in millimetres from the resection surface to the closest tumour on histologic slides.

Results The five year and ten year disease-specific survival was 88% and 58%, respectively, and the local recurrence (LR) rate was 48%. The LR rate with 0-mm, < 1.5-mm, and ≥ 1.5-mm margin was 50% (group 1), 50% (group 2: RT−, 61%; group 3: RT+, 14%), and 0% (group 4), respectively. We observed a significantly lower LR rate in patients with adjuvant photon/proton RT (18%) than without it (57%; $p = 0.026$), and no LR was observed after post-operative proton RT. The combined factor of margin with RT clearly stratified the LR risk: patients of group 1 (positive margin) and 2 (< 1.5-mm margin, RT−) had approximately 7.5× LR risk ($p = 0.049$) compared with those of group 3 (< 1.5-mm margin, RT+) and 4 (≥ 1.5-mm margin).

Conclusion This study identified the lowest risk of local failure in tumour resection with ≥ 1.5-mm margin or negative but < 1.5-mm margin with the use of adjuvant photon/proton radiotherapy for sacral chordoma. Early results of adjuvant proton RT demonstrated excellent local control.

Keywords Chordoma · Sacrum · Surgery · Margin width · Radiotherapy

Introduction

Chordoma is a rare primary bone tumour accounting for 1–4% of all bone malignancies [1–5], arising in the sacrum (50–60%), skull base (35%) or vertebral bodies (15%) [5, 6]. En bloc resection has been the mainstay of the treatment [5, 7–11], although recent evidence has underlined the increasing role of adjuvant radiotherapy [12–16]. Although chordoma is histologically characterized as low grade, it is highly recurrent and aggressive and associated with a poor prognosis [17]. The reported local recurrence (LR) rate after surgery is 30–75% [4, 11], and five and ten year overall survival (OS) rates are 70–86% [13, 14, 18, 19] and 35–59% [7, 9, 19–23], respectively.

To date, several prognostic factors influencing local control and survival have been reported: age (LR-free survival [LRFS] [24]; OS [21, 25]), location (LRFS [19, 24]; OS [19, 25, 26]), surgical margin (LRFS [5, 7–10, 21, 26, 27]; OS [21, 27]), size (OS [10, 27]), volume (LRFS [9, 26]; OS [26]), micro-skip metastasis (LRFS [11]), vascular invasion (OS [11]), and previous diagnostic/surgical procedure (LRFS [22, 26]). Despite the discrepancy among previous studies in terms of the prognostic factor, most of these publications described resection margin a crucial factor among the others.

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✉ Tomohiro Fujiwara
tomomedvn@gmail.com

[1] Oncology Service, The Royal Orthopaedic Hospital NHS Foundation Trust, Birmingham, UK

[2] Department of Orthopaedic Surgery, Okayama University Graduate School of Medicine, Dentistry, and Pharmaceutical Sciences, Okayama, Japan

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There is no consensus on how surgical margins for bone and soft-tissue sarcomas are reported among different institutes worldwide, with most of the existing investigations having been performed on the system of Enneking et al.: intralesional, marginal, wide, and radical [28]. In addition, the interpretation of what is a marginal and wide resection remains inherently subjective and may vary depending on the investigators [29]. The adoption of a simple system incorporating measurable and reproducible variables would allow standardisation of treatment and monitoring and reduce bias. The closest surgical margin in millimetres could replace any subjective methods of surgical margin. Recently, the Birmingham classification for osteosarcoma, devised on the bases of the margin in millimetres and the response of chemotherapy, was superior to the conventional margin classification by Enneking for predicting LR [29]. The predictive role of margins in millimetres was also investigated in chondrosarcoma, which clearly stratified LRFS between groups in all histological grades with a surgical margin of > 4 mm [30]. However, no study has investigated the role of surgical margin in chordoma with a focus on the closest margin in millimetres.

The efficacy of adjuvant radiotherapy for sacral chordoma remains controversial [12, 13, 31–33]. Several retrospective studies at a single institution demonstrated that neo-adjuvant and/or adjuvant radiotherapy in combination with surgical resection led to better local relapse-free survival than surgical treatment alone [12, 13, 32, 33]. Conversely, a recent multicentre study reported that radiotherapy was not associated with local disease control, but it was associated with complications [31]. These inconsistencies might be attributed to the unstandardized treatment paradigms among multiple institutions, such as timing of treatment (pre- or post-operative), type of radiotherapy (photon, proton, or carbon ion), and radiation dose. Notably, the benefits of proton radiotherapy in an adjuvant setting have been unclear [34–36], while carbon ion [15, 18, 37] or proton radiotherapy [12, 15, 18, 38] plays a role in unresectable cases.

In the era of modern multidisciplinary treatment, prognostic risk prediction based on a single treatment-related factor may not provide precise information. We hypothesised that an approach combining surgical margin and the use of adjuvant radiotherapy might provide more precise prognostic risk stratification. The purpose of this study was to investigate the prognostic role of surgical margin width, adjuvant radiotherapy, and the combined factor of these in patients with sacral chordoma.

Patients and methods

We conducted a retrospective study of patients with sacral chordoma who underwent surgical treatment between 1996 and 2016 at a single institution. During this period, a total of 82 consecutive patients were diagnosed with a chordoma and 61 of these underwent surgical resection as initial treatment, excluding those who were treated with definitive radiotherapy, treated palliatively, and initially treated elsewhere and referred for the management of a recurrence. Patients with chordoma arising from sites other than the sacrum, those with minimum follow-up less than two years for patients alive, and those whose resection margin in millimetres was unavailable were also excluded.

Details of the clinical data which were collected from the notes included age at diagnosis, sex, tumour site, tumour size, level of resection, details of operations, surgical margin, pathological reports, and oncological outcome. Tumour volume was measured on histopathologic specimens or on coronal, transverse, and sagittal magnetic resonance (MR) imaging of the lesion; the volume was calculated using the formula of an ellipsoid mass volume: $(\pi/6) \times \text{height} \times \text{width} \times \text{depth}$ [26]. Margins were microscopically measured in millimetres from the resection surface to the closest tumour on histologic slides following gross examination of the specimen by pathologists highly experienced in bone and soft-tissue sarcomas.

Histological diagnosis was pre-operatively confirmed and a treatment plan was discussed at a multidisciplinary meeting for all patients. The surgical indications were determined under considerations for the location and size of the lesion, its potential margins, absence of metastatic disease at presentation, the predicted surgical morbidity and mortality, and the patient's preference. For tumours at or below S3 level, resections were performed through a posterior approach, whereas tumours at S1/2 levels were resected using a combined anterior and posterior approach [5]. Depending on the cases, a vertical rectus abdominis myocutaneous flap was used to fill the dead space after tumour resection. Radiotherapy was considered in the postoperative setting if the resection margin was marginal or intralesional but also considered regardless of the margin width since 2014. Proton radiotherapy was recommended since 2012, due to the proximity of the rectum and side effects of external beam radiotherapy. Decision on the use of radiotherapy was made according to the post-operative local conditions such as wound healing after a multidisciplinary team discussion.

Post-operatively, patients remained on bed rest for the first five days. Following review of the wound, they were mobilised fully weight bearing under the guidance of a physiotherapist. Routine follow-up for patients was performed every three months for the first two years, every six months for the next three years, and then annually thereafter unless the patient developed new symptoms. Patients underwent spinal

Table 1 Univariate analysis for local recurrence-free survival and disease-specific survival

Variables	No. of patients	%, range	LRFS		DSS	
			% (5-year)	*p* value	% (5-year)	*p* value
Total	48	–	48%	–	88%	–
Age (mean, 61 years)				0.224		0.929
< 60 years	16	33%	29%		94%	
≥ 60 years	32	67%	59%		84%	
Sex				0.677		0.673
Male	28	58%	50%		85%	
Female	20	42%	41%		95%	
Tumour size (mean, 9.3 cm)				0.160		0.524
< 8 cm	34	71%	54%		89%	
≥ 8 cm	14	29%	30%		86%	
Tumour volume (mean, 347 cm^3)				0.003		0.900
< 205 cm^3	21	44%	76%		95%	
≥ 205 cm^3	27	56%	25%		84%	
Highest level of tumour involvement				0.271		0.045
Above S3	14	29%	36%		75%	
At or below S3	34	71%	52%		97%	
Bone resection level				0.200		0.105
Above S3	20	42%	37%		77%	
At or below S3	28	58%	53%		96%	
Adjuvant treatment for primary tumour				0.045		0.577
None	37	77%	37%		89%	
Radiotherapy (adjuvant)	11	23%	82%		75%	
Presence of dedifferentiation				0.104		0.418
Yes	2	4%	0%		10%	
No	46	96%	49%		88%	
Presence of micro-satellite lesion				0.526		0.347
Yes	3	6%	67%		100%	
No	45	94%	45%		88%	
Presence of vascular invasion				0.201		0.618
Yes	2	4%	100%		50%	
No	46	96%	43%		100%	

MR imaging at each visit and a chest radiograph annually for the screening of pulmonary metastases.

Disease-specific survival and local recurrence-free survival were analysed using the Kaplan-Meier analysis. Disease-specific survival was defined as the period from the date of diagnosis to the last date when the patient was recorded to be alive or the date of tumour-related death. LRFS was defined as the period from the date of treatment and censored at the date of LR. The variables of each group were compared using the chi-square test, Student *t* test, or Mann-Whitney *U* test. All statistical analyses were performed using the SPSS software (version 23; IBM, Armonk, New York, USA). Differences were considered to be statistically significant at a *p* value < 0.05.

Results

Patient characteristics

After exclusion criteria, a total of 48 patients were available for analysis. The patient demographics and therapies are summarised in Table 1. The mean age at diagnosis was 61 years (range, 16 to 86 years) with a slight male predominance ($n = 28$; 58%). The mean tumour size was 9.3 cm (range, 3.0 to 17.5 cm), and the mean tumour volume was 347 cm^3 (range, 5 to 2136 cm^3). The highest level of tumour was at S1 in seven patients (14.5%), S2 in 7 (14.5%), S3 in 12 (25%), S4 in 12 (25%), S5 in six (13%), and coccyx in four (8%). Of 48 patients who underwent surgical treatment, 11 patients (23%) received post-operative radiotherapy.

Table 2 The margin in millimetres and local recurrence according to the use of postoperative radiotherapy (RT)

Closest margin	Total				RT−				RT+			
	No.	LR+	LR −	%LR	No.	LR+	LR −	%LR	No.	LR+	LR −	%LR
0 mm	4	2	2	50%	2	1	1	50%	2	1	1	50%
< 0.1 mm	1	1	0	100%	1	1	0	100%	–	–	–	–
0.1 mm	5	0	5	0%	4	0	4	0%	1	0	1	0%
0.5 mm	11	5	6	45%	8	4	4	50%	3	1	2	33%
0.6 mm	1	1	0	100%	1	1	0	100%	–	–	–	–
< 1 mm	11	9	2	82%	11	9	2	82%	–	–	–	–
1 mm	11	5	6	45%	8	5	3	63%	3	0	3	0%
1.5 mm	2	0	2	0%	1	0	1	0%	1	0	1	0%
3 mm	1	0	1	0%	1	0	1	0%	–	–	–	–
5 mm	1	0	1	0%	–	–	–	–	1	0	1	0%
Total	48	23	25	48%	37	21	16	57%	11	2	9	18%

Histological investigation identified micro-satellite lesion in three (6%) and vascular invasion in two (4%). The mean follow-up period was 77 months (range, 8 to 206 months).

The role of surgical margin in local control

The surgical margins measured in millimetres are shown in Table 2. The closest margins were observed at the anterior resections in 27 patients (56%), posterior resections in ten (21%), lateral resections in seven (15%), and superior resections in four (8%). The overall LR rate was 48% ($n = 23$). The mean duration from primary surgery to LR was 22.4 months (range, 3 to 52 months). LR-free survival was 46% at both five and ten years. The relationship of the closest margin in millimetre and LR is shown in Table 2. All of the LRs were observed in patients with a margin below 1.5 mm; hence, this was chosen as our cut-off for further analysis. Univariate analysis revealed that a larger tumour volume (over 205 cm^3) and the use of adjuvant radiotherapy were positive factors for LR (Table 2). The surgical margin width below 1.5 mm did not significantly stratify the LRFS ($p = 0.104$; Supplementary Fig. 1).

Table 3 The use of post-operative radiotherapy and local recurrence

Post-operative radiotherapy	Total	LR		%LR
		Yes	No	
No	37	21	16	57%
Yes	11	2	9	18%
Photon	7	2	5	29%
Proton	4	0	4	0%
Total	48	23	25	48%

The role of adjuvant radiotherapy in local control

The LR rate was significantly lower in patients with post-operative radiotherapy (18%) than those without it (57%; $p = 0.026$; Table 3) as described. The five year LRFS in patients with and without post-operative radiotherapy was 82% and 37%, respectively ($p = 0.045$; Table 1, Supplementary Fig. 2A). We observed no LR in patients who underwent post-operative proton radiotherapy, while two of seven patients (29%) had LR after post-operative conventional photon radiotherapy ($p = 0.053$; Table 2, Supplementary Fig. 2B).

Combined risk stratification in local control according to surgical margin and adjuvant radiotherapy

The relationship between margin width in millimetres and LR stratified by post-operative radiotherapy is shown in Table 2. When we focus on the patients with close margin below 1.5 mm, there was a significant difference in LR rate in patients with and without radiotherapy (61% and 14%, respectively; $p = 0.033$). We then divided patients into four groups based on the combined factor of margin and adjuvant radiotherapy: group 1, intralesional margins; group 2, margins less than 1.5 mm without post-operative radiotherapy; group 3, margins less than 1.5 mm with post-operative radiotherapy; and group 4, margins over 1.5 mm (Table 4). The LR rate was 57%, 56%, 14%, and 0%, respectively ($p = 0.048$; Table 4). Although LRFS was not statistically stratified among these four groups because of the limited number of patients in each ($p = 0.102$; Fig. 1), the combination of these groups (group 1 + 2 vs 3 + 4) demonstrated a significant difference in the incidence of LR between high and low risk of local failure ($p = 0.013$; Fig. 2a), suggesting that obtaining a clear margin with the addition of radiotherapy is crucial for local control.

Table 4 Cox regression model based on the surgical margin and the use of post-operative radiotherapy for local recurrence-free survival

Classification	LR rate	LRFS (5-year)	*p* value	LRFS (5-year)	HR	95% CI	*p* value
Group A				35.1%	7.502	1.008–55.837	0.002
1: margins = 0 mm	50%	50.0%	0.128				
2: margins < 1.5 mm without postop RT	61%	32.8%	0.053				
Group B				90.9%	Reference	–	–
3: margins < 1.5 mm with postop RT	14%	85.7%	0.450				
4: margins ≥ 1.5 mm	0%	100%	Reference				

Multivariate analysis revealed that tumour volume (≥ 205 cm^3 hazard ratio [HR], 3.746; 95% confidence interval [CI], 1.383–10.141; $p = 0.009$ versus < 205 cm^3 HR, 1) and the combined factor of surgical margin and the use of adjuvant radiotherapy (group 1 + 2 HR, 7.502; 95% CI, 1.008–55.837; $p = 0.049$ versus group 3 + 4 HR, 1) were independent prognostic predictors for LRFS.

Predictors of disease-specific survival

The disease-specific survival rate was 88% at 5 years and 58% at 10 years. Univariate analysis revealed that the highest level of tumour involvement above S3 ($p = 0.045$) was a negative prognostic factor. The use of adjuvant radiotherapy was not a prognostic factor for disease-specific survival, but the patients treated with adjuvant proton radiotherapy are all alive with a mean follow-up period of 45 months (range, 27 to 81 months). Although the combined factor of surgical margin and post-operative radiotherapy was not a significant prognostic factor for disease-specific survival ($p = 0.157$), we observed a trend toward better prognosis in patients with group 3 + 4 (Fig. 2b). None of these factors achieved statistical significance in multivariate analysis because of the limited number of patients.

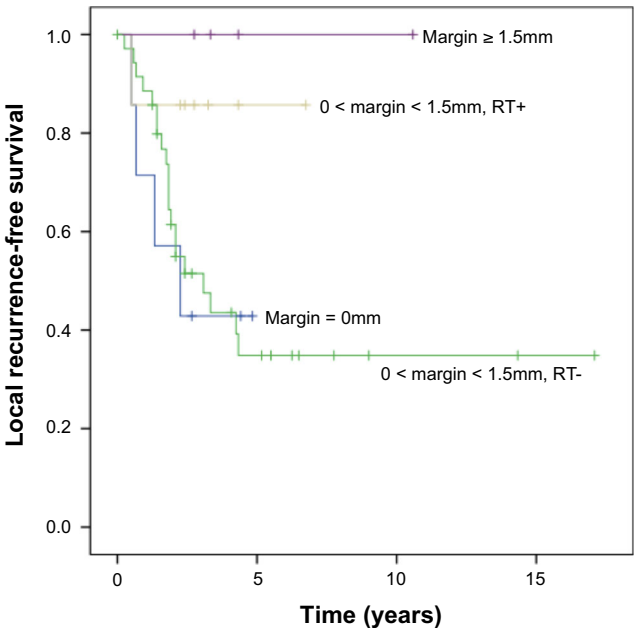

Fig. 1 Kaplan-Meier curves showing local recurrence-free survival stratified by the combined factor with resection margins in millimetres and adjuvant radiotherapy: 0 mm, 0 mm < margin < 1.5 mm, and margin ≥ 1.5 mm ($p = 0.102$, log-rank test)

Discussion

It is well known that surgical margin remains a crucial prognostic factor for sacral chordoma; however, previous literature has described margins by the Enneking system (intralesional, marginal, or wide) [28] or R classification (intralesional or clear) [39]. Importantly, a surgical margin defined as wide and marginal varies depending on the reporter and not fully reproductive [29]. This study is the first to describe the role of margin width in millimetres for sacral chordoma. Obtaining a wide margin greater than 1.5 mm is technically demanding for this disease because of the anatomical proximity to the rectum, which was confirmed in this study. Therefore, it is important to stratify and predict the oncologic risk especially for patients with a close margin below 1.5 mm. We propose the adoption of a simple system incorporating measurable and reproducible variables, replacing the subjectivity of 'wide', 'marginal', or 'microscopic tumour at margin', which will allow standardisation of treatment and improve communication and future research.

The role of adjuvant radiotherapy for sacral chordoma remains a subject of debate, and its value in local control is inconclusive [4, 8, 21, 27, 31, 33]. In this study, we identified a significantly lower LR rate in patients who received adjuvant radiotherapy (18%) than in those who did not (57%). Our results were consistent with those by van Wulfften et al. [33]. In a multicentre study, Houdek et al. reported no significant benefit by neo- and/or adjuvant radiotherapy but suggested that this might be attributed to no standardised treatment strategy existing among multiple institutions including regarding radiation dose, field, or indication [31]. Our study was based on the results of post-operative radiotherapy, which we believe would provide useful information based on the safer use of radiotherapy. Further research involving larger cohorts with less bias of therapeutic details would be necessary to

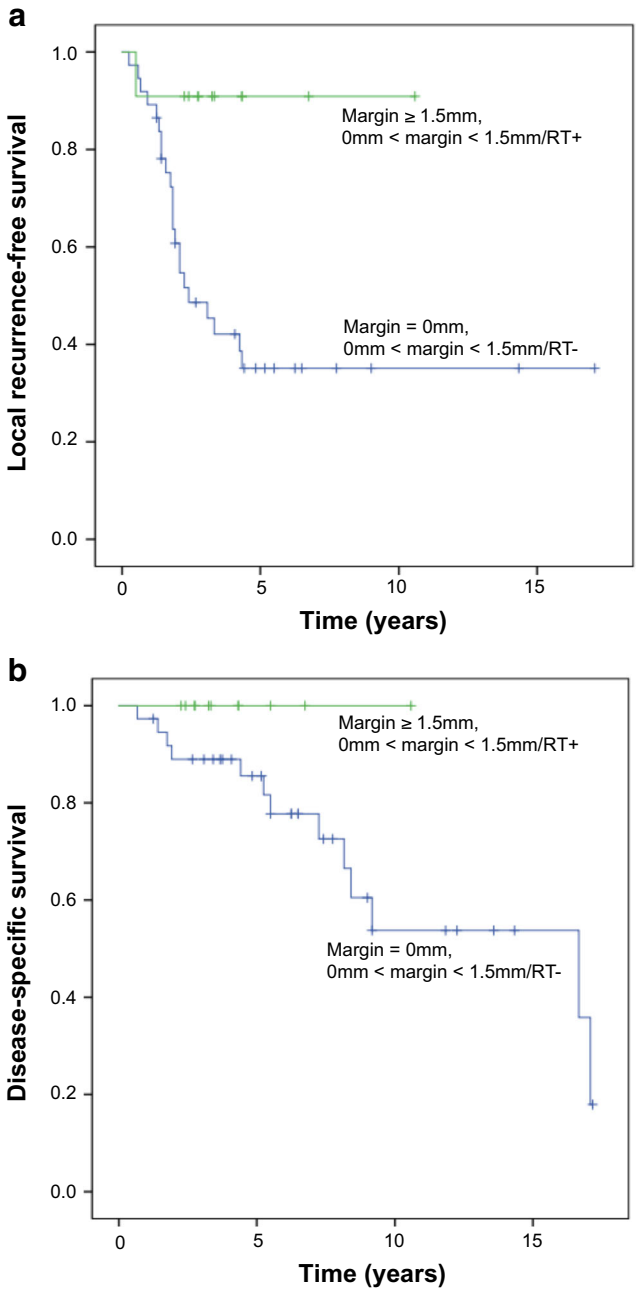

Fig. 2 Kaplan-Meier curves showing local recurrence-free survival (**a**) and disease-specific survival (**b**) stratified by the combined factor of surgical margin and adjuvant radiotherapy (**a**, $p = 0.013$; **b**, $p = 0.157$; log-rank test)

clarify the benefits of the use of radiotherapy for sacral chordoma.

The effect of proton radiotherapy in an adjuvant setting has been unclear, whereas recent studies have reported favourable early results with proton radiotherapy as definitive treatment, with local control rates of over 90% at 3 years [15, 19]. As an adjuvant treatment, proton radiotherapy was reported to result in a local control rate of 33–95% with a relatively short follow-up (Table 5) [15, 19, 34, 35, 38]. The wide range of local control rates among these studies might be attributed to the heterogeneous settings among the study cohorts, such as margin status and pre-/postoperative use of proton radiotherapy, which hinder effective comparisons of the outcomes associated with the adjuvant use of conventional photon radiotherapy [40]. In a multicentre study by Houdek et al., there was no association between local control and the use of proton radiotherapy [31]. However, the authors postulated that this outcome might be related to the insufficient number of patients in specific subsets. In the current study, we found excellent local control with the use of adjuvant proton radiotherapy despite the relatively short follow-up period in patients with negative resection margins. Further investigation with longer follow-up is necessary to elucidate the effects of adjuvant proton radiotherapy.

Regardless of the use of adjuvant radiotherapy, intralesional resection was associated with a high rate of LR, as described in a number of previous publications. In this study, we identified that the LR rate in patients with a clear but close margin below 1.5 mm was worse (61%) than that of intralesional margins (50%) without adjuvant radiotherapy. However, the LR decreased to 14% in patients with a clear but close (< 1.5 mm) margin when adjuvant radiotherapy was administered. These data indicated that the risk of local failure with narrow margins (< 1.5 mm) may be salvaged by adjuvant radiotherapy. Although we identified no LR in patients with a margin over 1.5 mm, we cannot determine the necessity of adjuvant radiotherapy for them because of the limited numbers and follow-up periods. Considering the possible presence of a microsatellite lesion and the reported LR rate even in the patients with a wide margin over 1.5 mm [41, 42], adjuvant radiotherapy could be effective regardless of the margin extent.

In the era of multidisciplinary treatment for sarcomas, we face the limitation in risk assessment only by the single clinicopathological factor. A recent study has demonstrated that more precise risk stratification is achieved by combining two prognostic factors in patients with osteosarcoma. The best predictor of LR was the combination of a resection margin of ≤ 2 mm and a chemotherapy response of < 90% necrosis compared with a single factor of either resection margin or response to chemotherapy [29]. In this study, clear stratification in LR was possible using the combined factor of margin in millimetres and adjuvant radiotherapy, which was impossible only by the surgical margin. This was attributed to not a small number of patients with clear but close margin below 1.5 mm, indicating the importance of risk stratification with the use of adjuvant radiotherapy

Table 5 Summary of the literature showing the outcomes in patients with sacral chordoma who underwent photon/proton radiotherapy

Author	Year	*N*	Location (chordoma)	Treatment	Surgical margin	Outcome	Follow-up period (months)	Refs
Chen	2013	24	Mobile spine = 5 Sacrum = 19	Definitive photon/proton RT	–	LRFS: 90.4% (3-year), 79.8% (5-year) MFS: 86.5% (3-year), 76.3% (5-year) DSS: 90.4% (3-year), 79.8% (5-year)	56 (median)	[18]
Mima	2014	23	Sacrum = 23	Definitive proton RT = 7 Definitive carbon ion = 16	–	LRFS: 94% (3-year) OS: 83% (3-year) PFS: 68% (3-year)	38 (median)	[15]
Boriani	2006	52	Mobile spine = 48 Sacrum = 0	Surgery = 14[1] Surgery + photon RT = 24[2] Photon RT + palliative surgery = 10[3]	[1]R0 = 10, R1/2 = 4 [2]R1/2 = 16, NR = 8 [3]R1/2 = 10	[1]LR: 43%, NED: 54%, DOD: 7% [2]LR: 67%, NED: 38%, DOD: 38% [3]LR: 100%, NED: 0%, DOD 100%	NR	[37]
Delaney	2014	50	Mobile spine = 23 Sacrum = 27	Surgery + pre/post photon/proton RT	R0 = 8 R1 = 17 R2 = 13	Primary case; LR: 1/23 (4%) Recurrent case; LR: 3/6 (50%) R0; LR: 0/7 (0%), R1; 1/10 (10%), R2; 1/3 (33%)	88 (median)	[33]
Rotondo	2015	127	Mobile spine = 56 Sacrum = 71	Surgery + postop proton RT[1] = 58 Surgery + pre/postop proton RT[2] = 60 Definitive proton RT = 9[3]	R0 = 34 R1 = 57 R2 = 30	Primary case [1]LRFS (5-year): 56%, DCR (5-year): 82%, OS (5-year): 80% [2]LRFS (5-year): 85%, DCR (5-year): 78%, OS (5-year): 85% Recurrent case [1]LRFS (5-year): 44%, DCR (5-year): 57%, OS (5-year): 83% [2]LRFS (5-year): 47%, DCR (5-year): 92%, OS (5-year): 71% [3]LRFS (5-year): 56%, DCR (5-year): 40%, OS (5-year): 83%	41 (median)	[36]
Baumann	2019	20	Skull base = 10 Mobile spine = 3 Sacrum = 5	Surgery + proton RT = 17 Definitive proton RT = 2 Proton RT for LR = 1	R0 = 4 R1/R2 = 16	LRFS: 95% (2-year), 86% (3-year) PFS: 90% (2-year), 81% (3-year)	37 (median)	[35]

Abbreviations: *LR* local recurrence, *NED* no evidence of disease, *DOD* dead of disease, *LRFS* local recurrence-free survival, *MFS* metastasis-free survival, *DSS* disease-specific survival, *OS* overall survival, *DCR* distant control rate, *PFS* progression-free survival, *NR* not reported

among these patients. Collectively, the combination of the key therapeutic factors could provide more precise information for the prognostic prediction and help in the decision-making of further treatment.

We acknowledge several limitations of this study. First, data on the quality of surgical margin were not available but further analysis considering margin quantity would provide a more accurate prognostic indicator. If the margin quality could be predicted prior to resection, particularly when the resection may require close dissection or even the excision of nearby vital structures, it may be possible to give more accurate information for preoperative planning. Second, the follow-up periods in patients with adjuvant radiotherapy, especially with proton radiotherapy, were relatively short, despite no statistical difference among them. Longer follow-up for them would further determine the efficacy of postoperative photon/proton radiotherapy. Third, this study was retrospective in nature and was based on the records of the patients at a single institution. Further well-designed, retrospective studies with a larger cohort would be useful for decision-making of treatment. Despite these limitations, we believe that our analyses, which first demonstrate the role of margin in millimetres in combination with the use of adjuvant radiotherapy, provide more precise oncological prediction and help physicians and patients in making informed decisions of treatments and follow-ups.

In summary, the present study identified the lowest risk of local failure in tumour resection with ≥ 1.5 mm margin and adjuvant photon/proton radiotherapy for sacral chordoma. In patients with clear margin but narrower than 1.5 mm, risk of LR is as high as those with the intralesional margin unless adjuvant radiotherapy is performed. Although longer follow-up is required, early results demonstrated the excellent local control by adjuvant proton radiotherapy.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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