Image-guided resection of aggressive sacral tumors

Doniel Drazin, MD, MA,¹ Neil Bhamb, MD,² Lutfi T. Al-Khouja, MD,¹ Ari D. Kappel, BS,³
Terrence T. Kim, MD,^{1,2} J. Patrick Johnson, MD,^{1,4} and Earl Brien, MD²

Departments of ¹Neurosurgery and ²Orthopaedic Surgery, Cedars-Sinai Medical Center, Los Angeles, California; ³Department of Neurosurgery, Stony Brook University Medical Center, Stony Brook, New York; and ⁴Department of Neurosurgery, University of California, Davis, Sacramento, California

OBJECTIVE The aim of this study was to identify and discuss operative nuances utilizing image guidance in the surgical management of aggressive sacral tumors.

METHODS The authors report on their single-institution, multi-surgeon, retrospective case series involving patients with pathology-proven aggressive sacral tumors treated between 2009 and 2016. They also reviewed the literature to identify articles related to aggressive sacral tumors, their diagnosis, and their surgical treatment and discuss the results together with their own experience. Information, including background, imaging, treatment, and surgical pearls, is organized by tumor type.

RESULTS Review of the institutional records identified 6 patients with sacral tumors who underwent surgery between 2009 and 2016. All 6 patients were treated with image-guided surgery using cone-beam CT technology (O-arm). The surgical technique used is described in detail, and 2 illustrative cases are presented. From the literature, the authors compiled information about chordomas, chondrosarcomas, giant cell tumors, and osteosarcomas and organized it by tumor type, providing a detailed discussion of background, imaging, and treatment as well as surgical pearls for each tumor type.

CONCLUSIONS Aggressive sacral tumors can be an extremely difficult challenge for both the patient and the treating physician. The selected surgical intervention varies depending on the type of tumor, size, and location. Surgery can have profound risks including neural compression, lumbopelvic instability, and suboptimal oncological resection. Focusing on the operative nuances for each type can help prevent many of these complications. Anecdotal evidence is provided that utilization of image-guided surgery to aid in tumor resection at our institution has helped reduce blood loss and the local recurrence rate while preserving function in both malignant and aggressive benign tumors affecting the sacrum.

<https://thejns.org/doi/abs/10.3171/2016.6.FOCUS16125>

KEY WORDS aggressive sacral tumors; image-guided surgery; spine malignancy; chondrosarcoma; giant cell tumor; chordoma

P RIMARY bone malignancy is relatively rare, accounting for 0.2% of all cancers and less than 5% of all osseous neoplasms.¹⁵ Primary tumors of the spine are particularly rare, accounting for 2.8%⁹ to 13%⁶ of all primary bone tumors. Patients with spinal tumors typically present with variable and nonspecific signs and symptoms, but 85% of these patients present with pain.¹⁶ Patients with sacral tumors typically complain of low-back pain that is insidious in onset and not related to activity. Other symptoms may include radicular pain, weakness, bowel or bladder dysfunction, and paresthesia. Point tenderness over the spine is a common physical finding, but patients only infrequently present with a palpable mass. Due to the low incidence of sacral tumors and the difficulty of identifying tumors on plain radiographs, a high clinical suspicion

is required for a timely diagnosis; consequently, delayed diagnosis is common.

Imaging features of various spinal tumors are often characteristic, but because of the overlying bowel gas, lytic, destructive lesions are difficult to identify on plain radiographs and require MRI or CT evaluation. Definitive diagnosis is based on histological evaluation of a specimen obtained through either core needle biopsy or open biopsy. Once the diagnosis has been determined, surgical therapy may be undertaken, but surgical treatment for sacral tumors can be quite challenging, with complications of neural compression, lumbopelvic instability, and suboptimal oncological resection. Complications resulting from sacrificing sacral nerves intraoperatively can be burdensome for the patient. Removing more than 50% of the S-1 vertebra/

ABBREVIATIONS ABC = aneurysmal bone cyst; GCT = giant cell tumor; IGS = image-guided surgery; WBB = Weinstein-Boriani-Biagini.

SUBMITTED April 1, 2016. **ACCEPTED** June 21, 2016.

INCLUDE WHEN CITING DOI: 10.3171/2016.6.FOCUS16125.

sacral ala can result in lumbopelvic instability. Sacrificing the S2–4 nerve roots bilaterally results in erectile dysfunction as well as bowel and bladder dysfunction. However, preserving a single S-2 root usually preserves continence. Sacrifice of the S-3 nerve root usually results in minimal dysfunction, with preservation of sphincter function. A thorough understanding of these operative nuances, and applying them to routine practice, can result in substantial benefit for patients.

The newest developments in intraoperative stereotactic navigation have added to the accuracy and preciseness for addressing aggressive sacral tumors in spine surgery. The use of stereotactic navigation with cone-beam fluoroscopy and CT to obtain 3D imaging has been well described for the safe and accurate placement of pedicle screws.^{44,52} CT guidance has also been described in surgical planning for resection of nonsacral spinal tumors.^{76,85,86} It has been used to aid in localization of spinal lesions, visualize operative margins, and plan osteotomies in order to optimize surgical outcome. In this paper, we identified and discussed these operative nuances, including image-guided resection, in order to help reduce risks and complications for patients needing operative therapy for aggressive sacral tumors.

Methods

We performed a retrospective review of a single-institution, multi-surgeon, series of cases of pathology-proven sacral tumors that were treated surgically between 2009 and 2016. Patients were identified through a search of our institutional database, and data were collected through review of patient charts.

We also performed a literature review, using PubMed to identify articles relating to aggressive sacral tumors, their diagnosis, and their surgical treatment. The key words used in the search queries included the following: aggressive sacral tumors, chordoma, osteosarcoma, chondrosarcoma, giant cell tumor, surgical resection, adjuvant treatment, computer-assisted surgery, and image-guided surgery (IGS).

Surgical Technique With Image Guidance

Patient Positioning

All patients in our case series were placed prone on a Jackson radiolucent spinal operating table, and all pressure points were padded appropriately. The dorsal lumbosacral spine was sterilely prepared, and care was taken to drape the entire sacral spine as widely as possible. We recommend having a wide draping area as it allows for skin surface anatomy identification (posterior superior iliac spine, iliac crest, and midline spinous processes) and provides orientation during the entire procedure.

Navigated Reference Frame for Sacral Surgery

The ideal reference frame location is always dependent on the operative goals of the surgeon and the anatomy of the patient. For sacral surgery, the options for a percutaneous reference pin into the ilium or a spinous process reference clamp are debatable. In our earlier experiences, we found that the percutaneous pin placed in the posterior superior iliac spine often interfered with the surgeon's

FIG. 1. Operating room setup showing the percutaneously placed posterior superior iliac spine reference frame (left) and the O-arm moving into position (right).

or assistant's operative field and commonly caused line-of-sight issues (Fig. 1). As a result, we currently elect to proceed with the reference clamp percutaneously placed on a proximal lumbar spinous process and directed away from the surgical area. The StealthStation workstation (Medtronic) and LED detector camera were placed at the head or the foot of the bed. Careful attention must be paid to placement of the navigated reference frame and StealthStation, an example of the issues that a surgeon must consider in order to maximize navigated workflow efficiency in sacral surgery.

CT Image Acquisition

CT images were obtained using a cone-beam mobile CT scanner (O-arm, Medtronic) and were transferred to the computer-assisted StealthStation surgical navigation workstation. 3D reconstruction images were created on the StealthStation for navigation purposes. All navigated instruments were calibrated according to the manufacturer's guidelines. Although it is possible to keep the O-arm in the sterile surgical field during the entire procedure, we prefer to remove the O-arm and station it in the operating room.

Incision

Midline skin incisions were planned using a navigated probe, and biopsy tracks were excised en bloc with the specimen in cases of malignant tumors. Exposure of the sacrum and the extent of the tumor were determined using the navigated probe. Once the bony sacrum was exposed, depending on the type of resection (intralesional, wide resection, en bloc, etc.), the margins of the desired resection were marked for tumor removal.

Navigated Tumor Resection

The navigated probe is the main instrument used to identify and verify exact bony landmarks and tumor margins. As many destructive sacral tumors are lytic in nature, the ability of CT image-guided navigation to identify non-lytic bony margins makes it an ideal imaging modality. A second instrument that we commonly use in sacral tumor resection is the SureTrak reference frame attachment on a Midas drill (Medtronic) or osteotome. Once the navigated Midas drill has been calibrated, it allows the surgeon to make exact bony cuts for osteotomies and perform neural

TABLE 1. Summary of retrospective, single-institution, multi-surgeon review of cases involving patients with aggressive sacral tumors who underwent image-guided surgery*

Case No.	Pt Age (yrs), Sex	Diagnosis	Spinal Level	Procedure Performed	EBL (ml)	OR Time (mins)	LOS (days)	Complications	Neuro Status
1	70, M	Osteosarcoma	S1–3	Rt S1–3 laminectomies, medial sacral osteotomies of sacral pelvic tumor	2500	221	12	None	Rt L-4 radiculopathy
2	67, M	Chordoma	S2–3	Radical sacrectomy, neurolysis of left S-1 nerve root, lt S-2 & S-3 rhizotomies	1300	298	6	None	Urinary retention
3	20, M	Chondrosarcoma	Lt sacrum	En bloc radical resection w/ partial sacrectomy, hemipelvectomy	600	353	4	None	Intact
4	58, F	Chondrosarcoma	Rt acetabulum, pelvis	Type II internal hemipelvectomy w/ en bloc radical pelvic resection & reconstruction	1000	226	7	None	Intact
5	24, M	GCT	Lt sacrum	Biopsy, curettage, partial lt sacrectomy, neurolysis of S-1 & S-2 nerve roots, lt-sided S1–2 laminectomies	3000	210	3	None	Intact
6	51, F	GCT	L5–S1	Resection of giant cell tumor w/ cryotherapy	2800	180	4	None	Rt L-5 radiculopathy 2/2 stenosis

EBL = estimated blood loss; GCT = giant cell tumor; LOS = length of stay; neuro = neurological; OR = operating room; pt = patient.

* O-arm imaging was used for guidance in all cases.

decompression in otherwise distorted anatomy. The ability of CT image-guided navigation to visualize deep bony anatomy allows for maximal ability to resect the sacral tumor with minimal damage to surrounding soft tissue. Equally important, the anterior bone surface of the sacrum can be measured and the depth of the osteotome can be predetermined to avoid injury to the anterior structures.

Intraoperative Assessment of Tumor Resection

Intraoperative post-tumor resection CT images can be obtained with the mobile cone-beam CT scanner to assess adequacy of tumor margins in conjunction with intraoperative examination of frozen sections. This was done routinely in all our sacral tumor cases to confirm wide resection and avoid additional postoperative imaging and possible revision surgery. Margins were also sent for pathological examination to confirm wide excision.

Results

We identified 6 patients (2 women and 4 men) with sacral tumors who underwent surgery at our institution between 2009 and 2016 (Table 1). A total of 4 surgeons operated on the 6 patients. The age of the patients ranged from 20 to 70 years at the time of operation. The diagnosis was chondrosarcoma in 2 cases, giant cell tumor in 2 cases, chordoma in 1 case, and osteosarcoma in 1 case. In all 6 cases, IGS (based on O-arm technology) was performed. No operative complications were reported in any case. One patient was noted to have right L-4 radiculopathy postoperatively, one had urinary retention requiring Foley catheter placement upon discharge, and one had new-onset right L-5 radiculopathy approximately 7 years postoperatively, which was attributed to spinal stenosis. Two cases were selected for further presentation and are described below.

Illustrative Cases

Case 1

This 70-year-old man with a history of osteoarthritis originally presented with pain in his right hip area. On examination, he had tenderness around the right posterior superior iliac spine, iliac crest, and sacroiliac joint. His gait and station were within normal limits and he had 5/5 strength in his iliopsoas, quadriceps, tibialis anterior, extensor hallucis longus, and gastrocnemius muscles. He underwent a workup including MRI of the bilateral hips and lumbosacral spine, plain radiographs of the pelvis, and a CT scan of the pelvis (Fig. 2). Osteosarcoma was diagnosed, and the patient subsequently underwent a planned en bloc resection of the tumor under image guidance, with the surgery performed by a team of spine surgeons and orthopedic oncologists.

Right S1–3 laminectomies were performed under O-arm guidance without complications. Images from the IGS can be seen in Fig. 3. The estimated blood loss from the procedures was 2.5 L, and the patient was noted to do well postoperatively with the exception of right L-4 radiculopathy. Postoperative images were obtained and can be seen in Fig. 4. Further follow-up showed persistent right L-4 radiculopathy, which was attributed to probable pelvic instability. The patient was not a candidate for pelvic reconstruction given that he was being treated with concurrent chemotherapy.

Case 2

This 67-year-old man had a history of a sacral mass for 8 years prior to presentation; the mass had been shown to be increasing in size over the last 2 years. Imaging showed a 2-cm lytic lesion in the left sacrum at the S2–3 level involving the neural foramina (Fig. 5). The patient was referred to orthopedic oncology for further evaluation. At the time of presentation, he did not have any neurological

FIG. 2. Case 1. Preoperative axial T2-weighted MR (**upper**) and CT (**lower**) images.

deficits or bowel/bladder dysfunction. A CT-guided biopsy was performed. The pathology report on the specimen describes a bone marrow lesion within the left S2–3 segment of the sacrum involving the neural foramina and ob-

FIG. 3. Case 1. Intraoperative StealthStation screenshots showing localization of the lesion utilizing image (O-arm) guidance.

FIG. 4. Case 1. Postoperative axial CT image.

scuring the nerve roots, consistent with a chordoma (Fig. 6). Immunohistochemical testing was positive for pancytokeratin and S100 (Fig. 6C and 6D, respectively) as well as for INI-1 (MRQ-27).

The patient was referred to the neurosurgery team for further surgical evaluation. He subsequently underwent an en bloc radical sacrectomy of S-1, S-2, S-3, and S-4, neurolysis of the left S-1 nerve root, and sacral rhizotomies of the left S-2 and S-3 nerve roots, performed under CT image-guided and stereotactic navigation (Fig. 7). The estimated blood loss was 1300 ml, and there were no operative complications. Pelvic imaging was performed postoperatively (Fig. 8). The patient's postoperative course was complicated by ileus, which resolved after a bowel regimen, and urinary retention requiring straight catheterization; ultimately, a Foley catheter was placed. He was subsequently discharged home with a Foley catheter and was noted to be otherwise neurologically intact.

Discussion

From our literature research and anecdotal experience with aggressive sacral tumors, we have put together a review categorized by type of tumor. The mainstay of our research findings is the nuances in treating these sacral tumors with CT image-guided navigation to achieve optimal oncological resection, to reduce neurological complications, and to minimize recurrence. Malignant tumors are nearly always eccentric, and in order to achieve clear margins, excising the involved sacral nerves with the tumor en bloc is most often required. En bloc resection is most critical in low-grade malignancies, such as chordoma and chondrosarcoma, because adjuvant therapy has limited value. Wide en bloc excision with clear margins should not be sacrificed for neurological function in patients with malignant tumors because local recurrence and eventual spread of disease are nearly universal when the tumor is violated during resection.

Image-Guided Navigation

Background

To our knowledge, this study reports on the largest

FIG. 5. Case 2. Preoperative axial T1-weighted MR (upper) and CT (lower) images.

experience with aggressive sacral tumors with the use of image-guided CT navigation. Previous published reports have described the use of IGS in other areas of the spine.^{2,3,5} Two published reports describe the use of IGS in a total of 4 patients with aggressive sacral tumors—1 patient with Ewing's sarcoma¹ and 3 patients with sacral chordoma.²² In both reports, IGS was found to be a useful adjunct to the surgeon's anatomical knowledge and to decrease the likelihood of injury to vital adjacent structures. Additionally, by minimizing violation of the tumor capsule and increasing the likelihood of including appropriate surrounding tissue in wide resection, IGS was found to minimize recurrence in these studies and others.⁴⁹

Chordoma

Background

Chordomas are histologically low- to intermediate-grade tumors that arise from notochord remnants from Rathke's pouch to the coccyx. While slow growing, chordomas are locally invasive, aggressive, and highly recurrent.^{4,6} They may demonstrate regional spread and distant

FIG. 6. Case 2. Photomicrographs of specimens from image-guided resection of the sacral tumor showing a conventional chordoma. **A and B:** H & E-stained sections. The tumor cells are characterized by epithelioid morphology with pale eosinophilic cytoplasm embedded in a myxoid matrix. The tumor also demonstrates entrapment of host bone (A). Occasional tumor cells contain one or more intracytoplasmic vacuoles, creating a bubbly appearance, so-called "physaliphorous" cells (B). **C and D:** Immunohistochemical staining. The tumor cells are strongly positive for keratin (C) and S-100 protein (D). Original magnification $\times 100$ (A and D), $\times 400$ (B), and $\times 200$ (C).

metastasis and therefore may be considered malignant tumors.³⁹ Distant metastasis may occur to lungs, regional lymph nodes, lungs, liver, peritoneum, bone, muscle, and other soft tissues.^{7,9} Chordomas are extremely rare, with an estimated prevalence of 0.8 per million.¹⁸ They were first reported in 1894 by Ribbert, and since that time not many more than 1000 cases have been reported.¹⁸ However, excluding lymphoproliferative neoplasms, chordomas are the most common primary malignant tumors of the spine, reported to represent between 22.0%¹⁶ and 36.0%⁹ of primary spinal tumors.¹⁹ Furthermore, approximately 33% of primary osseous neoplasms in the sacral spine are chordomas.⁹ Chordomas are distributed along the distal and proximal ends of the axial skeleton. Fifty percent of chordomas have been reported to be found in the sacrum, particularly in lower sacral areas, S-3 and S-4; 35%, near the clivus; and 15%, in the cervical region.^{19,23} More re-

FIG. 7. Case 2. Intraoperative StealthStation images showing localization of the lesion under O-arm guidance.

FIG. 8. Case 2. Postoperative axial CT images.

cent studies, however, have shown a more even distribution along the axial skeleton.⁶⁸

Epidemiology

Chordomas are most commonly found in patients aged 30–60 years, with a peak incidence in the 5th and 6th decades of life. Chordomas are more common in men than in women (ratio 1.7:1).¹⁸ Patients usually present with localized pain of insidious onset. Neurological deficits, bladder or bowel dysfunction, and radiculopathies are less common complaints.¹² Chordomas are slow-growing but aggressive bulky tumors that can cause severe bone destruction and constipation. Due to the nonspecific symptoms associated with these tumors, patients often present with advanced disease.⁶

Imaging

CT imaging typically reveals a destructive, lytic lesion involving the midline of a vertebral body, but the lesion is often eccentric with a large associated soft-tissue mass.⁷ Frequently, there is osseous expansion and intratumoral calcification. T1-weighted MRI demonstrates low signal intensity and a mildly heterogeneous mass. T2-weighted MRI shows hyperintense signal within a lobular mass associated with punctate foci of low signal intensity. Histologically, chordomas contain clear cells with intracytoplasmic vacuoles and abundant intracellular and extracellular mucin, termed physaliphorous cells. Chordomas are distinctly lobular, and the neoplastic cells are arranged in interlacing cords between the mucoid stroma. Atypical or dedifferentiated chordomas may contain chondroid or osteoid elements.¹⁷ These tumors must often be differentiated from other clear-cell tumors, including metastatic renal carcinoma, melanoma, and chondrosarcoma.

Treatment

These tumors are minimally responsive to chemotherapy and conventional radiotherapy; therefore, resection is the mainstay of treatment.^{8,9} Radiotherapy with only debulking surgery is ineffective.¹⁰ Radiotherapy may be used

as an adjuvant therapy, but its effectiveness in providing local control is contested in the literature.^{11–15} This may be due, in part, to studies using heterogeneous radiation and surgical treatment protocols as well as variance in patient factors between groups with limited follow-up.⁶ According to a systematic review, chordomas are generally insensitive to conventional chemotherapies.^{4,13,16} Effects have been reported with anthracycline, cisplatin, and alkylating agents, but these reports involved small numbers of patients without long-term follow-up.^{17,18} Greater response was seen in dedifferentiated tumors, but these constitute only 2%–4% of chordomas.^{6,17,19}

Surgical Pearls

In patients with sacrococcygeal chordoma, a wide surgical margin is the most important predictor of survival and lower rates of recurrence.¹² To obtain a sufficient margin, an anterior approach may be required in addition to a traditional posterior approach for tumors with extensive anterior extension. The approach is dependent on the cephalad and anterior extent as well as tumor size.^{6,8,9} A combined anteroposterior approach may better facilitate a wide resection.^{20,21} This is particularly important for tumors that are cephalad to the S-3/sacroiliac joint.¹² Tumors that lie below this level may be treated with a posterior-only approach, which is preferable as it presents less operative morbidity.^{4,6} However despite being a single procedure with a shorter operative time, a posterior-only approach does carry the hazard of injury to pelvic viscera as well as the ureters; the anterior structures are not directly visualized during osteotomy.²¹ Even with anterior and posterior approaches, centers vary on whether these are performed simultaneously or sequentially. A simultaneous approach allows direct anterior visualization during osteotomy.^{23–25} Utilization of the anterior approach involves a transperitoneal exposure via a midline laparotomy. After the posterior parietal peritoneum is opened, pelvic structures may be directly identified. The middle sacral artery, as a direct aortic branch, may bleed briskly during the approach.²⁰ To reduce bleeding during tumor resection, the middle sacral, lower lumbar segmental, iliolumbar, and additional branches of the internal iliac vessels may be ligated along with draining veins. The ureters and rectum may be mobilized and the sacrum exposed proximal to the tumor.^{4,9,21} The anterior approach allows the creation of a transabdominal myocutaneous rectus abdominis flap for coverage.²⁶ The flap is created as part of the anterior approach and placed into the pelvis and then used in the reconstruction of the sacrectomy defect posteriorly. The use of acellular dermal matrix between abdominal contents and flap coverage may be associated with a decrease in bowel-related complications.²⁷ Postoperative deficits are directly correlated to sacrifice of sacral and sciatic nerve roots as dictated by tumor involvement and the necessity of obtaining a wide margin. Preoperative bladder, bowel, and motor function as well as the tumor level with its related resection level have been shown to be the most important predictors of postoperative function.^{28,29} Bilateral L-5 and S-1 sparing facilitates a functional ambulatory gait, bilateral S-2 sparing is needed for a gait that allows normal activities of daily living.^{4,30} Sparing the S-2 nerve root alone results in a 50% chance of satisfactory bladder and bowel function.^{20,31} Bilateral S-3

nerve root preservation is necessary for normal bladder, bowel, and sexual function.^{28,30} The prognosis of chordoma is poor overall. Studies report 5-year survival rates of between 45% and 77% and 10-year survival rates between 28% and 60%.^{20,32–36}

Chondrosarcoma

Background

Chondrosarcomas are malignant tumors of cartilaginous matrix. Chondrosarcoma is a rare disease, with an estimated incidence of 1 in 200,000 per year. There are several histological subtypes, including myxoid, mesenchymal, dedifferentiated, and clear cell, but these are rare, and conventional chondrosarcoma accounts for more than 80% of all cases. Secondary chondrosarcomas may arise from enchondromas or osteochondromas, and low-grade (Grade I) chondrosarcoma may progress to high-grade (Grade II or III) disease.³⁷

Epidemiology

Although rare overall, chondrosarcoma is the second most common primary malignant tumor of bone (25.8%), after osteosarcoma (35.1%).^{8,15} and is the most common malignant tumor of flat bones in adults. In the spine, chondrosarcoma is more common than osteosarcoma. The spine is the primary site in 3%–12% of patients with chondrosarcoma,^{10,23} and in the spine, chondrosarcomas are the second most common malignant tumors after chordomas.^{9,16,21} The thoracic spine is the most commonly involved region, with the sacrum being affected in approximately 20% of cases.²⁵ Primary chondrosarcoma is predominantly found in the vertebral body and posterior elements, described as Zones 10–3 by the Weinstein-Boriani-Biagini (WBB) grading system.⁴ In the sacrum, however, chondrosarcoma is more commonly found eccentrically, with local involvement of the sacroiliac joints.¹¹ Patients usually present with localized pain of insidious onset. The incidence of chondrosarcoma peaks between 50 and 70 years of age, and there is a strong male predominance.⁴ Chondrosarcomas are slow-growing tumors, and their clinical course is typically long. A palpable mass over the spine is relatively common, signifying involvement of the posterior arch. The 5-year survival rates for chondrosarcoma in general approach 70%, with dedifferentiated and mesenchymal subtypes being the most lethal.¹⁴ Bone destruction with characteristic punctate calcifications and chondroid matrix mineralization are the predominant findings in primary chondrosarcoma of the spine.²⁵

Imaging

In patients with chondrosarcoma, CT and MRI often reveal a destructive lesion of bone with an associated soft-tissue mass with high water content in nonmineralized areas. In 35% of cases, there is extension into the intervertebral disc.²¹ T1-weighted MRI typically demonstrates a hypointense mass with canalicular extension. The central portion of the tumor is typically poorly enhancing due to myxoid and chondral tissue, but peripheral nodular enhancement may be seen.^{10,19} There is significant diagnostic difficulty in differentiating cartilage tumors based on histology because other hyaline cartilage-forming lesions, such as en-

chondroma, can have similar histological findings.^{38,75} The clinical and radiological findings are essential in differentiating enchondroma from chondrosarcoma, and enchondroma should not break out of the bone, a common finding with chondrosarcoma of the sacrum and spine.

Treatment

Chondrosarcomas are typically highly resistant to conventional radiotherapy and chemotherapy, but there is a contested effect of chemotherapy on mesenchymal and dedifferentiated subtypes.^{39–41} Radiation therapy has been described for the treatment of surgically inaccessible sites and positive margins as well as in palliative therapy for symptom relief, but it is rarely effective in curing these tumors.^{41–45}

Surgical Pearls

Due to chondrosarcoma's resistance to adjuvant therapies, surgery is the cornerstone of treatment. Chondrosarcoma is surgically treated in a manner similar to that of chordoma, with the goal being a wide margin (en bloc resection).^{46–48} En bloc resection of chondrosarcoma with or without radiation therapy has better outcomes than curettage.⁴ We believe that pelvic and spinal chondrosarcomas should not be treated with curettage and cryoablation because of the unacceptably high local recurrence rate and eventual spread of the tumor. Boriani and colleagues¹⁰ demonstrated a 20% recurrence rate with en bloc resection and even lower rates with successful, wide margins compared with a nearly 100% recurrence or progression rate with piecemeal excision and curettage. While low-grade chondrosarcoma has been treated with intralesional resection in selected cases outside the pelvis, for pelvic chondrosarcoma, wide resection has typically been recommended.^{50–53} For Grade I tumors within the pelvis, Donati has suggested that contaminated margins may be acceptable in certain cases.²⁵ In a study of 153 patients, Fiorenza and colleagues³² identified the primary risk factors for recurrence as inadequate margins at the time of resection and initial tumor size > 10 cm. The importance of surgical margins has been repeatedly demonstrated.^{54,55} Five-year survival rates as high as 90% have been reported for patients with low-grade tumors, while the corresponding rates for patients with high-grade tumors are 40%–50%.^{46,55–59} We have used image guidance in treating patients with chondrosarcoma to improve our surgical margins while limiting our complications by avoiding excessive bone resection and preserving neurovascular structures. Our intraoperative goal is to obtain at least a 2-cm margin from the tumor seen on intraoperative CT and correlated with MRI. Currently, we are utilizing a program that allows the integration of both CT and MRI intraoperatively, and this can further define the extent of tumor as well.

Giant Cell Tumors

Background

Giant cell tumors (GCTs) are benign but highly locally aggressive mesenchymal tumors. They form lytic, expansile lesions that include osteoclast-like giant cells and lack matrix mineralization. GCTs are rare tumors, accounting for approximately 5% of all primary bone tumors in

adults.¹³ The most common sites for GCT are the epiphyses of the knee as well as the distal radius, followed by the sacrum. Only 8% of GCTs occur in the spine,^{20,26} and within the spine there is a strong predilection for the sacrum, which is affected in 90% of cases.²⁴ Patients with sacral GCT typically present with radicular pain, weakness, and sensory deficits. Abdominal, bowel, and bladder complaints may occur.⁶⁰ The peak incidence is in the 3rd and 4th decades of life. Unlike most primary bone tumors, GCTs are more common in women than men, with a male to female ratio of approximately 1:1.3.²⁰ Histologically, GCTs are composed of stromal ovoid to spindle mononuclear cells with varying uniformity of multinucleated giant cells.⁶¹ Sacral GCT often involves both sides of the midline, and extension across the sacroiliac joint is common.¹⁹

Imaging

In patients with GCTs, CT typically demonstrates an expansile lesion associated with an anterior soft-tissue mass. T1- and T2-weighted MRI sequences demonstrate a large area of sacral destruction with a soft-tissue mass. MRI typically shows a low- to intermediate-intensity lesion due to fibrosis. GCT is the most common tumor associated with secondary aneurysmal bone cysts (ABCs). This can be identified on MRI by a characteristic finding of fluid/fluid levels and is important because local recurrence is thought to be higher and bleeding may be greater in patients with GCTs associated with ABCs.¹⁹

Treatment

Adjuvant therapies often have significant roles in the treatment of GCT, in contrast to chordoma and chondrosarcoma. Radiation therapy has been used in the sacrum, especially as an adjunct to intralesional surgery, or as primary therapy in cases in which resection is difficult.^{62–66} Leggon et al.⁶⁰ presented data to suggest radiation therapy may be more appropriate for large lesions only. While radiotherapy may be used alone, it poses a risk of radiation-induced sarcoma in addition to immediate local morbidity. Consequently, we have never used radiation therapy in the management of GCT. The literature includes only limited support for the use of traditional chemotherapy in the treatment of GCT, but newer therapies, including diphosphonates, denosumab, and interferons, may have a role, although their current use is currently primarily experimental.⁶⁸ Diphosphonates are antiosteoclastic and have been shown to have a possible role in the treatment of GCT in the extremities.⁶⁹ Denosumab, an antibody to receptor activator of nuclear factor- κ B ligand (RANKL) that is expressed by osteoclasts, has been shown to generate a tumor response.^{70,71}

Surgical Pearls

Surgical treatment options for GCT vary considerably. Preoperative embolization minimizes risk of hemorrhage when performed prior to surgery. Its ability to halt growth of tumor has been described.^{72–74} Lackman et al.⁵⁸ reported on 5 cases of sacral GCT treated solely with recurrent arterial embolization, with 4 demonstrating no growth or recurrence. Intralesional curettage is the mainstay of treatment in long bones and is often combined with local adjuvants such as cryotherapy, peroxide, ethanol, phenol, and

bone cement to reduce recurrence.^{61–63,77,78} However, due to the proximity of critical neurological structures, such as adjuvants may not be appropriate or must be used only with care in the sacrum. Intralesional resection in the sacrum may potentially preserve neurological and other critical structures but present a greater risk of local recurrence, whereas wide excision may sacrifice neurological function to reduce recurrence.^{67,79–84} In a series of 17 cases, Leggon et al.⁶⁰ reported a 47% recurrence rate for intralesional resection, a 46% recurrence rate for intralesional resection plus radiotherapy, and 0% recurrence rate for wide excision.⁶⁰ The recently published 35-year experience of Memorial Sloan Kettering comprises 24 patients treated with intralesional excision, 19 of whom were also treated with adjuvant cryotherapy, with a local recurrence rate of 30%.²⁴ Currently, we are utilizing intraoperative image guidance probes to identify loculations of tumor to improve curettage and applying selective cryoablation with excellent results. This is essential because honeycomb involvement of the sacrum with GCT is common and often difficult to identify without image guidance.

Osteosarcoma

Background

Osteosarcoma, also known as osteogenic sarcoma, is the most common primary tumor of bone, accounting for approximately 35.1% of all primary bone tumors.⁴ Primary osteosarcoma of the vertebral column is rare. The incidence ranged from 0.85% to 4.0% in several large series of primary osteosarcoma.^{6–8} There is a male predilection.⁸ Appendicular osteosarcoma has a bimodal distribution, whereas osteosarcoma localized to the vertebral column has a peak incidence in the 4th decade.⁶ The prognosis of vertebral osteosarcoma is poor, with death usually occurring within 1 year of diagnosis. In patients with sacral osteosarcoma, the prognosis is worse.¹⁰ Osteosarcoma is a high-grade malignant lesion that is predominantly osteosclerotic. In the vertebral column, it typically arises in the posterior elements and may invade the vertebral body or spinal canal. In 17% of cases, there is involvement of 2 vertebral levels.⁶ The tumor is characterized by osteoid production, an immature matrix, and mineralization. Secondary osteosarcoma may be due to Paget's disease or previous radiation therapy. Primary osteosarcoma may arise at any spinal level, but it is more common in the thoracolumbar region than in sacral or cervical locations.⁶ Patients present with pain, a palpable mass, and neurological symptoms related to nerve root compression. High serum alkaline phosphatase levels are seen on laboratory evaluation.

Imaging

On plain radiography and CT imaging, osteosarcoma typically appears as a heterogeneous mass with ossified and nonossified components representing a mixed osteosclerotic-osteolytic lesion. A classic description of an ivory vertebral body (also seen in lymphoma) may be seen, with a moth-eaten pattern of bone destruction, cortical interruption, and a soft-tissue mass, and the lesion must be differentiated from lymphoma.⁸ Loss of vertebral height may also occur. Distinguishing between osteosarcoma and benign osteoblastoma may be difficult in some cases.⁷ Absence of a soft-tissue mass in 10% of osteosarcomas

makes the lesions indistinguishable from osteoblastoma.⁶ In such cases, biopsy is necessary for definitive diagnosis, and even then, the tumors can be difficult to distinguish from osteoblastoma. If a diagnosis of osteoblastoma is determined, close monitoring with MRI for local recurrence should be strongly considered. MRI is most useful for evaluating the soft-tissue component of the lesion and extension into the spinal canal and adjacent nerve roots. Mineralized portions appear hypointense on T1- and T2-weighted MRI, and nonmineralized portions appear hyperintense on T2-weighted MRI.⁸ Categorization into lytic, sclerotic, or mixed subtypes is considered to be of practical importance.¹⁰ Purely osteolytic lesions represent approximately 20% of cases.⁶ Telangiectatic osteosarcoma is predominantly osteolytic, and demonstrates a fluid-fluid level on MRI.

Surgical Pearls

Osteosarcoma of the spine is characterized by high rates of recurrence, metastasis, and mortality. Complete resection was previously considered impossible in cases of spinal osteosarcomas.⁷ Advances in total surgical and reconstruction techniques¹¹ have allowed total en bloc resection to be performed in selected patients with spinal osteosarcoma.^{12,13} A wide margin is necessary for optimal treatment due to the aggressive nature of the disease and high rate of local recurrence. Neoadjuvant chemotherapy and postoperative chemotherapy may improve survival, but the prognosis remains poor.¹²

Conclusions

Aggressive sacral tumors can be an extremely difficult challenge for both the patient and the treating physician. The type of surgical intervention varies depending on the type of tumor, its size, and the location. Surgery can have profound risks, including neural compression, lumbopelvic instability, and suboptimal oncological resection. Focusing on the operative nuances for each tumor type can help prevent many of these complications. Utilization of IGS to aid in tumor resection has been useful in reducing blood loss and the local recurrence rate while preserving neurological function in both malignant and aggressive benign tumors affecting the sacrum.

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Disclosures

Dr. Kim reports a consultant relationship with DePuy Synthes and receipt of clinical or research support from Medtronic. Dr. Johnson reports receipt of grant funding from Medtronic.

Author Contributions

Conception and design: Drazin, Bhamb, Kappel, Kim, Johnson, Brien. Acquisition of data: all authors. Analysis and interpretation of data: all authors. Drafting the article: all authors. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Drazin. Statistical analysis: Kappel, Kim. Administrative/technical/material support: Drazin, Bhamb, Al-Khouja, Johnson, Brien. Study supervision: Drazin, Bhamb, Kappel, Kim, Johnson, Brien.

Correspondence

Doniel Drazin, Department of Neurosurgery, Cedars-Sinai Medical Center, Advanced Health Sciences Pavillion-Neurosciences, 8700 Beverly Blvd., 6th Fl., Los Angeles, CA 90048. email: doniel.drazin@cshs.org.