10.5005/jp-journals-10039-1069

REVIEW ARTICLE

Minimally Invasive Techniques for the Treatment of Primary Spinal Column Lesions

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ABSTRACT

Minimally invasive spine surgery is becoming more prevalent as surgeons seek to provide definitive treatment without the morbidity and dysfunction associated with traditional, open surgical procedures. Minimally invasive surgery has been applied with success to the treatment of degenerative disease and traumatic injuries of the spine. Approaches to metastatic and primary spinal column tumors have also evolved rapidly as clinicians seek to minimize tissue disruption, postoperative pain and blood loss in these susceptible patient populations who may also require adjuvant therapies. The various noninvasive and minimally invasive techniques available for the treatment of these primary spinal tumors are reviewed, and their indications, benefits, and limitations discussed.

Keywords: Corpectomy, Minimally invasive spinal surgery, Percutaneous, Vertebral tumors.

How to cite this article: Balamurali G, Kothari AR, Anaizi AN, Voyadzis JM, O'toole J, Fessler RG. Minimally Invasive Techniques for the Treatment of Primary Spinal Column Lesions. J Spinal Surg 2015;2(4):132-140.

Source of support: Nil

Conflict of interest: None

INTRODUCTION

The spinal column represents the most common site for bony metastatic spread and consequently metastatic disease of the spine is encountered far more frequently than primary tumors.[4,5,9,41,73,74,92,98] Primary tumors of the vertebral column are relatively rare comprising 10% or less of all vertebral column tumors.[11] Benign primary lesions of the spine include osteoid osteoma, osteoblastoma, osteochondroma, chondroblastoma, giant-cell tumor, aneurysmal bone cyst, eosinophilic granuloma and cavernous hemangioma.[88] Malignant or locally aggressive primary tumors include osteosarcoma, Ewing's sarcoma, soft tissue sarcoma, chordoma, chondrosarcoma, solitary plasmacytoma and multiple myeloma.[88] A thorough knowledge of the spectrum of lesions that can affect the vertebral column is essential in providing the appropriate work-up and therapeutic interventions. Also, knowledge of their radiological appearance on computerized tomography (CT) and magnetic resonance imagining (MRI) scans are essential to initiate a treatment plan.

Minimally invasive techniques have been devised to treat a myriad of conditions affecting the spine. Decompression, arthrodesis and instrumentation are now performed routinely with minimal access spinal technology (MAST) through the use of tubular retractors and percutaneous instrumentation systems.[21,38,50,59,77,82,87] The demonstrated benefits include less tissue dissection, decreased postoperative pain, reduced length of hospital stay, and earlier mobilization and return to work.[20,23,40,51] These ongoing efforts to minimize surgical morbidity have also been applied to spinal oncology with the goal of providing greater therapeutic options and adding to the surgeon's technical armamentarium. This is particularly important in the medically compromised tumor patient who may not be a good candidate for an extensive surgical procedure.

TREATMENT GOALS

The realistic objectives of the surgical treatment for any spinal tumor must be clearly defined. In some cases, diagnosis may be the primary goal, which can be achieved by a percutaneous method of CT guided biopsy. For many extradural tumors this can be accomplished by CT-guided biopsy with 71 to 96.5% diagnostic accuracy.[6] A lasting cure is the goal of surgery for most primary spinal column tumors. As such, the choice of surgical technique is critical in achieving access and definitive excision. Numerous studies have demonstrated that negative margins with en bloc resection of primary malignant tumors of the spine significantly decrease recurrence rates and prolong survival.[4,5,7,9,41,73,74,98] The surgical approach must be tailored to meet this goal. The important objectives involved are:

- Diagnosis
- Tumor removal for local control and/or cure,

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- Circumferential spinal cord decompression
- Symptomatic pain relief and
- Spinal stability.

Where indicated, treatment options should incorporate arthrodesis, deformity correction, and fixation for levels that have been destabilized either by the tumor or by the treatment itself.[35,53,55,92,102]

METHODS

A comprehensive literature search using the Ovid gateway of the MEDLINE database from 1950 to December 2009 was performed. The following keywords were queried individually and in combination: 'minimally invasive spine surgery,' 'vertebral tumors,' 'primary spinal tumors' 'lumbar', 'thoracic', 'spinal metastasis' and 'endoscopic spinal surgery'. The search was limited to human studies published in English. A manual hand search of references from the identified papers was then also performed. All studies were carefully scrutinized for patient clinical characteristics, type of spinal tumor, radiographic characteristics, and treatment modality employed. The data are all presented in this extensive review.

DRAWBACKS OF TRADITIONAL SURGICAL APPROACHES

Traditional open surgical procedures for spinal tumors can carry an up to 30% complication rate, including neurological deterioration, severe medical complications, massive hemorrhage, wound complications including infection and dehiscence, hardware complications, cerebrospinal fluid leaks and death.[2,17,18,29,34,35,53-55,63,86,96,102,105-107] If a patient has had previous radiation treatment to the surgical site, the rate of wound complications can be as high as 40%.[28,76,107] There are numerous potential complications that accompany an open thoracotomy including atelectasis, pulmonary contusion, pleural effusion, hemothorax, chylothorax, intercostal neuralgia or significant postoperative pain due to rib resection and chest wall retraction (post-thoracotomy syndrome). These complications affect at least 11% of patients.[8,17,22,97,99] During an anterior or posterior thoracic approach, an incidental durotomy can cause a subarachnoid-pleural fistula. This rare complication is seen in 2.4% patients with anterior approach and 0.23% from a posterior approach. Eight out of nine patients required surgical repair of the fistula in one series.[34]

Traditional open posterior laminectomy, requires a subperiosteal dissection resulting in denervation and devascularization of the paraspinal muscles. This ultimately results in diminished postoperative axial muscle strength and performance.[42,44-48,62,79,90,91,95,104] In the cervical spine, injury to the semispinalis capitis and cervices muscles along with disruption of the bony and ligament us components of the posterior tension band can result in a post-laminectomy kyphosis. This has been shown to negatively affect outcome.[10,94] It can be seen in 10 to 40% of adults and 24 to 100% of pediatric patients undergoing posterior laminectomy and is most commonly seen after intradural tumor surgery.[3,10,94]

MINIMALLY INVASIVE TECHNIQUES

The aim of any minimally invasive intervention for the treatment of spinal neoplasms is to minimize the collateral damage to normal surrounding spinal anatomy.[6,56,67,69] This should ultimately translate into shorter operative times, less blood loss, fewer complications, decreased postoperative pain, shorter hospital stays and decreased medical resource utilization.[20,23,40,51] For this review, we have categorized then into percutaneous, noninvasive techniques and minimally invasive surgical techniques.

PERCUTANEOUS AND NONINVASIVE TECHNIQUES

Percutaneous radiofrequency ablation (RFA) is a minimally invasive option for the treatment of certain tumors of the vertebral column.[6,13,30,80,85] Radiofrequency ablation is a CT or fluoroscopically guided method by which thermal energy is delivered to a target. Asteroid stomas have been treated successfully in this manner with success rates of 79 to 89%.[83,100] Most of these lesions were treated with single fraction radiation with similar success rates.[13,26,32,100] There have also been reports of its successful use in the treatment of metastatic disease of the spine.[30] Given the use of thermal energy in RFA, it is limited by lesion size and proximity to neural structures.[26] Most authors recommend that the target for treatment is no closer than 1 cm to a sensitive neural structure (i.e. theca sac, nerve root) and require the presence of a layer of cortical bone between the lesion and neural structures in order for patients to be considered for RFA.[13,26,32,33] Although this treatment modality comes with significant limitations it offers an attractive treatment option, i.e. relatively simple, economically feasible and avoids the morbidity associated with traditional surgical resection.

Vertebroplasty and kyphoplasty are additional minimally invasive therapeutic options for the treatment of compression fractures due to vertebral column tumors. These techniques both involve the injection of acrylic cement into the vertebral body. Kyphoplasty is meant to provide a greater restoration of vertebral height than injection of cement alone by creating a cavity, prior to injection of the cement. These are minimally invasive techniques meant to provide pain relief and improved stability of the vertebral body. Vertebroplasty and kyphoplasty are ideal options for patients with intractable pain, more extensive disease involving multiple vertebral bodies, patients with a poor prognosis and limited life span and patients that would not tolerate more invasive surgical options, such as en bloc resection and instrumentation.[6,24,55] Both of these procedures have been widely used in multiple myeloma compression fractures.[57] Improvement in Oswestry Disability Index (ODI) of 86% and partial restoration of vertebral height was achieved in the anterior and middle columns in 76 and 91% of levels treated, respectively.[57] A randomized controlled trial of 300 patients published by Wardlaw et al in the Lancet in 2009 found that patients with vertebral compression fractures treated with balloon kyphoplasty had significant improvements in quality of life, function, mobility, and pain relief when compared to patients treated non-surgically.[103] A more recent randomized controlled trial of 131 patients published by Kallmes et al in the New England Journal of Medicine in 2009 comparing vertebroplasty to a sham procedure for osteoporotic compression fractures disputes the aforementioned results.[43]

As with any invasive procedure, vertebroplasty and kyphoplasty carry their own potential complications. These include as follows:

- Leakage of cement and
- Fracture of adjacent vertebral bodies.

Cement may leak into one of several compartments including the disk space, paravertebral tissue, paravertebral venous plexus (potentially leading to a pulmonary embolism) or the epidural space (potentially compressing neural elements).[75] Kyphoplasty appears to carry a negligible leak rate when compared to vertebroplasty.[6] Adjacent level fracture is a greater concern in osteoporotic patients than patients with euplastic lesions and can be as high as 25%.[25]

Percutaneous techniques and non-invasive therapies have also been used in combination.[27,30,33,39,70] Radiofrequency ablation has been used in conjunction with vertebroplasty through the same bone biopsy needle port for the palliative treatment of malignant bone lesions, particularly metastases.[30,70] In one series, 19 spinal tumors were treated in this fashion with a 100% rate of significant decreases in VAS scores and post-procedural tumor necrosis seen in a mean of 71% of total tumor volumes.[78] Neural injury was seen in four of these patients, in whom the tumor had violated the cortex of the posterior vertebral body or pedicle, emphasizing the need for intact cortex between RFA electrodes and neural structures.[85] It has been theorized that RFA may reduce intravascular cement leakage during subsequent vertebroplasty via thrombosis of the intravertebral venous plexus.[33] Combination therapy of kyphoplasty and spinal radiosurgery (SRS) for metastatic spinal lesions[27] has been reported with 92% of patients who experienced pain relief, in the absence of cement leakage. To date, no such studies have been performed on primary spinal lesions.

The percutaneous injection of pharmacological agents, under CT or fluoroscopic guidance, has been used in the treatment of vertebral column tumors. Aneurysmal bone cysts have been injected under CT or fluoroscopic guidance with sclerosing agents or calcitonin and methylprednisolone to induce ossification in patients with pain but without neurological compression or spinal instability.[16,31,78]

MINIMALLY INVASIVE SURGICAL TECHNIQUES

A number of minimally invasive surgical approaches to the spine have been developed to minimize surgical morbidity. When adopting the following approaches for the treatment of primary spinal column tumors, the surgeon must carefully weigh the benefits of these techniques *vs* the risk of failing to achieve the defined surgical objectives. Insufficient exploration during a minimally invasive approach can lead to an incomplete and, therefore, noncurative resection, inadequate decompression of the neural elements and unsatisfactory stabilization.

Thoracoscopic surgery represents a major advance in minimizing the morbidity associated with resection of tumors of the thoracic spine.[15,80,83] This technique involves placement of 3 to 4 ports through small incisions in the chest and placement of a rigid endoscope, allowing visualization of the anterior thoracic spine (T3–T12). Corpectomy and reconstruction is performed using specialized long instruments.[40] The advantages of this approach over the traditional thoracotomy include decreased incisional pain, earlier ambulation, shorter hospital stays, decreased incidence of intercostals neuralgia, shoulder girdle dysfunction and post-thoracotomy syndrome.[6,18,80,83] As with a traditional thoracotomy, this approach requires lung deflation and subsequent chest tube drainage, and hence the potential for postoperative pulmonary complications, and consequent prolonged hospital stay, remains. The rate of pulmonary complications has been reported to be 10 to 29%.[15,37,63] Moreover, the surgical learning curve for thoracoscopic techniques and equipment costs can be prohibitive for some surgeons and centers.[15,22,80,84]

Endoscopic systems have also been applied to traditional surgical approaches with the objective of reducing incision size and tissue dissection while maintaining or enhancing visualization. Endoscopes have been used in the ventral cervicothoracic and upper thoracic spine (C7–T3) while sparing the sternum, clavicle and ribs.[60] This was performed through a 6 to 8 cm anterior incision and multiple ports through which the endoscope and specialized instruments were used to perform a corpectomy and reconstruction. The endoscope has also been utilized in performing a posterolateral thoracic corpectomy using a transpedicular or costotransversectomy approach.[55,65,66] The angled endoscope allows for safe, complete ventral decompression and reconstruction under improved visualization when compared to traditional transpedicular or costotransversectomy approaches. This approach also spares the patient the morbidity of a lateral extracavitary (LEC) or transthoracic approach.

Several authors have described a mini-transthoracic or mini-retroperitoneal approach for thoracolumbar corpectomy.[36,56,69] Six vertebral tumors out of 65 spinal tumors were removed in this manner.[56] A 5 cm skin incision was used but otherwise were similar to traditional anterolateral techniques. In general, these approaches take advantage of specialized retractor systems that permit continued visualization through the constrained working space.[56,69] These studies report modest improvements in blood loss, length of stay, complications, and operative times.[36,56,69]

Extreme or direct lateral minimally invasive approaches to the thoracic and lumbar spine have been developed to achieve interbody fusion. With the same approach current tubular retractors systems allow for enough exposure to perform corpectomy and stabilization from T4 to L4. These procedures still typically require separate positioning and incisions for posterior fixation and arthrodesis. A case of successful T6 corpectomy and T5 to T7 anterior fusion utilizing an extreme lateral minimally invasive approach for the management of a T6 metastatic lesion has been reported.[49]

Posterolateral approaches to the thoracic and lumbar spine in the prone position avoid the morbidity associated with a transthoracic or abdominal approach and allow for the placement of instrumentation without the need for repositioning.[19,58,64,81] In 2007, a mini-open posterior approach for lumbar corpectomies was reported. This was done through bilateral 2 to 3 cm incisions extending from the superior aspect of the rostral disk space to the inferior aspect of the pedicle of the vertebral body of interest.[61] Through this incision they performed a complete facetectomy, and discectomy of the superior disk space. The corpectomy was subsequently performed with the disk space serving as a space for extravasations of bone fragments. This was done bilaterally. An underbody graft was placed within the superior disk space. Subsequently, percutaneous pedicle screws and rods were placed caudal and rostral to the vertebral body of interest. In their series, corpectomies were performed for the management of traumatic lumbar burst fractures with retropulsed bone. This can, however, be applied to certain euplastic conditions, particularly in patients that cannot tolerate a more invasive anterior approach. This technique is limited in its ability to assure complete ventral decompression of the theca sac as well as the ability to perform dorsal decompression if indicated. In 2008, a series of 8 patients with metastatic disease to the thoracic spine with acute neurologic compromise that underwent minimally invasive transpedicular vertebrectomy without instrumentation. Five of eight (62.5%) patients improved at least 1 grade on the Nurick scale and had significant pain relief postoperatively. This method may be an attractive option for palliative treatment of malignant lesions of the thoracic spine.[14]

Percutaneous pedicle screw fixation alone is a palliative minimally invasive option for rigid fixation in the treatment of spinal instability. Many patients with vertebral column tumors will require fusion in conjunction with other therapeutic options, such as vertebroplasty/kyphoplasty or RFA. This can be done with or without stereotactic image-guidance.[1,20] This technique is ideal for patients with spinal instability and limited life-expectancy or poor candidates for open surgical fusion.

Our group recently studied the feasibility of minimally invasive posterolateral thoracic corpectomies in cadavers beginning 3, 6 and 9 cm lateral to the midline[72] (Fig. 1). We studied the extent of bony removal and degree of ventral decompression. The specimens were placed in the prone position. A 3.5 cm longitudinal skin incision was made at varying distances off of the midline. Dilators were used to spread the fibers of the altissimo dorsa and serratus anterior muscles until the rib was in view. The rib was dissected in the typical subperiosteal

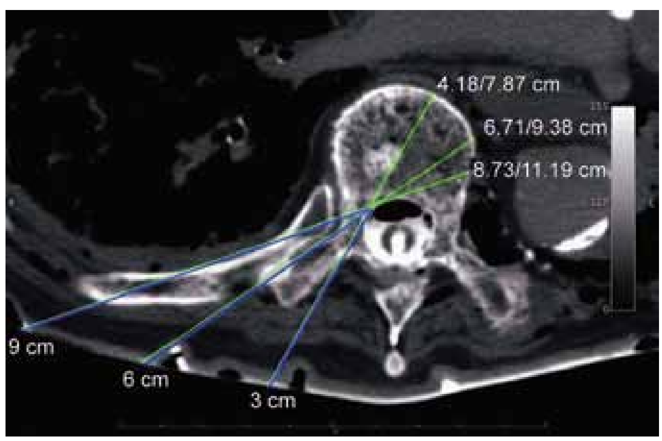


Fig. 1: Axial computed tomography scan of a T8 vertebral body at the level of the pedicle. This illustrates the measurements of the distance from skin incision to the ventral spinal canal (blue) and the contralateral vertebral body cortex

fashion, followed as far medially as possible, stripped of the intercostals neurovascular bundle and underlying pleura and respected. A tubular retractor was then placed at the medial extent of our dissection and the rib was dissected medially to the transverse process (TP), which was then drilled away. The pedicle was removed exposing the lateral dural and exiting nerve roots. The vertebral body was then dissected and the segmental vessels and sympathetic chain legated. Using a drill, rongeurs and curettes the vertebral body was removed as far medially as could be performed safely. The endplates were then prepared and an appropriate underbody strut was inserted. Using post-procedure fine cut CT scans the average percentage of corpectomy was found to be 81.5% and the extent of ventral decompression was 92% (Fig. 2). We found an approach 6 cm off midline to be ideal for proper exposure and vertebral body resection. Lateral

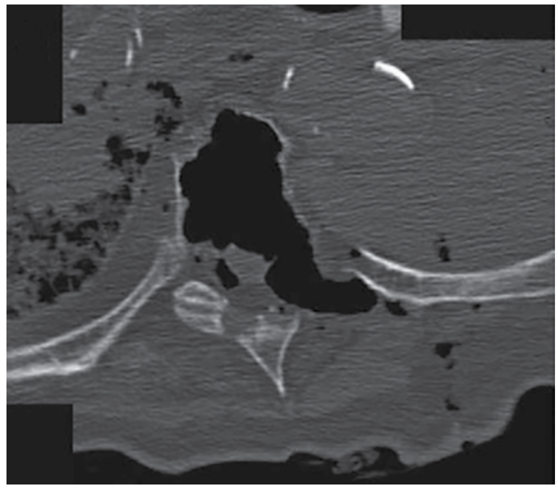
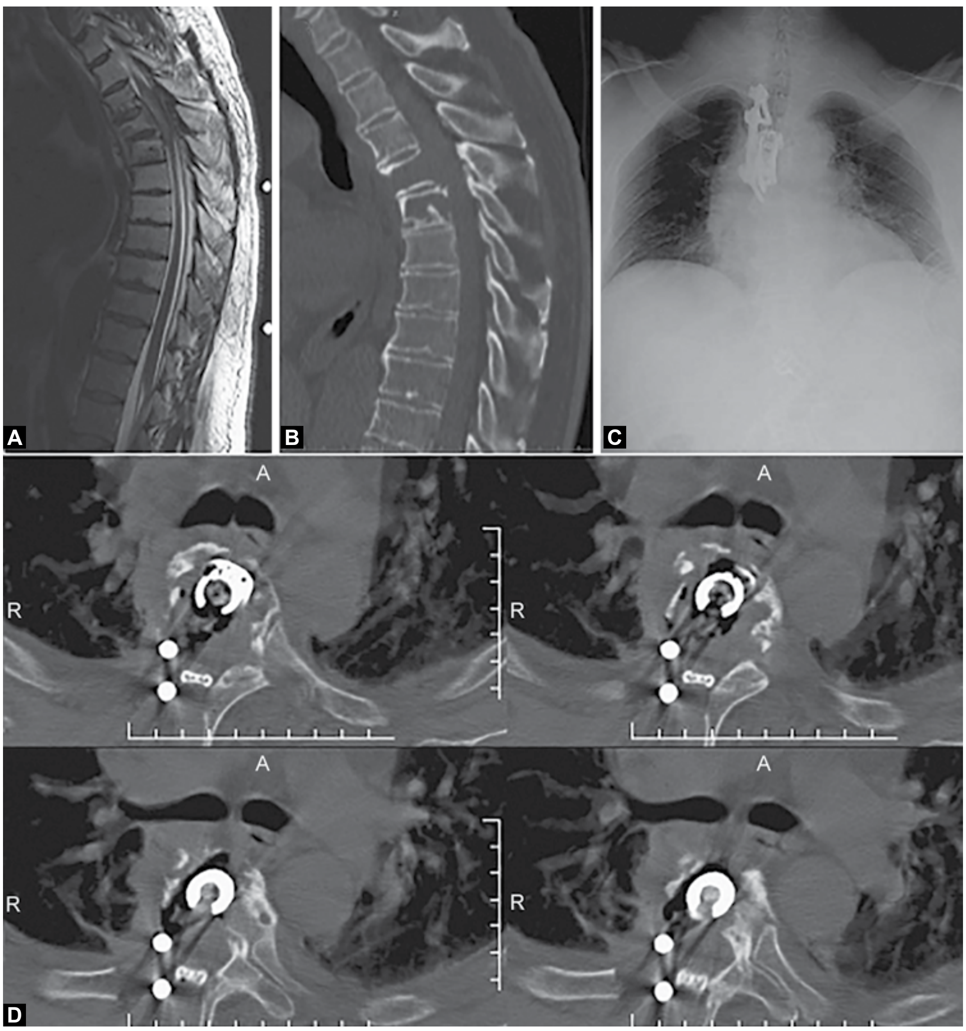
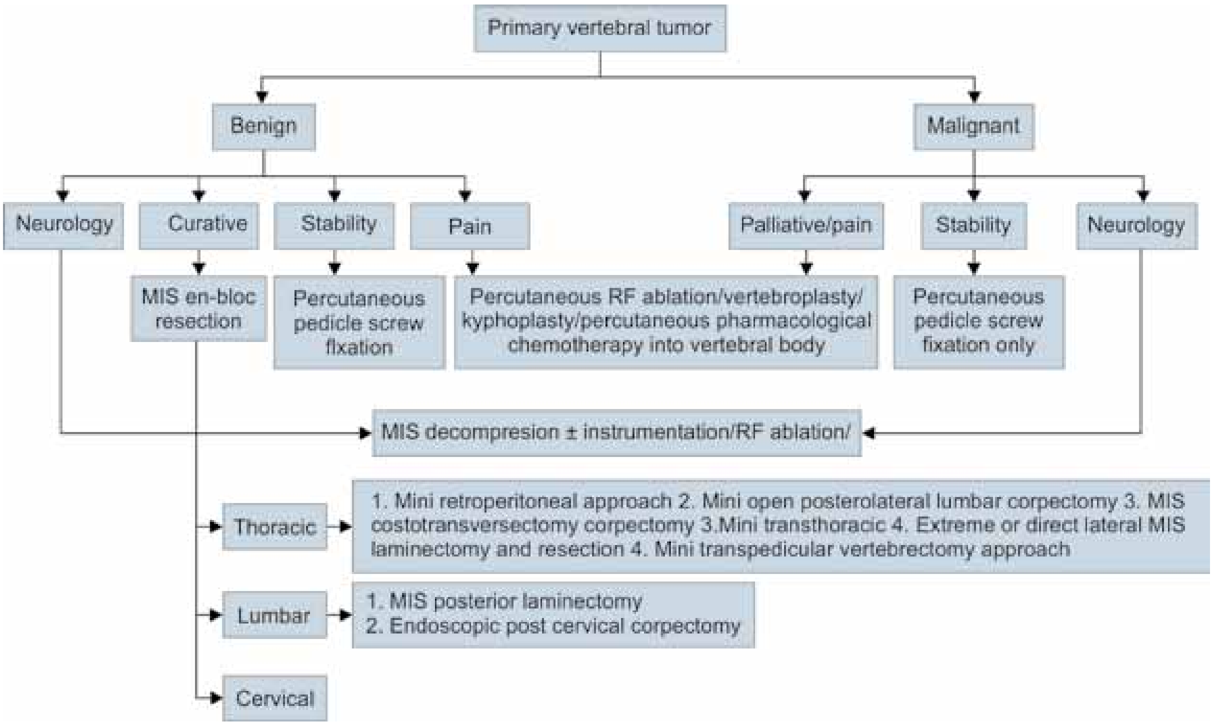


Fig. 2: Post-procedural axial computed tomography scan after a minimal access LEC thoracic corpectomy in a cadaver model demonstrate satisfactory spinal canal decompression and vertebral body resection from 6 cm



Figs 3A to D: A 59-year-old man presented with chronically progressive myelopathy from thoracic plasmacytoma despite radiation therapy. (A) Sagittal T2-weighted MRI reveals plasmacytoma of the T4 and T5 vertebral bodies with collapse and epidural spinal cord compression, (B) sagittal reconstruction of the CT scan of the same patient demonstrates replacement of the T4 and T5 bodies with tumor, (C) anteroposterior radiograph of same patient after a right-sided minimal access LEC corpectomy of T4 and T5. The defect was reconstructed using an expandable titanium cage and ipsilateral vertebral body and pedicle screws with rod fixation and (D) postoperative axial CT images show the extent of bone removal from a right-sided approach, with satisfactory placement of the autograft-filled intervertebral cage. The rods connecting the screws are seen on the right side of the defect, and a surgical drain is seen overlying the laminectomy site (A: anterior; R: right)

Flow Chart 1: Minimal invasive techniques in the management of spinal vertebral tumors



vertebral body screws can be placed if additional anterior fixation is desired. Alternatively, posterior instrumentation can be inserted at the same setting through the same incision ipsilaterally and percutaneously on the contralateral side. A gentleman with T4 to T5 plasmacytoma was managed using this surgical technique with adequate decompression and reconstruction (Figs 3A to D). We also recently described several other cases of patients operated upon using this technique.[52]

Finally, in 2009, a thoracolumbar neurofibroma was successfully removed using a transdiaphragmatic robotic assisted laparoscopic approach utilizing the da Vinci robot (Intuitive Surgical, Sunnyvale, CA). Minimally invasive retroperitoneal laparoscopic access was obtained, the urologic surgeons opened the diaphragm and the robot was docked. The neurosurgeon then operated the robot and excised the neurofibroma from its nerve origin. The mass was completely resected without complications.[68] The use of robotics in spine surgery is not commonplace but represents yet another potential therapeutic application that warrants consideration.

RECOMMENDATIONS

Based on the assessment of the literature and our own experience, several conclusion and recommendations can be made. The most important of all is achieving the goals of treatments that are out layed in the paper. Treatment should be tailored to each individual patient's general condition, preoperative comorbidity, prognosis of the tumor if pathology known, surgeons and patient preference and availability of resources and technology. No specific treatment modality can be recommended unless these issues are considered. The available techniques based on the clinical goal of treatment related to pain or palliative control, neurological compromise, stability or curative treatment is summarized in Flow Chart 1.

CONCLUSION

Minimally invasive techniques for the removal of spinal column tumors are continuing to evolve. Many of these approaches compare favorably with the more traditional operations in their ability to achieve adequate neural decompression and recovery of function.[1,6,12,13,15,20,23,24,36,66,69,71,89,93] The surgeon must carefully weigh the benefits of reducing operative morbidity *vs* the risks of failing to achieve surgical objectives, notably curative resection. The application of these techniques is of particular use for the palliative care of the medically compromised patient who would otherwise not tolerate a more traditional surgical approach. Further advances in retractor systems, surgical instrumentation, targeted chemotherapeutic delivery systems and osteobiologic agents hold great promise as we continuously strive to improve the quality of life of patients with neoplastic disease.

REFERENCES

1. Acosta FL Jr, Thompson TL, Campbell S, Weinstein PR, Ames CP. Use of intraoperative isocentric C-arm 3D fluoroscopy for sextant percutaneous pedicle screw placement: case report and review of the literature. Spine J 2005 May-Jun;5(3): 339-343.

2. Aebi M. Spinal metastasis in the elderly. Eur Spine J 2003 Oct; 12 (Suppl 2):S202-213.
3. Bell DF, Walker JL, O'Connor G, Tibshirani R. Spinal deformity after multiple-level cervical laminectomy in children. Spine 1994 Feb 15;19(4):406-411.
4. Bergh P, Gunterberg B, Meis-Kindblom JM, Kindblom LG. Prognostic factors and outcome of pelvic, sacral, and spinal chondrosarcomas: a center-based study of 69 cases. Cancer 2001 Apr 1;91(7):1201-1212.
5. Bergh P, Kindblom LG, Gunterberg B, Remotti F, Ryd W, Meis-Kindblom JM. Prognostic factors in chordoma of the sacrum and mobile spine: a study of 39 patients. Cancer 2000 May 1;88(9):2122-2134.
6. Binning MJ, Gottfried ON, Klimo P Jr, Schmidt MH. Minimally invasive treatments for metastatic tumors of the spine. Neurosurg Clin N Am 2004 Oct;15(4):459-465.
7. Bohinski RJ, Rhines LD. Principles and techniques of en bloc vertebrectomy for bone tumors of the thoracolumbar spine: an overview. Neurosurg Focus 2003 Nov 15;15(5):E7.
8. Bohlman HH, Zdeblick TA. Anterior excision of herniated thoracic discs. J Bone Joint Surg Am 1988 Aug;70(7):1038-1047.
9. Boriani S, De Iure F, Bandiera S, et al. Chondrosarcoma of the mobile spine: report on 22 cases. Spine 2000 Apr 1;25(7): 804-812.
10. Casha S, Engelbrecht HA, DuPlessis SJ, Hurlbert RJ. Suspended laminoplasty for wide posterior cervical decompression and intradural access: results, advantages, and complications. J Neurosurg Spine 2004 Jul;1(1):80-86.
11. Chi JH, Bydon A, Hsieh P, Witham T, Wolinsky JP, Gokaslan ZL. Epidemiology and demographics for primary vertebral tumors. Neurosurgery Clinics of North America 2008;19(1): 1-4.
12. Chiou SM, Eggert HR, Laborde G, Seeger W. Microsurgical unilateral approaches for spinal tumour surgery: 8 years' experience in 256 primary operated patients. Acta Neurochir (Wien) 1989;100(3-4):127-133.
13. Cove JA, Taminiau AH, Obermann WR, Vanderschueren GM. Osteoid osteoma of the spine treated with percutaneous computed tomography-guided thermocoagulation. Spine 2000 May 15;25(10):1283-1286.
14. Deutsch H, Boco T, Lobel J. Minimally invasive transpedicular vertebrectomy for metastatic disease to the thoracic spine. Spinal Disorders and Techniques 2008;21(2):101-105.
15. Dickman CA, Rosenthal D, Karahalios DG, et al. Thoracic vertebrectomy and reconstruction using a microsurgical thoracoscopic approach. Neurosurgery 1996 Feb;38(2):279-293.
16. Duncan IC, Fourie PA, Alberts AS. Direct percutaneous intratumoral bleomycin injection for palliative treatment of impending quadriplegia. Am J Neuroradiol 2004 Jun-Jul;25(6): 1121-1123.
17. Faciszewski T, Winter RB, Lonstein JE, Denis F, Johnson L. The surgical and medical perioperative complications of anterior spinal fusion surgery in the thoracic and lumbar spine in adults: a review of 1223 procedures. Spine 1995 Jul; 20(14):1592-1599.
18. Ferson PF, Landreneau RJ, Dowling RD, et al. Comparison of open versus thoracoscopic lung biopsy for diffuse infiltrative pulmonary disease. J Thorac Cardiovasc Surg 1993 Aug; 106(2):194-199.
19. Fessler RG, Dietze DD Jr, Millan MM, Peace D. Lateral parascapular extrapleural approach to the upper thoracic spine. J Neurosurg 1991 Sep;75(3):349-355.
20. Fessler RG, Eichholz KM, Kim DH, Song J, Christie S, Toole JEO. Minimally invasive lateral thoracic vertebrectomy. Annual Meeting of the American Association of Neurological Surgeons. San Francisco 2006.
21. Fessler RG, Khoo LT. Minimally invasive cervical microendoscopic foraminotomy: an initial clinical experience. Neurosurgery 2002;51(Suppl 5):S37-45.
22. Fessler RG, Sturgill M. Review: complications of surgery for thoracic disc disease. Surg Neurol 1998 Jun;49(6):609-618.
23. Foley KT, Gupta SK. Percutaneous pedicle screw fixation of the lumbar spine: preliminary clinical results. J Neurosurg 2002 Jul;97(Suppl 1):7-12.
24. Fourney DR, Schomer DF, Nader R, et al. Percutaneous vertebroplasty and kyphoplasty for painful vertebral body fractures in cancer patients. J Neurosurg 2003 Jan;98(Suppl 1):21-30.
25. Frankel BM, Monroe T, Wang C. Percutaneous vertebral augmentation: an elevation in adjacent-level fracture risk in kyphoplasty as compared with vertebroplasty. Spine J 2007;7(5):575-582.
26. Gangi A, Basile A, Buy X, Alizadeh H, Sauer B, Bierry G. Radiofrequency and laser ablation of spinal lesions. Semin Ultrasound CT MR 2005 Apr;26(2):89-97.
27. Gerszten PC, Germanwala A, Burton SA, Welch WC, Ozhasoglu C, Vogel WJ. Combination kyphoplasty and spinal radiosurgery: a new treatment paradigm for pathological fractures. J Neurosurg Spine 2005 Oct;3(4):296-301.
28. Ghogawala Z, Mansfield FL, Borges LF. Spinal radiation before surgical decompression adversely affects outcomes of surgery for symptomatic metastatic spinal cord compression. Spine 2001 Apr;26(7):818-824.
29. Gokaslan ZL, York JE, Walsh GL, et al. Transthoracic vertebrectomy for metastatic spinal tumors. J Neurosurg 1998 Oct;89(4):599-609.
30. Gronemeyer DH, Schirp S, Gevargez A. Image-guided radiofrequency ablation of spinal tumors: preliminary experience with an expandable array electrode. Cancer J 2002 Jan-Feb; 8(1):33-39.
31. Guibaud L, Herbreteau D, Dubois J, et al. Aneurysmal bone cysts: percutaneous embolization with an alcoholic solution of zein-series of 18 cases. Radiology 1998 Aug;208(2):369-373.
32. Hadjipavlou AG, Lander PH, Marchesi D, Katonis PG, Gaitanis IN. Minimally invasive surgery for ablation of osteoid osteoma of the spine. Spine 2003 Nov;28(22):E472-477.
33. Halpin RJ, Bendok BR, Sato KT, Liu JC, Patel JD, Rosen ST. Combination treatment of vertebral metastases using image-guided percutaneous radiofrequency ablation and vertebroplasty: a case report. Surg Neurol 2005 May;63(5): 469-474.
34. Hentschel SJ, Rhines LD, Wong FC, Gokaslan ZL, McCutcheon IE. Subarachnoid-pleural fistula after resection of thoracic tumors. J Neurosurg 2004 Apr;100(4 Suppl Spine):332-336.
35. Hirabayashi H, Ebara S, Kinoshita T, et al. Clinical outcome and survival after palliative surgery for spinal metastases: palliative surgery in spinal metastases. Cancer 2003 Jan;97(2): 476-484.
36. Huang TJ, Hsu RW, Chen SH, Lee YY. Minimal access surgery in managing anterior lumbar disorders. Clin Orthop Relat Res 2001 Jun;(387):140-147.
37. Huang TJ, Hsu RW, Sum CW, Liu HP. Complications in thoracoscopic spinal surgery: a study of 90 consecutive patients. Surg Endosc 1999 Apr;13(4):346-350.
38. Isaacs RE, Podichetty VK, Santiago P, Sandhu FA, Spears J, Kelly K, Rice L, Fessler RG. Minimally invasive microendoscopy-

assisted transforaminal lumbar interbody fusion with instrumentation. J Neurosurg Spine 2005;3(2):98-105.
39. Jang JS, Lee SH. Efficacy of percutaneous vertebroplasty combined with radiotherapy in osteolytic metastatic spinal tumors. J Neurosurg Spine 2005 Mar;2(3):243-248.
40. Johnson JP. Thoracoscopic management of spinal tumors. In: Kim DH, Fessler RG, Regan JJ, editors. Endoscopic Spine Surgery and Instrumentation: Percutaneous Procedures. New York: Thieme; 2005. p. 143-148.
41. Kager L, Zoubek A, Potschger U, et al. Primary metastatic osteosarcoma: presentation and outcome of patients treated on neoadjuvant Cooperative Osteosarcoma Study Group protocols. J Clin Oncol 2003 May;21(10):2011-2018.
42. Kahanovitz N, Viola K, Gallagher M. Long-term strength assessment of postoperative diskectomy patients. Spine 1989 Apr;14(4):402-403.
43. Kallmes DF, Comstock BA, Heagerty PJ, Turner JA, Wilson DJ, Diamond TH, Edwards R, Gray LA, Stout L, Owen S, et al. A randomized trial of vertebroplasty for osteoporotic spinal fractures. N Engl J Med 2009 Aug 6;361(6):569-579.
44. Kawaguchi Y, Matsui H, Gejo R, Tsuji H. Preventive measures of back muscle injury after posterior lumbar spine surgery in rats. Spine 1998 Nov;23(21):2282-2287.
45. Kawaguchi Y, Matsui H, Tsuji H. Back muscle injury after posterior lumbar spine surgery. Part 1: Histologic and histochemical analyses in rats. Spine 1994 Nov;19(22):2590-2597.
46. Kawaguchi Y, Matsui H, Tsuji H. Back muscle injury after posterior lumbar spine surgery. Part 2: Histologic and histochemical analyses in humans. Spine 1994 Nov;19(22):2598-2602.
47. Kawaguchi Y, Matsui H, Tsuji H. Back muscle injury after posterior lumbar spine surgery: histologic and enzymatic analysis. Spine 1996 Apr;21(8):941-944.
48. Kawaguchi Y, Yabuki S, Styf J, et al. Back muscle injury after posterior lumbar spine surgery. Topographic evaluation of intramuscular pressure and blood flow in the porcine back muscle during surgery. Spine 1996 Nov 15;21(22):2683-2688.
49. Keshavarzi S, Park MS, Aryan HE, Newman CB, Amene CS, Gonda D, Taylor WR. Minimally invasive thoracic corpectomy and anterior fusion in a patient with metastatic disease: case report and review of the literature. Minim Invas Neurosurg 2009 Jun;52(3):141-143.
50. Khoo LT, Fessler RG. Microendoscopic decompressive laminotomy for the treatment of lumbar stenosis. Neurosurgery 2002;51(Suppl 5):S146-154.
51. Kim DH, Jaikumar S, Kam AC. Minimally invasive spine instrumentation. Neurosurgery 2002 Nov;51(Suppl 5):S15-25.
52. Kim DH, O'Toole JE, Ogden AT, Eichholz KM, Song J, Christie SD, Fessler RG. Minimally invasive posterolateral thoracic corpectomy: cadaveric feasibility study and report of four clinical cases. Neurosurgery 2009 Apr;64(4):746-752.
53. Klimo P Jr, Dailey AT, Fessler RG. Posterior surgical approaches and outcomes in metastatic spine-disease. Neurosurg Clin N Am 2004 Oct;15(4):425-435.
54. Klimo P Jr, Kestle JR, Schmidt MH. Treatment of metastatic spinal epidural disease: a review of the literature. Neurosurg Focus 2003 Nov;15(5):E1.
55. Klimo P Jr, Schmidt MH. Surgical management of spinal metastases. Oncologist 2004;9(2):188-196.
56. Kossmann T, Jacobi D, Trentz O. The use of a retractor system (SynFrame) for open, minimal invasive reconstruction of the anterior column of the thoracic and lumbar spine. Eur Spine J 2001 Oct;10(5):396-402.
57. Lane JM, Hong R, Koob J, et al. Kyphoplasty enhances function and structural alignment in multiple myeloma. Clin Orthop Relat Res 2004 Sep;(426):49-53.
58. Larson SJ, Holst RA, Hemmy DC, Sances A Jr. Lateral extracavitary approach to traumatic lesions of the thoracic and lumbar spine. J Neurosurg 1976 Dec;45(6):628-637.
59. Le H, Sandhu FA, Fessler RG. Clinical outcomes after minimal-access surgery for recurrent lumbar disc herniation. Neurosurg Focus 2003;15(3):E12.
60. Le Huec JC, Lesprit E, Guibaud JP, Gangnet N, Aunoble S. Minimally invasive endoscopic approach to the cervicothoracic junction for vertebral metastases: report of two cases. Eur Spine J 2001 Oct;10(5):421-426.
61. Maciejczak A, Barnas P, Dudziak P, Jagiello-Bajer B, Litwora B. Minimally invasive posterior corpectomy of the lumbar spine with transpedicular fixation. Neurol Neurochir Pol 2004 Nov-Dec;38(6):511-516.
62. Mayer TG, Vanharanta H, Gatchel RJ, et al. Comparison of CT scan muscle measurements and isokinetic trunk strength in postoperative patients. Spine 1989 Jan;14(1):33-36.
63. McAfee PC, Regan JR, Zdeblick T, et al. The incidence of complications in endoscopic anterior thoracolumbar spinal reconstructive surgery: a prospective multicenter study comprising the first 100 consecutive cases. Spine 1995 Jul 15; 20(14):1624-1632.
64. McCormick PC. Surgical management of dumbbell and paraspinal tumors of the thoracic and lumbar spine. Neurosurgery 1996 Jan;38(1):67-74.
65. McLain RF. Spinal cord decompression: an endoscopically assisted approach for metastatic tumors. Spinal Cord 2001 Sep;39(9):482-487.
66. Mobbs RJ, Nakaji P, Szkandera BJ, Teo C. Endoscopic assisted posterior decompression for spinal neoplasms. J Clin Neurosci 2002 Jul;9(4):437-439.
67. Moore T, McLain RF. Image-guided surgery in resection of benign cervicothoracic spinal tumors: a report of two cases. Spine J 2005 Jan-Feb;5(1):109-114.
68. Moskowitz RM, Young JL, Box GN, Pare LS, Clayman RV. Retroperitoneal transdiaphragmatic robotic-assisted laparoscopic resection of a left thoracolumbar neurofibroma. JSLS 2009 Jan-Mar;13(1):64-68.
69. Muhlbauer M, Pfisterer W, Eyb R, Knosp E. Minimally invasive retroperitoneal approach for lumbar corpectomy and anterior reconstruction: technical note. J Neurosurg 2000 Jul; 93(1 Suppl):161-167.
70. Nakatsuka A, Yamakado K, Maeda M, et al. Radiofrequency ablation combined with bone cement injection for the treatment of bone malignancies. J Vasc Interv Radiol 2004 Jul;15(7):707-712.
71. Nakatsuka A, Yamakado K, Maeda M, et al. Radiofrequency ablation combined with bone cement injection for the treatment of bone malignancies. J Vasc Interv Radiol 2004 Jul;15(7):707-712.
72. Ogden AT, Eichholz K, O'Toole J, Smith J, Gala V, Voyadzis JM, Sugimoto K, Song J, Fessler RG. Cadaveric evaluation of minimally invasive posterolateral thoracic corpectomy: a comparison of three approaches. J Spinal Disord Tech 2009 Oct;22(7):524-529.

73. Ozaki T, Flege S, Kevric M, et al. Osteosarcoma of the pelvis: experience of the cooperative osteosarcoma study group. J Clin Oncol 2003 Jan 15;21(2):334-341.
74. Ozaki T, Liljenqvist U, Halm H, Hillmann A, Gosheger G, Winkelmann W. Giant cell tumor of the spine. Clin Orthop Relat Res 2002 Aug;401:194-201.
75. Ozgur BM, Aryan HE, Pimenta L, Taylor WR. Extreme lateral interbody fusion: a novel surgical technique for anterior lumbar interbody fusion. Spine J 2006 Jul-Aug;6(4):435-443.
76. Patchell RA, Tibbs PA, Regine WF, et al. Direct decompressive surgical resection in the treatment of spinal cord compression caused by metastatic cancer: a randomised trial. Lancet 2005 Aug 20-26;366(9486):643-648.
77. Perez-Cruet MJ, Kim BS, Sandhu F, Samartzis D, Fessler RG. Thoracic microendoscopic discectomy. J Neurosurg Spine 2004;1(1):58-63.
78. Rai AT, Collins JJ. Percutaneous treatment of pediatric aneurysmal bone cyst at C1: a minimally invasive alternative: a case report. Am J Neuroradiol 2005 Jan;26(1):30-33.
79. Rantanen J, Hurme M, Falck B, et al. The lumbar multifidus muscle 5 years after surgery for a lumbar intervertebral disc herniation. Spine 1993 Apr;18(5):568-574.
80. Regan JJ, Mack MJ, Picetti GD 3rd. A technical report on video-assisted thoracoscopy in thoracic spinal surgery: preliminary description. Spine 1995 Apr 1;20(7):831-837.
81. Resnick DK, Benzel EC. Lateral extracavitary approach for thoracic and thoracolumbar spine trauma: operative complications. Neurosurgery 1998 Oct;43(4):796-802; discussion 802-793.
82. Rosen DS, O'Toole JE, Eicholz KM, Hrubes M, Huo D, Sandhu FA, Fessler RG. Minimally invasive lumbar spinal decompression in the elderly: outcomes of 50 patients aged 75 years and older. Neurosurgery 2007;60(3):503-509.
83. Rosenthal D, Marquardt G, Lorenz R, Nichtweiss M. Anterior decompression and stabilization using a microsurgical endoscopic technique for metastatic tumors of the thoracic spine. J Neurosurg 1996 Apr;84(4):565-572.
84. Rosenthal D, Rosenthal R, de Simone A. Removal of a protruded thoracic disc using microsurgical endoscopy: a new technique. Spine 1994 May 1;19(9):1087-1091.
85. Rosenthal DI, Hornicek FJ, Torriani M, Gebhardt MC, Mankin HJ. Osteoid osteoma: percutaneous treatment with radiofrequency energy. Radiology 2003 Oct;229(1):171-175.
86. Ryken TC, Eichholz KM, Gerszten PC, Welch WC, Gokaslan ZL, Resnick DK. Evidence-based review of the surgical management of vertebral column metastatic disease. Neurosurg Focus 2003 Nov 15;15(5):E11.
87. Sandhu FA, Santiago P, Fessler RG, Palmer S. Minimally invasive surgical treatment of lumbar synovial cysts. Neurosurgery 2004;54(1):107-111.
88. Sansur CA, Pouratian N, Dumont AS, Schiff D, Shaffrey CI, Shaffrey ME. Spinal-cord neoplasms—primary tumours of the bony spine and adjacent soft tissues. Lancet Oncol 2007 Feb;8(2):137-147.
89. Sario-Glu AC, Hanci M, Bozkus H, Kaynar MY, Kafadar A. Unilateral hemilaminectomy for the removal of the spinal space-occupying lesions. Minim Invasive Neurosurg 1997 Jun;40(2):74-77.
90. Sasaoka R, Nakamura H, Konishi S, Nagayama R, Suzuki E, Terai H, Takaoka K. Objective assessment of reduced invasiveness in MED Compared with conventional one-level laminotomy. Eur Spine J 2006 May;15(5):577-582. Epub 2005 May 31.
91. Sihvonen T, Herno A, Paljarvi L, Airaksinen O, Partanen J, Tapaninaho A. Local denervation atrophy of paraspinal muscles in postoperative failed back syndrome. Spine 1993 Apr;18(5):575-581.
92. Simmons ED, Zheng Y. Vertebral tumors: surgical versus nonsurgical treatment. Clin Orthop Relat Res 2006 Feb;443: 233-247.
93. Sridhar K, Ramamurthi R, Vasudevan MC, Ramamurthi B. Limited unilateral approach for extramedullary spinal tumours. Br J Neurosurg 1998 Oct;12(5):430-433.
94. Steinmetz MP, Kager CD, Benzel EC. Ventral correction of postsurgical cervical kyphosis. J Neurosurg 2003 Jan; 98(1 Suppl):1-7.
95. Styf JR, Willen J. The effects of external compression by three different retractors on pressure in the erector spine muscles during and after posterior lumbar spine surgery in humans. Spine 1998 Feb 1;23(3):354-358.
96. Sundaresan N, Rothman A, Manhart K, Kelliher K. Surgery for solitary metastases of the spine: rationale and results of treatment. Spine 2002 Aug 15;27(16):1802-1806.
97. Sundaresan N, Shah J, Foley KM, Rosen G. An anterior surgical approach to the upper thoracic vertebrae. J Neurosurg 1984 Oct;61(4):686-690.
98. Talac R, Yaszemski MJ, Currier BL, et al. Relationship between surgical margins and local recurrence in sarcomas of the spine. Clin Orthop Relat Res 2002 Apr;397:127-132.
99. Turner PL, Webb JK. A surgical approach to the upper thoracic spine. J Bone Joint Surg Br 1987 Aug;69(4):542-544.
100. Vanderschueren GM, Obermann WR, Dijkstra SPD, Taminiau AHM, Bloem JL, van Erkel AR. Radiofrequency ablation of spinal osteoid osteoma: clinical outcome. Spine 2009;34(9): 901-903.
101. Varga PP, Hoffer Z, Bors I. Computer-assisted percutaneous transiliac approach to tumorous malformation of the sacrum. Comput Aided Surg 2001;6(4):212-216.
102. Wai EK, Finkelstein JA, Tangente RP, et al. Quality of life in surgical treatment of metastatic spine disease. Spine 2003 Mar 1;28(5):508-512.
103. Wardlaw D, Cummings SR, Meirhaeghe JV, Bastian L, Tillman JB, Ranstam J, Eastell R, Shabe P, Talmadge K, Boonen S. Efficacy and safety of balloon kyphoplasty compared with non-surgical care for vertebral compression fracture (FREE): a randomised controlled trial. Lancet 2009;373:1016-1024.
104. Weber BR, Grob D, Dvorak J, Muntener M. Posterior surgical approach to the lumbar spine and its effect on the multifidus muscle. Spine 1997 Aug 1;22(15):1765-1772.
105. Weigel B, Maghsudi M, Neumann C, Kretschmer R, Muller FJ, Nerlich M. surgical management of symptomatic spinal metastases: postoperative outcome and quality of life. Spine 1999 Nov 1;24(21):2240-2246.
106. Wise JJ, Fischgrund JS, Herkowitz HN, Montgomery D, Kurz LT. Complication, survival rates, and risk factors of surgery for metastatic disease of the spine. Spine 1999 Sep 15;24(18):1943-1951.
107. Yao KC, Boriani S, Gokaslan ZL, Sundaresan N. En bloc spondylectomy for spinal metastases: a review of techniques. Neurosurg Focus 2003 Nov 15;15(5):E6.