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Radiosurgery for Spinal Metastases

Clinical Experience in 500 Cases From a Single Institution

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Study Design. A prospective nonrandomized, longitudinal cohort study.

Objective. To evaluate the clinical outcomes of single-fraction radiosurgery as part of the management of metastatic spine tumors.

Summary of Background Data. The role of stereotactic radiosurgery for the treatment of spinal lesions has previously been limited by the availability of effective target immobilization and target tracking devices. Large clinical experience with spinal radiosurgery to properly assess clinical experience has previously been limited.

Methods. A cohort of 500 cases of spinal metastases underwent radiosurgery. Ages ranged from 18 to 85 years (mean 56). Lesion location included 73 cervical, 212 thoracic, 112 lumbar, and 103 sacral.

Results. The maximum intratumoral dose ranged from 12.5 to 25 Gy (mean 20). Tumor volume ranged from 0.20 to 264 mL (mean 46). Long-term pain improvement occurred in 290 of 336 cases (86%). Long-term tumor control was demonstrated in 90% of lesions treated with radiosurgery as a primary treatment modality and in 88% of lesions treated for radiographic tumor progression. Twenty-seven of 32 cases (84%) with a progressive neurologic deficit before treatment experienced at least some clinical improvement.

Conclusions. The results indicate the potential of radiosurgery in the treatment of patients with spinal metastases, especially those with solitary sites of spine involvement, to improve long-term palliation.

Key words: CyberKnife®, image-guided surgery, robotic surgery, spine metastases, spine tumors, stereotactic radiosurgery. **Spine 2007;32:193–199**

In the past decade, surgical spinal oncology has focused on new surgical approaches to the spine, the application of new instrumentation to spinal reconstruction, various forms of radiation delivery systems, and, most importantly, complication avoidance. Patients with metastatic spine tumors are usually debilitated and at a high risk for surgical morbidity. For patients with limited life expectancies from their underlying disease, high surgical complication rates with a subsequent decrease in quality of life are most unacceptable. The role of radiation therapy in the treatment of metastatic tumors of the spine is well established and is often the initial treatment modality.[1–7] The goals of local radiation therapy in the treatment of spinal tumors have been palliation of pain, prevention of pathologic fractures, and halting progression of or reversing neurologic compromise.[8] Surgery is usually reserved for spinal instability or subluxation, in patients with neurologic deficits, despite other forms of therapy, and those with intractable pain attributable to an isolated lesion.[9–12]

Studies have previously determined the clinical efficacy of single-fraction therapy for painful bone metastases.[13,14] A primary factor that limits radiation dose for local vertebral tumor control with conventional radiotherapy is the relatively low tolerance of the spinal cord to radiation. Conventional external beam radiotherapy lacks the precision to deliver large single-fraction doses of radiation to the spine near radiosensitive structures such as the spinal cord. It is the low tolerance of the spinal cord to radiation that often limits the treatment dose to a level that is far below the optimal therapeutic dose.[1,15,16] Radiotherapy may provide less than optimal clinical response since the total dose is limited by the tolerance of the spinal cord. Precise confinement of the radiation dose to the treatment volume, as is the case for intracranial radiosurgery, should increase the likelihood of successful tumor control at the same time that the risk of spinal cord injury is minimized.[16–24]

In stereotactic radiosurgery, a high dose of radiation is delivered in a single fraction to a well-defined intracranial or extracranial target.[25] Radiosurgery has been shown to be very effective for controlling intracranial malignancies.[26–32] Stereotactic radiosurgery has been demonstrated to be an effective treatment for brain metastases, either with or without whole-brain radiation therapy, with an 85% to 95% control rate. The emerging technique of spinal radiosurgery represents a logical extension of the current state-of-the-art radiation therapy.

Since Hamilton *et al*[33] first described the possibility of linear-accelerator based spinal stereotactic radiosurgery in 1995, multiple centers have attempted to pursue large-fraction conformal radiation delivery to spinal lesions using a variety of technologies.[16,19–24,33–41] Recent technological developments, including imaging technology for 3-dimension localization and pretreatment planning, the advent of intensity modulated radiated therapy and a higher degree of accuracy in achieving target dose conformation while sparing normal surrounding tissue have allowed clinicians to

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expand radiosurgery applications to treat malignant vertebral body lesions within close proximity to the spinal cord and cauda equina. Researchers have shown the feasibility and clinical efficacy of hypofractionated stereotactic body radiotherapy for metastases to the spine.[16,18–24,42–45] Stereotactic radiosurgery for tumors of the spine has more recently been demonstrated to be accurate, safe, and efficacious.[16,19,20,22–24,33–38] Others have demonstrated the effectiveness of protons for spinal and paraspinal tumors.[46] There has been a rapid increase in the use of radiosurgery as a treatment alternative for malignant tumors involving the spine.[6,8,19,28,46] The purpose of this study was to evaluate the clinical outcomes of radiosurgery for the treatment of metastases to the spine to see if such a radiosurgery technique parallels the efficacy that has been demonstrated for the treatment of intracranial metastases.

Materials and Methods

This study involved the prospective evaluation of 500 lesions of histologically proven metastases to the spine that were treated using the CyberKnife® Image-Guided Radiosurgery System with the Dynamic Tracking System 3.0 software. This represented a total of 393 patients; some patients had a second lesion subsequently treated. All cases were analyzed individually, addressing the outcome of that particular lesion treated. All patients were treated at the University of Pittsburgh Medical Center, Pittsburgh, PA, and University of Pittsburgh's institutional review board approved the protocol. Computed tomography (CT) and/or magnetic resonance imaging was used to diagnose spinal metastases. Table 1 summarizes the characteristics of the treatment group, including the primary indications for spinal stereotactic radiosurgery that were used for patient selection for this study. Table 2 summarizes the primary sites.

Information regarding the first 95 patients in this series was previously published.[47] No acute radiation toxicity or new neurologic deficits occurred in that series. These same patients were further followed and included in the current series. Their inclusion allowed for longer-term follow-up of both the safety as well as the long-term efficacy of spinal radiosurgery.

Three hundred forty-four lesions had previously undergone external beam irradiation that precluded further conventional irradiation to the involved level. In these 344 cases, prior irradiation was delivered using fractionation schedules ranging from 3 Gy × 10 to 2.5 Gy × 14. Radiosurgery was felt indicated in order to limit further radiation dose to the neural structures. Tumor dose was not decreased in a uniform manner in these previously irradiated patients. Instead, the maximum dose to the spinal cord or cauda equina was more strictly limited, constrained by the CyberKnife's® inverse treatment planning system. The combination of a steep dose gradient and high conformality of the CyberKnife® treatment allows for such high doses to be delivered so close to the adjacent critical structures (*e.g.*, the spinal cord). Except in a single case, patients with myelopathy or cauda equina syndrome from direct tumor progression were not felt to be candidates for radiosurgery treatment. Exclusion criteria for CyberKnife® treatment were: (1) evidence of overt spinal instability or (2) neurologic deficit resulting from bony compression of neural structures. For evaluation of pain relief, a 10-point visual analog scale with an intensity description was administered to all patients before radiosurgery and one month after radiosurgery. Pain scores range from (0 = no pain) to 10 (10 = worst imaginable pain). This score was recorded in each patient's clinical chart as well as within a prospectively collected database. Furthermore, subsequent evaluations of pain were obtained directly from the patient on subsequent follow-up visits to either the oncology, radiation oncology, or neurosurgical service as part of the continued multidisciplinary cancer management at the University of Pittsburgh Cancer Institute. This last point of contact was used as the last date of follow-up. The last pain score referable to the treated lesion was used to determine long-term pain control. Pain improvement was operationally defined as a pain score improvement of 3 points. Analgesic usage was also documented to ensure that subsequent pain improvement was not offset by an increase in the amount or type of analgesic usage. Radiographic tumor control was determined by direct comparison by at least 2 of the authors of the most recently obtained images to the immediate pretreatment images. The final written radiology report was also referenced.

The CyberKnife® consists of a 6-mV compact linear accelerator that is smaller and lighter in weight than linear accelerators used in conventional radiotherapy.[48–51] The smaller size allows it to be mounted on a computer-controlled 6-axis robotic manipulator that permits a much wider range of beam orientations than can be achieved with conventional radiotherapy devices.[16,34,52,53] Two diagnostic radiograph cameras are positioned orthogonally (90° offset) to acquire real-time images of the patient's internal anatomy during treatment. The images

Table 1. Characteristics of the Treatment Group (n = 500)

Characteristic	No. Cases
Previous external beam irradiation	344
Primary indications for radiosurgery treatment	
Pain	336
Primary treatment modality	65
Tumor progression	51
Progressive neurologic deficit	32
Postsurgical treatment	9
Radiation boost	7
Levels treated	
Cervical	73
Thoracic	212
Lumbar	112
Sacral	103
Skull tracking	68
Fiducial tracking	432
Mean/median tumor volume (range)	46/29 cm^3 (0.20–264)
Mean maximum dose (range)	20 Gy (12.5–25)
Mean volume of spinal canal dose >8 Gy	0.6 cm^3

Table 2. Lesion Histopathologies (n = 500)

	No.
Renal cell	93
Breast	83
Lung	80
Melanoma	38
Colon	32
Sarcoma	26
Prostate	24
Multiple myeloma	18
Unknown primary	14
Squamous cell (laryngeal)	12
Thyroid	11
Other	69

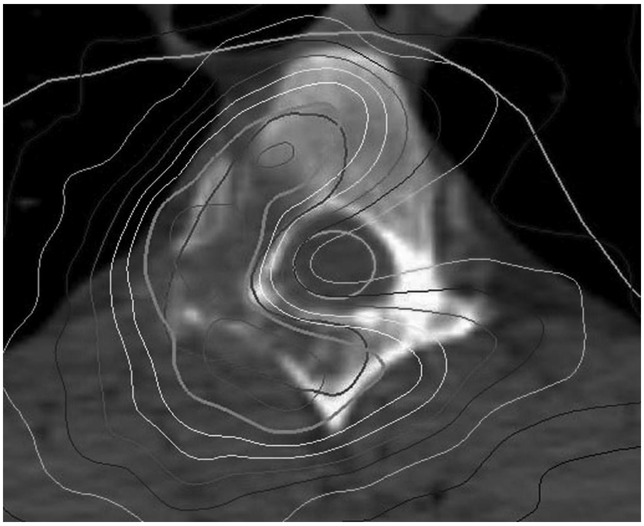

Figure 1. A representative case of a 42-year-old man with a painful melanoma metastasis of the T3 vertebral body. He had not received prior irradiation. The treatment plan was designed to treat the tumor with a prescribed dose of 18 Gy that was calculated to the 80% isodose line; the maximum tumor dose was 22.5 Gy. The tumor volume was 16.8 cm^3 and the spinal cord received a maximum dose of 10 Gy. Notice the conformality of the isodose line around the spinal cord.

are processed to identify radiographic features (skull bony landmarks or implanted fiducials) and then automatically compared to the patient's CT treatment planning study. The precise tumor position is communicated through a real-time control loop to a robotic manipulator that aligns the radiation beam with the intended target.[13] An analysis of the accuracy of the CyberKnife® radiosurgery system found that the machine has a clinically relevant accuracy of 1.1 ± 0.3 mm using a 1.25-mm CT slice thickness.[53]

The CyberKnife® spinal radiosurgery treatment consists of 3 distinct components: (1) CT image acquisition based on skull bony landmarks or implanted bone fiducials, (2) treatment planning, and (3) the treatment itself.[54] All cervical lesions down to C7 were tracked relative to skull bony landmarks. All patients with cervical lesions were fitted with a noninvasive molded Aquaplast facemask (Aquaplast Corp., Wyckoff, NJ) that stabilized the head and neck on a radiographically transparent headrest. All other lesions were tracked relative to fiducial markers placed within the bone adjacent to the lesion. Because these implanted fiducials have a fixed relationship with the bone in which they are implanted, any movement in the vertebrae would be detected as movement in the fiducials, and this movement is detected and compensated for by the CyberKnife®.

For cervical spine lesions, CT images were acquired using 1.25-mm thick slices from the top of the skull to the bottom of the cervical spine. All other lesions underwent fluoroscopically guided percutaneous placement of 4–6 gold fiducial markers (α-Omega Services, Inc., Bellflower, CA) into the pedicles immediately adjacent to the lesion to be treated using a standard Jamshidi Bone Marrow Biopsy Needle (Allegiance Healthcare Corp., McGraw Park, IL), as previously described.[54] The fiducial placement procedure was performed in the operating room in an outpatient setting before undergoing the planning CT. The patient was placed in a supine position in a conformal alpha cradle during CT imaging as well as during treatment. CT images were acquired using 1.25-mm thick slices to include the lesion of interest, as well as all fiducials and critical structures.

The second component of the CyberKnife® treatment is the development of the radiosurgical treatment plan. In each case, the radiosurgical treatment plan was designed based on tumor geometry, proximity to spinal cord, and location (Figures 1 and 2). The tumor dose was maintained at 12.5–25 Gy contoured to the edge of the target volume (mean 20 Gy). The prescription dose was chosen based on currently used intracranial radiosurgery doses as well as the limitation of the maximum dose to the spinal cord as the primary critical structure for each treatment plan. The planning treatment volume was defined as the gross tumor volume with no margin. The dose was prescribed to the 80% isodose line, which covered the planning treatment volume in all cases. The prescription dose was independent of the tumor volume. For each case, the spinal cord and/or cauda equina was outlined as a critical structure. At the level of the cauda equina, the spinal canal was outlined. Therefore, at the level of the cauda equina, the critical volume is the entire spinal canal and not actual neural tissue. The maximum dose was defined as the dose delivered to a single pixel. Given their relative radiosensitivity, a limit of 2 Gy was set as the maximum dose received by each of the kidneys.

The third component of the CyberKnife® treatment is the actual treatment delivery. All treatments were performed using a single-fraction technique. The patients were placed on the CyberKnife® treatment couch in a supine position with the appropriate immobilization device. Preoperative analgesics, sedation, or steroids were not routinely given. During the treatment, real-time digital radiograph images of the implanted fiducial markers were obtained. The location of the vertebral body being treated was established from these images and is used to determine tumor location as previously described. Closed circuit television was used to observe the patient

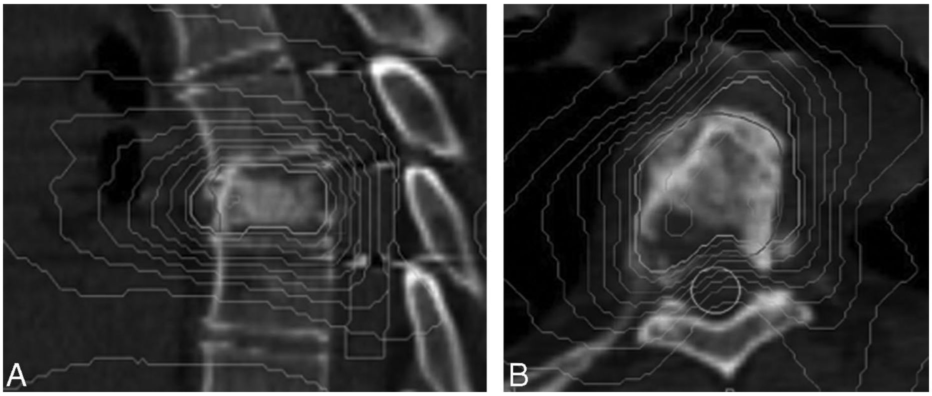

Figure 2. A representative case of a 66-year-old woman with an isolated painful T6 metastasis previously treated with 30 Gy external beam irradiation in 10 fractions. Sagittal and axial projections of the isodose lines of the treatment plan (A and B). The 80% isodose line represents the prescribed dose of 16 Gy, the tumor volume is 10.3 cm^3, and 0.3 cm^3 of the spinal cord received greater than 8 Gy. The patient experienced pain relief within 1 month.

Table 3. Summary of Pain and Radiographic Outcome for the 4 Most Common Histopathologies (n = 294)

Long-term pain improvement	
All patients	86%
Renal cell	94%
Breast	96%
Lung	93%
Melanoma	96%
Long-term radiographic control	
All patients	88%
Renal cell	87%
Breast	100%
Lung	100%
Melanoma	75%

throughout the treatment. The mean treatment time (patient on the couch) is approximately 90 minutes.

Results

Table 1 provides a summary of the clinical characteristics and treatment of the patient cohort. There were 251 women; ages ranged from 18 to 85 years (mean 56). Follow-up ranged from 3 to 53 months (median 21). Sixty-eight cases (*i.e.*, all lesions limited to the cervical spine) were treated using bony landmarks for image guidance. The remaining 432 cases (thoracic, lumbar, and sacral cases) were treated using fiducial tracking. Tumor volume ranged from 0.2 to 264 cm^3 (mean 46). During a follow-up ranging from 3 to 53 months (median 21), there were no clinically detectable neurologic signs that could be attributable to the acute or subacute radiation-induced spine cord injury. Posttreatment magnetic resonance imaging failed to reveal any changes suggestive of radiation induced spinal cord toxicity.

The most frequent indication for the treatment of spinal tumors is pain, and pain was the primary indication for spinal radiosurgery in 336 cases (67%). Spinal radiosurgery was found to be highly effective at decreasing pain in this difficult patient population, with an overall long-term improvement of pain in 290 of the 336 cases (86%), depending on primary histopathology (Table 3). Long-term pain improvement was demonstrated in 96% of women with breast cancer, 96% of cases with melanoma, 94% of cases with renal cell carcinoma, and 93% of lung cancer cases.[55,56]

Sixty-five cases (13%) underwent spinal radiosurgery as their primary treatment modality (meaning no prior irradiation to the lesion). When used as a *primary* treatment modality, long-term tumor control was demonstrated on follow-up imaging in 90% of cases (in all breast, lung, and renal cell carcinoma metastases, and 75% of melanoma metastases).[55,56]

Spinal radiosurgery was used to treat radiographic tumor progression in 51 cases (10%). These lesions had already received irradiation with significant spinal cord doses. Currently, spinal radiosurgery is often employed as a "salvage" technique for those cases in which further conventional irradiation or surgery is not appropriate. Overall long-term radiographic tumor control was 88% for all cases (Table 3). Radiographic tumor control differed based on primary pathology: breast (100%), lung (100%), renal cell (87%), and melanoma (75%). Seven cases with radioresistant tumors (*e.g.*, renal cell carcinoma, melanoma, sarcoma) were treated with spinal radiosurgery after conventional irradiation, with or without intensity modulated radiotherapy for a "boost" treatment with equal long-term radiographic control. In this series, there were no cases of tumor progression at the immediate adjacent levels.

Thirty of 35 cases (85%) with progressive neurologic deficits before treatment experienced at least some improvement based on independent physical examination by 2 of the authors. The 5 patients (renal cell carcinoma 3, lung 2) who failed to improve after radiosurgery had all received prior conventional irradiation. In all 5 of these cases, open surgical decompression was precluded because of medical comorbidities. In 3 cases, the neurologic status stabilized; the remaining 2 progressed to paraplegia. In these 2 cases, imaging revealed clear tumor progression and spinal cord compression; neurologic impairment was felt not to be due to radiation-induced spinal cord injury.

Discussion

Standard treatment options for spinal tumors include radiotherapy alone, radionuclide therapy, radiotherapy plus systemic chemotherapy, hormonal therapy, or surgical decompression and/or stabilization followed by radiotherapy.[7,57] The role of radiation therapy in the treatment of metastatic tumors of the spine is well established and is often the initial treatment modality.[1–7,45] The goals of local radiation therapy in the treatment of spinal tumors have been palliation of pain, prevention of pathologic fractures, and halting progression of or reversing neurologic compromise.[8]

During the past 2 decades, several clinical trials have compared the relative efficacy of various dose-fractionation schedules in producing pain relief.[14] The idea of single-fraction radiotherapy for symptomatic bone metastases is not new. Several studies, including a Radiation Therapy Oncology Group Phase III trial as well as a metaanalysis, found no significant difference in complete and overall pain relief between single-fraction and multi-fraction palliative radiation therapy for bone metastases.[13,14] Most of these trials used 8 Gy in a single fraction. However, none of these trials were specifically evaluating spinal metastases. In addition, the prescribed doses that were delivered in our study were far greater than 8 Gy (median dose of 19 Gy), possibly translating into a more durable symptomatic response as well as local control. Furthermore, the issue of re-irradiation could not be analyzed by the metaanalysis.

The spinal radiosurgery program at the University of Pittsburgh Medical Center began in 2001 with the implementation of extracranial image-guided radiosurgery technology. Our institution's experience currently represents the largest spinal radiosurgery series in the world.[22–24,26] This new modality was initially introduced into the treatment paradigm for spinal tumors to a subset of our institution's oncology patient population that did not meet the criteria for other forms of therapy, including conventional radiotherapy and the latest in open surgical techniques. The indications for spinal radiosurgery at our institution have evolved over time and will continue to evolve as clinical experience increases. This is similar to the evolution of indications for intracranial radiosurgery that occurred in the past.

There is no large experience to date with spinal radiosurgery or hypofractionated radiotherapy that has previously developed optimal doses for these treatment techniques. Other centers, using intensity modulated, near-simultaneous, CT image-guided stereotactic radiotherapy techniques have used doses of 6–30 Gy in 1–5 fractions.[20,21,24,43–45] We initially chose to use a single-fraction radiosurgery technique as opposed to fractionate therapy because of our background of intracranial radiosurgery principles using the Leksell Gamma Knife. Given the lack of adverse consequences to normal tissue, including the spinal cord, we have continued to employ a single-fraction treatment paradigm for our spinal radiosurgery program.

In our series, maximum tumor dose was maintained at 15–22.5 Gy delivered in a single fraction. The appropriate dose for spinal radiosurgery for metastatic tumors to the spine has not been determined. In this series, a maximum tumor dose of 20 or 16 Gy to the tumor margin appeared to provide a good tumor control, with no radiation-induced spinal cord or cauda equina injury. Spinal radiosurgery was found to be safe at doses comparable to those used for intracranial radiosurgery without the occurrence of radiation-induced neural injury. In the current series, there was no clinically or radiographically identifiable acute or subacute spinal cord damage attributed to the radiation dose with a follow-up period long enough to have seen such events were they to occur.[2,58–63]

In this series, pain was the primary indication for radiosurgery treatment. Radiation is well known to be effective as a treatment for pain associated with spinal malignancies. This, of course, is different than the primary indication for intracranial radiosurgery for brain metastases. Eighty-six percent of cases were found to have long-term improvement in their pain after radiosurgery treatment accounting for level of pain medication use. This is similar to the success reported by others using hypofractionated radiotherapy techniques.[18–22,42–45] Conventional external beam irradiation may provide less than optimal pain relief since the total dose is limited by the tolerance of adjacent tissues (*e.g.*, spinal cord). In some cases, posttreatment imaging revealed pathologic fractures, likely the cause of pain and the reason for radiosurgical failure. Such fractures require either open or closed internal fixation to alleviate the pain due to spinal instability. Nevertheless, single-fraction spinal radiosurgery achieved rapid and durable pain control, as well as radiologically documented tumor control in the majority of this patient cohort.

Overall long-term radiographic tumor control was found to be 88% for all cases. When used as a primary treatment modality, long-term tumor control was demonstrated on follow-up imaging in all breast, lung, and renal cell carcinoma metastases, and 75% of melanoma metastases (overall 90%). Spinal radiosurgery was more frequently employed to treat lesions that had previously been treated with other forms of irradiation. The current status of spinal radiosurgery at the present time as it is used at many centers is as a "salvage" technique for patients in which further conventional irradiation or surgery is not appropriate. As greater experience is gained, the technique will likely evolve into an initial upfront treatment for spinal metastases in certain cases (*e.g.*, oligometastases). This is similar to the evolution that occurred for the treatment of intracranial metastases using radiosurgery that occurred over the past decade.

Nine cases in this series (2%) were treated as a postsurgical treatment. Fiducials were implanted at the time of open surgery. Given the steep falloff gradient of the target dose, such treatments can be given early in the postoperative period as opposed to the usual significant delay before standard external beam irradiation is permitted by the surgeon. With the ability to perform effectively spinal radiosurgery, the current surgical approach to these lesions might change. Open surgery for spinal metastases will likely evolve in a similar manner in which malignant intracranial lesions are debulked in such a way as to avoid neurologic deficits and minimize surgical morbidity. The spinal tumors can be removed away from neural structures allowing for immediate decompression, the spine can be instrumented if necessary, and the residual tumor can be safely treated at a later date with radiosurgery, thus further decreasing surgical morbidity. We have found that anterior corpectomy procedures in certain cases can be successfully avoided by posterior decompression and instrumentation alone, followed by radiosurgery to the remaining anterior lesion.

One concern that has been raised regarding radiosurgery for spinal metastases is that adjacent levels are not included in the radiation field. One possibility is that the tumor can progress within the adjacent levels. In this series, there were no cases of tumor progression at the immediate adjacent levels, justifying the treatment of the involved spine only. Other authors have also found this not to be the case.[37]

Further experience with spinal radiosurgery and careful patient follow-up will better define the clinical efficacy of this new treatment modality. There are several theoretical advantages to using a stereotactic radiosurgery technique as a primary treatment modality for spinal tumors. Early treatment of these lesions before the patient becomes symptomatic and the stability of the spine is threatened has obvious advantages.[22] Conformal radiosurgery avoids the need to irradiate large segments of the spinal cord. Early stereotactic radiosurgery treatment of spinal lesions may obviate the need for extensive spinal surgeries for decompression and fixation in these already debilitated patients. It may also avoid the need to irradiate large segments of the spinal column, known to have a deleterious effect on bone marrow reserve in these patients. Avoiding open surgery as well as preserving bone marrow function facilitate continuous chemotherapy in this patient population. Furthermore, improved local control such as has been the case with intracranial radiosurgery could translate into more effective palliation and potentially longer survival.

An advantage to the patient of using single-fraction radiosurgery is that the treatment can be completed in a single day rather than over the course of several weeks, which is not inconsequential for patients with a limited life expectancy. The technique may be useful to capitalize on possible advantages of radiosensitizers. In addition, cancer patients may have difficulty with access to a radiation treatment facility for prolonged, daily fractionated therapy. A large single fraction of irradiation may be more radiobiologically advantageous to certain tumors such as sarcomas, melanomas, and renal cell metastases compared to prolonged fractionated radiotherapy. Clinical response such as pain or improvement of a neurologic deficit might also be more rapid with a radiosurgery technique. Finally, the procedure is minimally invasive compared to open surgical techniques and can be performed in an outpatient setting.

■ Conclusions

In the largest clinical series to date, this study demonstrated that single-fraction spinal stereotactic radiosurgery for metastases is both safe and clinically effective. Spinal radiosurgery represents a logical extension of the current state-of-the-art radiation therapy. The major potential benefits of radiosurgical ablation of spinal metastases are relatively short treatment time in an outpatient setting combined with potentially better local control of the tumor with minimal risk of side effects. Such an outcome could translate into better palliation of symptoms and a longer survival period while avoiding the significant morbidity associated with open surgical intervention. In addition, this technique allows for the treatment of lesions previously irradiated using conventional external beam irradiation. Spinal radiosurgery offers an important new therapeutic modality for the treatment of spinal metastases. Further experience with higher irradiation doses as well as improved tumor imaging will likely lead to even better clinical outcomes.

■ Key Points

- Single-fraction radiosurgery was used to safely treat 500 spinal metastases.
- Overall long-term pain improvement occurred in 86% of cases.
- Overall long-term radiographic tumor control was demonstrated in 88% of cases.

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