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CLINICAL ASSESSMENT OF STEREOTACTIC IGRT: SPINAL RADIOSURGERY

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Abstract—The role of stereotactic radiosurgery for the treatment of intracranial lesions is well established. Its use for the treatment of spinal lesions has been limited because of the availability of effective target immobilization devices. Recent advances in stereotactic IGRT have allowed for spinal applications. Large clinical experience with spinal radiosurgery to properly assess clinical outcomes has previously been limited. At our institution, we have developed a successful multidisciplinary spinal radiosurgery program in which 542 spinal lesions (486 malignant and 56 benign lesions) were treated with a single-fraction radiosurgery technique. Patient ages ranged from 18 to 85 years (mean 56 years). Lesion location included 92 cervical, 234 thoracic, 130 lumbar, and 86 sacral. The most common metastatic tumors were renal cell (89 cases), breast (74 cases), and lung (71 cases). The most common benign tumors were neurofibroma (24 cases), schwannoma (13 cases), and meningioma (7 cases). Eighty-nine cervical lesions were treated using skull tracking. Thoracic, lumbar, and sacral tumors were tracked relative to either gold or stainless steel fiducial markers. The maximum intratumoral dose ranged from 12.5 to 30 Gy (mean 20 Gy). Tumor volume ranged from 0.16 to 298 mL (mean 47 mL). Three hundred thirty-seven lesions had received prior external beam irradiation with spinal cord doses precluding further conventional irradiation. The primary indication for radiosurgery was pain in 326 cases, as a primary treatment modality in 70 cases, for tumor radiographic tumor progression in 65 cases, for post-surgical treatment in 38 cases, for progressive neurological deficit in 35 cases, and as a radiation boost in 8 cases. Follow-up period was at least 3 to 49 months. Axial and/or radicular pain improved in 300 of 326 cases (92%). 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. Thirty of 35 patients (85%) with progressive neurological deficits experienced at least some improvement after treatment. Spinal stereotactic radiosurgery is now a feasible, safe, and clinically effective technique for the treatment of a variety of spinal lesions. The potential benefits of radiosurgical ablation of spinal lesions are short treatment time in an outpatient setting with essentially no recovery time and excellent symptomatic response. This technique offers a new therapeutic modality for the primary treatment of a variety of spinal lesions, including the treatment of neoplasms in medically inoperable patients, previously irradiated sites, for lesions not amenable to open surgical techniques, and as an adjunct to surgery.

Key Words: **Image-guided surgery, Spinal radiosurgery, Body radiosurgery, Body IGRT.**

INTRODUCTION

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.[1] 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 neurological compromise.[8]

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.[2,9,10] Radiotherapy may provide less than optimal clinical response because 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.[10–18]

The spinal radiosurgery program at the University of Pittsburgh Medical Center began in 2001 with the implementation of extracranial IGRT technology. Our institution's experience currently represents the largest spinal radiosurgery series in the world.[22–26] This new modality was initially introduced into the treatment paradigm for spinal tumors to a subset of our institution's oncology patient population who did not meet the criteria

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for other forms of therapy, including conventional radiotherapy and the latest in open surgical techniques. Spinal radiosurgery was adopted as part of an evolution of our comfort and clinical success with the modality of intracranial radiosurgery, a modality that had been pioneered by members of the University of Pittsburgh's Departments of Neurological Surgery and Radiation Oncology.

Spinal radiosurgery

During the past 2 decades, several clinical trials have compared the relative efficacy of various dose-fractionation schedules in producing pain relief.[19] 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 meta-analysis, found no significant difference in complete and overall pain relief between single-fraction and multifraction palliative radiation therapy for bone metastases.[19,20] 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 meta-analysis.

In stereotactic radiosurgery, a high dose of radiation is delivered in a single fraction to a well-defined intracranial or extracranial target.[21] Radiosurgery has been shown to be very effective for controlling intracranial malignancies.[22–28] Stereotactic radiosurgery has been demonstrated to be an effective treatment for brain metastases (including breast 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. Stereotactic radiosurgery for tumors of the spine has more recently been demonstrated to be accurate, safe, and efficacious.[10,13, 14,16–18,29–34]

Radiosurgery is defined as the delivery of a highly conformal, large radiation dose to a localized tumor by a stereotactic approach.[34] Since Hamilton *et al.*[31] 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[10,13–18,29–37] Researchers have shown the feasibility and clinical efficacy of spinal hypofractionated stereotactic body radiotherapy for metastases.[10,12–18,38] Others have demonstrated the effectiveness of protons for spinal and paraspinal tumors.[39] 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] 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 expand radiosurgery applications to treat malignant vertebral body lesions within close proximity to the spinal cord and cauda equina.

THE CYBERKNIFE IMAGE-GUIDED RADIOSURGERY SYSTEM

The CyberKnife Image-Guided Radiosurgery System (Accuray, Inc., Sunnyvale, CA) was first developed for the treatment of both benign and malignant intracranial lesions.[40–42] Treatment outcome has been similar to the results of conventional frame-based radiosurgery.[10] With the ability to treat lesions outside of the skull using fiducial tracking, a growing experience in the treatment of spinal lesions using the CyberKnife has emerged.[10,43,44] Unlike conventional radiation therapy that delivers a full dose to both the vertebral body and the spinal cord, the CyberKnife can surgically deliver a single high-dose fraction of radiation that conforms to the target tissue while sparing most of the adjacent spinal cord. The treatment plan can create a high gradient dose fall-off to the target tissue that should significantly reduce the possibility of radiation-induced myelopathy. This is a significant advantage to using stereotactic radiosurgery for treatment of spinal tumors. Therefore, it has the potential to significantly improve local control of spine metastases, which could translate into more effective palliation, delaying progression of neurological deficits requiring open surgical intervention, and potentially longer survival.

The CyberKnife consists of a 6-MV compact linear accelerator that is smaller and lighter in weight than linear accelerators used in conventional radiotherapy (Figs. 1 and 2).[45–48] 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.[10,29,40,49] Two diagnostic x-ray cameras are positioned orthogonally (90° offset) to acquire real-time images of the patient's internal anatomy during treatment. The images are processed to identify radiographic features (skull bony landmarks or implanted fiducials) and then automatically compared to the patient's computed tomography (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. 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.[49]

OVERVIEW OF SPINAL RADIOSURGERY TREATMENT

The CyberKnife spinal radiosurgery procedure can be divided into 4 sections: (1) immobilization and fiducial implantation, (2) CT imaging for treatment planning and generation of digitally reconstructed ra-

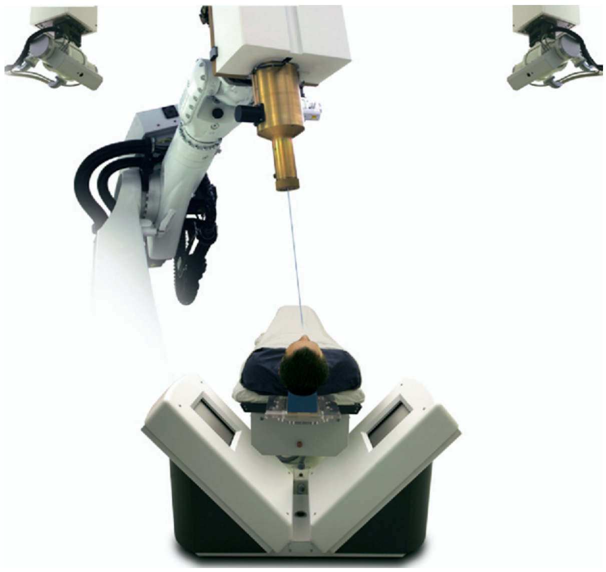

Fig. 1. The CyberKnife consists of a linear accelerator mounted on a 6-axis robotic manipulator that permits a wide range of beam orientations.

diographs (DRR), (3) planning of treatment, and (4) dose delivery (Table 1). Intracranial and cervical lesions are tracked relative to skull bony landmarks. All other lesions are tracked relative to fiducials placed adjacent to the lesion. Because these implanted fiducials have a fixed relationship with the bone in which they are implanted, any movement in the tumor in or adjacent to the vertebrae would be detected as movement in the fiducials, and this movement is detected and compensated for by the CyberKnife.

Fig. 2. The CyberKnife radiosurgical system. Note the 2 amorphous silicon x-ray screens positioned orthogonally to the treatment couch. The couch can move to position the fiducials in front of the cameras.

Table 1. Overview of the spinal radiosurgery treatment

1. Fiducials placed (lower spinal lesions only) or face-mask molded (cervical lesions).
2. CT image-guided simulation performed using 1.25-mm slices.
3. Treatment plan designed.
4. Patient returns for outpatient treatment:
Treatments may be fractionated if necessary.
Patient has the opportunity to stop and rest at any point during the treatment.
No recovery time.

Face mask and fiducial placement

All patients with cervical lesions are fitted with a noninvasive molded facemask that stabilizes the head and neck on a radiographically transparent headrest.[50] The patient then proceeds directly with imaging. CT images are acquired using 1.25-mm-thick slices from the top of the skull to the bottom of the cervical spine for cervical lesions. The CyberKnife is able to detect and track either straight 0.62- to 5.0-mm gold fiducials (Alpha-Omega Services, Inc., Bellflower, CA) or stainless steal screws (Accuray, Inc., Sunnyvale, CA) (Fig. 3). These fiducials are placed using fluoroscopic guidance using a percutaneous technique. The fiducial placement procedure is performed in the operating room in an outpatient setting. The gold fiducial markers are placed into the pedicles immediately adjacent to the lesion to be treated using a standard Jamshidi Bone Marrow Biopsy Needle (Allegiance Healthcare Corporation, McGraw Park, IL). The stainless steel

Fig. 3. Gold seed, stainless steel screws, or tacks are used as fiducial markers.

screws are screwed directly into the posterior bony elements via a specially designed cannula. If fiducials are placed in conjunction with an open surgical procedure, the stainless steal screws are easily screwed into any adjacent exposed bone.

Four to 5 fiducial markers are usually placed, 2 in the vertebrae above, 2 in the vertebrae below, and 1 or 2 in the vertebrae at the level of the lesion. A minimum of 4 fiducials is needed for tracking during treatment to allow for maximum accuracy. Tracking more than 4 fiducials adds little to target accuracy. Three fiducials are required to define a full spatial transformation in all 6 degrees of target translation and rotation. An extra fiducial is placed to allow for a margin of error in case one fiducial cannot be properly imaged or perhaps migrates after placement. Fiducial migration has rarely occurred in our experience.

The fiducials may be placed literally anywhere near or around the target. However, their positions must be fixed relative to the target location. For fiducials in the same vertebral body, it is preferential for them to be placed as closely as possible in the same coronal plane so that overlap in an orthogonal projection during x-ray imaging acquisition is minimized. For patients with lesions in non-adjacent vertebral bodies, fiducials are sometimes placed between the 2 lesions. For example, for 2 distinct lesions at T11 and L3, fiducials may be placed at T12, L1, and L2 without compromising target accuracy.

Treatment planning

The patient returns as an outpatient for the treatment planning CT. The patient is placed in a supine position in a conformal alpha cradle during CT imaging as well as during treatment. CT images are acquired using 1.25-mm-thick slices to include the lesion of interest as well as all fiducials. Images may be acquired using the addition of intravenous contrast enhancement. However, contrast is often not necessary for lesions that are completely within the bony elements. In fact, bony windowing is often more helpful for lesion localization and treatment planning than soft tissue windowing for many spinal lesions. For patients with allergies to intravenous contrast or renal function that precludes contrast, non-enhanced CT imaging is performed with little difficulty in determining precise lesion anatomy.

Each spinal radiosurgical treatment plan is devised jointly by a team comprised of a neurosurgeon, a radiation oncologist, and a radiation physicist. In each case, the radiosurgical treatment plan is designed based on tumor geometry, proximity to spinal cord, and location. The lesion is outlined based upon CT imaging or from an magnetic resonance (MR) fusion capability. In our experience, the mean tumor volume has been approximately 30 cc (range 0.16–298 cc). This is approximately 10 times the average volume of intracranial lesions treated by radiosurgery. Figure 4 is 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. Figure 5 is 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. The dose-volume histogram (C) for the same treatment plan shows that 80.4% of the tumor volume received 80% of the maximum dose of 20 Gy.

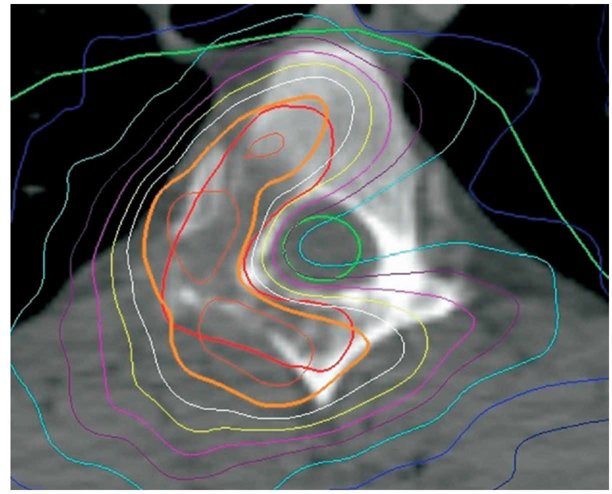

Fig. 4. A representative case of a 42-year-old man with a painful melanoma metastasis of the T3 vertebral body. Notice the conformality of the isodose line around the spinal cord.

For each case, the spinal cord and/or cauda equina is outlined as a critical structure. At the level of the cauda equina, the spinal canal is outlined. Therefore, at the level of the cauda equina, the critical volume is the entire spinal canal and not actual neural tissue. A limit of 8 Gy is set as the maximum spinal cord dose for treatment planning calculations. A limit of 2 Gy is set as the maximum dose to each of the kidneys. A limit of 4 Gy is set as the maximum dose to the bowel. This especially becomes important in the treatment of lower thoracic and lumbar vertebrae, even more so if the patient has undergone a nephrectomy or received nephrotoxic chemotherapy.

Dose prescriptions

The tumor dose is determined based upon the histology of the tumor, spinal cord tolerance, and previous radiation quantity to normal tissue, especially the spinal

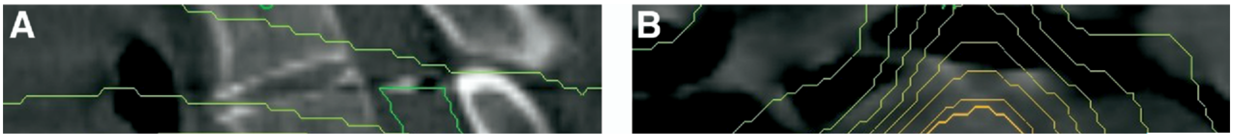

Fig. 5. A representative case of a 66-year-old woman with an isolated painful T6 vertebral body metastasis.

cord. 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, computed tomographic image-guided stereotactic radiotherapy techniques, have used doses of 6 to 30 Gy in 1 to 5 fractions.[10,16,18,40] At our institution, the tumor dose is prescribed to the 80% isodose line. Tumor dose is maintained at 12 to 20 Gy to the 80% isodose line contoured at the edge of the target volume (mean 17 Gy). The maximum intratumoral dose ranges from 15 to 30 Gy (mean 21 Gy). The higher doses were delivered to lesions further away from critical structures. In our center's experience, a maximum tumor dose of 20 Gy or 16 Gy to the tumor margin appears to provide a good tumor control with no radiation-induced spinal cord or cauda equina injury.

There is little experience regarding the tolerance of the human spinal cord to single fraction doses, and the tolerance of the spinal cord to a single dose of radiation has not been defined well.[18] Spinal cord tolerance related to IMRT techniques has also not yet been addressed. Therefore, one must still rely upon clinical data derived from external beam irradiation series in which the entire thickness of the spinal cord was irradiated. In a review of 172 patients treated with fractionated radiotherapy to the cervical and thoracic spine at the University of California, San Francisco (total dose of 40–70 Gy fractionated over 2–3 week period), Wara *et al.*[51] reported 9 cases of radiation-induced myelopathy. Three of 9 patients had mild cervical cord neurological deficits without any significant long-term symptoms. The length of the spinal cord that was exposed to radiation averaged from 4 to 22 cm.

Hatlevoll *et al.*[52] reported a series of 387 patients with bronchial carcinoma treated with a split-course regimen using large single fractions. Seventeen patients developed radiation myelitis with average total dose of 38 Gy. Kim *et al.*[3] reported 7 patients with transverse myelopathy from a group of 109 patients treated with definitive radiotherapy for head-and-neck cancers to a total dose of 57 to 62 Gy with an average field size of 10 $\times$ 10 cm. Abbatucci *et al.*[53] reported 8/203 cases of radiation-induced myelopathy with a total radiation dose of 54 to 60 Gy to the cervical and thoracic spine. McCuniff *et al.*[54] reported only 1 case of radiation myelopathy of 652 patients who had received greater than 60 Gy using standard fractionation. Phillips *et al.*[55] reported 3 cases of transverse myelitis in 350 patients treated with tumors to the chest to a total radiation dose of 33 to 43.5 Gy.

Spinal radiosurgery was found to be safe at doses comparable to those used for intracranial radiosurgery without the occurrence of radiation induced neural injury. We have had a single case of radiation-induced spinal cord injury following the treatment of a cervical lesion. In this case, fiducial markers were not used for image tracking. Symptoms of a Brown-Sequard Syndrome began 3 months after the treatment, and MR imaging revealed signal change within the spinal cord on the same side of the lesion. The maximum dose delivered to the edge of the spinal cord on the treatment plan was less than 90 Gy. The lesion had not previously undergone external beam irradiation. The patient's symptoms gradually improved with resolution of spinal cord edema on MR imaging at 12 months.

Fig. 6. Patient setup on the CyberKnife treatment couch. The patient is positioned supine with legs in an alpha cradle for comfort and to limit motion. The couch will move rostrally to place the fiducials between the amorphous silicon detectors.

Treatment delivery

The third and final component of the CyberKnife treatment is the actual treatment delivery.[50] Treatments may be performed using either a single or multiple fractions in an outpatient setting. We prefer a single-fraction technique. The patients are placed on the CyberKnife treatment couch in a supine position with the appropriate immobilization device (Fig. 6). During the treatment, real-time digital x-ray images of the patient are obtained to track either skull bony landmarks or implanted fiducials (Fig. 7). The location of the vertebral body being treated is established from these images and is used to determine tumor location. All 5 fiducials are tracked for thoracic, lumbar, and sacral lesions using real-time image guidance. Orthogonal digitally reconstructed radiographs (DRRs) are generated from the original CT. Throughout the treatment, the system correlates the original DRRs to the live images from the amorphous silicone detectors. The measured position as seen by both cameras is communicated through a real-time control loop to a robotic manipulator that redirects the beam to the precise intended target.

The CyberKnife delivery treatment follows a sequential format.[56] Once the patient is on the treatment couch, the imaging system acquires a pair of alignment radiographs and determines the initial location of the treatment site within the robotic coordinate system. This information allows initial positioning of the linear accelerator. The robotic arm then moves the linear accelerator through a sequence of preset points surrounding the patient. At each point, the linear accelerator stops and a new pair of images is acquired, from which the position of the target is redetermined. The coordinates of the target are forwarded to the robotic manipulator that reorients the beam to compensate for the small amount of patient movement. The linear accelerator then delivers the preplanned dose of radiation for that direction. The complete process is repeated at each point, for a total of approximately 150 points, or nodes.

The patient is observed throughout the treatment by closed-circuit television. No pulse oximetry or other monitoring is used during the treatment. The patient is asked to wave their hand or speak if they would like to temporarily halt the treatment. The duration of the treatment is approximately 1 to 2 hours. Intravenous sedation is not required. Some patients are in significant pain and are uncomfortable in the supine position for prolonged periods of time. Treatments may be delivered under

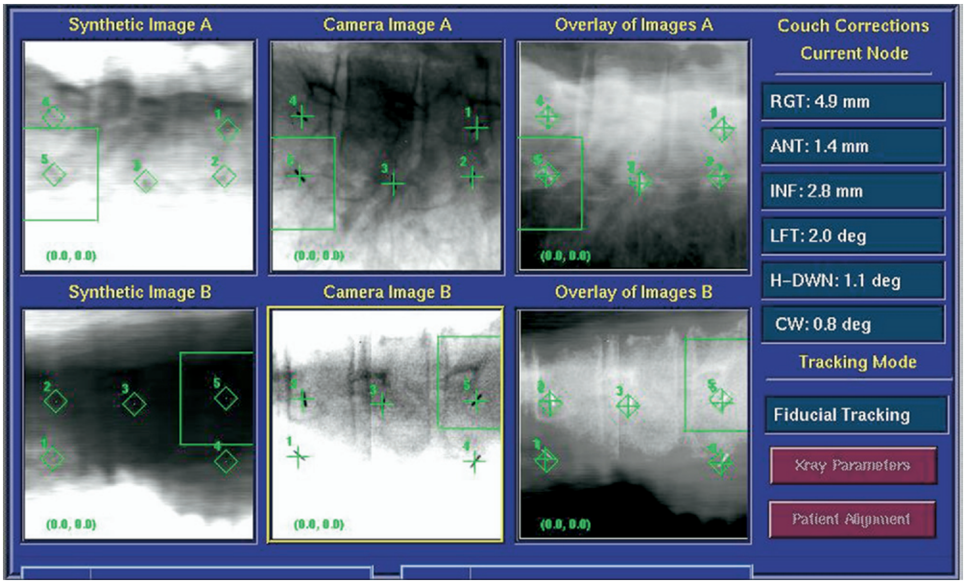

Fig. 7. All 5 fiducials are using real-time image guidance.

intravenous sedation or even a general anesthetic if necessary, with the patient being monitored by the anesthetist from outside the treatment room. For the majority of cases, it is very easy to pause the treatment at any time for the patient to sit up. After a brief rest, the patient returns to the supine position on the treatment couch and thereafter, the treatment resumes. Mild and transient nausea may be experienced by patients undergoing treatment to lesions of the lumbar spine. For these cases, patients are pretreated with anti-emetics.

SPINAL RADIOSURGERY INDICATIONS AND OUTCOMES

Our center has demonstrated both the feasibility as well as the clinical efficacy of spinal radiosurgery for a variety of both benign and malignant lesions.[22–24,26] The indications for CyberKnife 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. Table 2 summarizes the candidate lesions for spinal radiosurgery. Table 3 summarizes the characteristics of our first 542 patients treated with a single fraction radiosurgery technique, and Table 4 summarizes the histopathologies of the treated lesions. Ages ranged from 18 to 85 years (mean 56 years). Lesion location included 92 cervical, 234 thoracic, 130 lumbar, and 86 sacral.

Similar to intracranial radiosurgery, candidate lesions may be of either benign or malignant histology (Table 4). There were 486 malignant lesions and 56 benign lesions. The most common metastatic tumors were renal cell (89 cases), breast (74 cases), and lung (71 cases). The most common benign tumors were neurofibroma (24 cases), schwannoma (13 cases), and meningioma (7 cases). Our ratio of malignant to benign disease

Table 2. Candidate lesions for spinal radiosurgery

Well-circumscribed lesions
Minimal spinal cord compromise
Radioresistant lesions that would benefit from a radiosurgical boost
Residual tumor after surgery
Previously irradiated lesions precluding further external beam irradiation
Recurrent surgical lesions
Lesions requiring difficult surgical approaches
Relatively short life-expectancy as an exclusion criteria for open surgical intervention
Significant medical comorbidities precluding open surgical intervention
Lesions not requiring open spinal stabilization techniques

Table 3. Characteristics of the treatment group ($n = 542$)

Characteristic	No. of Cases
Patients with multiple lesions treated	112
Previous external beam irradiation	336
Primary indications for radiosurgery treatment	
Pain	326
Primary treatment modality	70
Tumor progression	65
Post-surgical treatment	38
Progressive neurologic deficit	35
Radiation boost	8
Levels treated	
Cervical	92
Thoracic	234
Lumbar	130
Sacral	86
Skull tracking	89
Fiducial tracking	453
Mean tumor volume (range 0.16–298) [cm^3]	47
Mean dose to 80% isodose line (range 10–25) [Gy]	18
Mean volume of spinal canal dose > 8 Gy [cm^3]	0.9

Table 4. Lesion histopathologies ($n = 542$)

Benign tumors	56
Neurofibroma	24
Schwannoma	13
Meningioma	7
Paraganglioma	7
Spinal Chordoma	5
Hemangioma	3
Hemangiopericytoma	2
AVM	1
Metastatic lesions	486
Renal cell	89
Breast	74
Lung	71
Colon	29
Melanoma	22
Prostate	17
Sarcoma	15
Multiple myeloma	14
Squamous cell (laryngeal)	9
Hemangioblastoma	6
Others	105

is therefore almost 9 to 1. Spinal vascular malformations are also amenable to spinal radiosurgery.[10]

The most frequent indication for the treatment of spinal tumors is pain, and pain was the primary indication for spinal radiosurgery in 326 of our patients (60%). Radiation is well known to be effective as a treatment for pain associated with spinal malignancies. We have found spinal radiosurgery to be highly effective at decreasing pain in this difficult patient population, with an overall improvement of pain in 300 of the 326 patients (92%), depending upon primary histopathology. Long-term pain improvement was demonstrated in 96% of women with breast cancer, 96% of patients with melanoma, 94% of patients with renal cell carcinoma, and 92% of patients with neurofibromatosis Type 1. Pain usually decreases within weeks after treatment, and occasionally within days. Spinal radiosurgery is also effective at alleviating radicular pain caused by tumor compression of adjacent nerve roots.

Seventy patients underwent spinal radiosurgery as their primary treatment modality. The benefits for this treatment option include a single treatment with minimal radiation dose to adjacent normal tissue. In addition, a much larger radiobiologic dose can often be delivered compared to external beam irradiation. When used as a primary treatment modality, long-term tumor control was demonstrated on follow-up imaging in all breast, renal cell carcinoma, meningioma, and neurofibroma lesions, with an overall tumor control rate for all histopathologies of 90%. Eight patients with radioresistant tumors (*e.g.*, renal cell carcinoma, melanoma, sarcoma) were treated with spinal radiosurgery after conventional irradiation with or without IMRT for a boost treatment with equal long-term radiographic control.

Spinal radiosurgery was used to treat radiographic tumor progression in 65 patients. The ideal lesion should be well circumscribed such that the lesion can be easily outlined (contoured) for treatment planning. The majority of these lesions had already received irradiation with significant spinal cord doses. Currently, spinal radiosurgery is often being used as a salvage technique for those cases in which further conventional irradiation or surgery are not appropriate. The overall long-term tumor control rate after radiosurgical treatment for tumor progression is 88% for all histopathologies (100% for breast carcinoma, 87% for renal cell carcinoma, 75% for melanoma).

If a tumor is only partially resected during an open surgery, fiducials can be left in place to allow for radiosurgery treatment to the residual tumor at a later date. Thirty-eight patients were treated as a post-surgical treatment. Given the steep fall-off gradient of the CyberKnife 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 effectively perform 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 neurological 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.

Other candidate lesions are those that would require difficult surgical approaches for adequate resection. Spinal radiosurgery can deliver radiation to anywhere along the spine. Candidate patients may have significant medical comorbidities precluding open surgical intervention or a relatively short life expectancy that would deem them inappropriate for open surgical intervention. With greater clinical experience, upfront radiosurgery perhaps will become more commonly used in certain cases such as patients with a single symptomatic spine tumor of a radioresistant histology. Thirty of 35 patients (85%) with progressive neurological deficits prior to treatment experienced at least some improvement.

ADVANTAGES OF SPINAL STEREOTACTIC IGRT

There are several advantages to using a stereotactic IGRT technique as a primary treatment modality for spinal tumors. Early treatment of these lesions prior to the patient becoming symptomatic and the stability of the spine threatened has obvious advantages.[16] This approach 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 facilitates continuous chemotherapy in this patient population. Furthermore, improved local control in the case of intracranial radiosurgery could translate into more effective palliation and potentially longer survival.

An advantage to using single-fraction radiosurgery is the completion of treatment in a single day rather than over a 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 breast cancer compared to prolonged fractionated radiotherapy. Clinical response such as pain or improvement of a neurological 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.

SUMMARY

Spinal stereotactic IGRT is now feasible, safe, and clinically effective for the treatment of a variety of spinal tumors. Spinal radiosurgery represents a logical extension of the current state-of-the-art radiation therapy. It has the potential to significantly improve local control of cancer of the spine, which could translate into better palliation. An advantage of this technique is the completion of treatment in a single day rather than over several weeks, something that is not inconsequential for patients with a limited life expectancy. In addition, cancer patients may have difficulty with access to a radiation treatment facility for prolonged, daily-fractionated therapy. The major benefits of radiosurgical ablation of spinal lesions are relatively short treatment time in an outpatient setting combined with better local control of the tumor with minimal risk of side effects. Spinal radiosurgery offers a new alternative therapeutic modality for the treatment of spinal metastases in medically inoperable patients, previously irradiated sites, and for lesions not amenable to open surgical techniques or as an adjunct to surgery.

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