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Cyberknife radiosurgery for metastatic spine tumors

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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 because of their underlying disease, high surgical complication rates with a subsequent decrease in quality of life are most unacceptable. To this end, radiation often has been used as an initial treatment modality in place of open surgery because of its perceived diminished risk of morbidity.

The role of radiation therapy in the treatment of tumors of the spine has been well established. The goals of local radiation therapy in the treatment of spinal tumors are palliation of pain, prevention of pathologic fractures, and halting progression of or reversing neurologic compromise. A primary factor that limits radiation dose for this tumor control with conventional radiotherapy is the low tolerance of the spinal cord to radiation. Spinal metastases often progress or recur as a result of insufficient doses used because of dose constraints imposed by spinal cord tolerance [1]. Furthermore, reirradiation of the spine is rarely possible using conventional techniques.

Conventional external beam radiotherapy lacks the precision to allow delivery of large doses of radiation 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 [2–4]. If the radiation dose could be confined more precisely to the treatment volume, as is the case for intracranial radiosurgery, the likelihood of successful tumor control should increase at the same time that the risk of spinal cord injury is minimized. Recent studies using hypofractionated or single-dose treatments for spinal metastases reported results that were comparable to those of conventional fractionation [5,6]. Ryu et al [7] reported on the use of image-guided shaped-beam spinal radiosurgery with good clinical results.

Intracranial stereotactic radiosurgery has gained widespread acceptance as a procedure for patients with brain metastases that has advantages over whole-brain irradiation and surgery in terms of conferring improved survival and tumor control, permitting reirradiation, and sparing normal brain tissue [8–10]. Intracranial stereotactic radiosurgery is an effective treatment for brain metastases, either with or without whole-brain radiation therapy, with an 85% to 95% control rate [11–14]. It is for this reason that there has been tremendous interest in expanding the role of radiosurgery to extracranial applications, such as the treatment of spinal metastases [7], to determine if similar clinical results can be achieved using this new treatment modality.

Spinal radiosurgery

Radiosurgery delivers a highly conformal and large radiation dose to a localized tumor by means of a stereotactic approach [7]. Stereotactic radiosurgery offers a method for delivering a high

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dose of radiation in a single or limited number of fractions to a small volume encompassing the tumor while minimizing the dose to adjacent normal structures. Current frame-based stereotactic radiosurgery devices do not have the capability of treating lesions below the foramen magnum using skull fixation devices. Conformal radiotherapy and intensity-modulated radiation therapy (IMRT) are limited by problems with target immobilization. This limitation of IMRT precludes large single-fraction treatment to spinal lesions. Treatment of spinal lesions by stereotactic conformal radiotherapy and IMRT has shown promising clinical results [15].

Conventional frame-based devices used for stereotactic radiosurgery for intracranial lesions utilize a rigid frame to immobilize the lesion at a known location in space. The use of multiple beams of radiation requires extremely precise control of position and movement of the linear accelerator (LINAC). In the past, stereotactic radiosurgery was limited to intracranial disease, because precise localization could be achieved only by means of neurosurgical frames fixed to the patient's skull. The frame acts as a fiducial reference system to provide accurate targeting and delivery of the radiation dose. As a corollary, treatment is typically limited to single-fraction treatments. Intracranial radiosurgery is practical because the lesions are fixed with respect to the cranium, which can be immobilized rigidly in a stereotactic frame. Spinal lesions also have a fixed relation to the spine. Stereotactic radiosurgery techniques developed for spinal lesions using standard LINACs require the placement of an invasive rigid external frame system directly to the spine, however, and thus have not been adopted for general use [16].

The image-guided frameless stereotactic radiosurgery delivery system known as the CyberKnife Stereotactic Radiosurgery System (Accuray, Sunnyvale, CA) was developed by Dr. John Adler, Jr. and his colleagues at Stanford University. It was approved in 2001 by the US Food and Drug Administration for use throughout the body [17]. The CyberKnife was first developed for treatment of brain tumors at Stanford University. Since 1994, the device has been used at a number of sites around the world to treat a variety of benign and malignant intracranial lesions [18,19]. As expected, treatment outcome has closely mirrored the results of conventional frame-based radiosurgery [3]. With the ability to treat lesions outside of the skull using fiducial tracking, a growing interest in the treatment of spinal lesions using the CyberKnife has emerged [3,20–22]. The CyberKnife technology is now being adopted worldwide as a feasible method to perform spinal radiosurgery.

CyberKnife system

The CyberKnife is a frameless image-guided stereotactic radiosurgical system that uses radiographic imaging in the treatment room to locate and track the treatment site while controlling the alignment of radiation beams via a robot-mounted LINAC [17]. The CyberKnife system consists of a lightweight LINAC (weighing 120 kg) mounted on a robotic arm (Fig. 1). Real-time imaging tracking allows for patient movement tracking with 1 mm of spatial accuracy [3,19,23]. Dosimetry compares favorably with that of other intracranial radiosurgery devices [24].

The CyberKnife was developed as a noninvasive means to align treatment beams precisely with targets. It differs from conventional frame-based radiosurgery in three fundamental ways [3]. First, it references the position of the treatment target to internal radiographic features, such as the skull or implanted fiducials, rather than a frame. Second, it uses real-time radiographic imaging to establish the position of the lesion during treatment and then dynamically brings the radiation beam into alignment with the observed position of the treatment target. Third, it aims each beam independently, without a fixed isocenter.

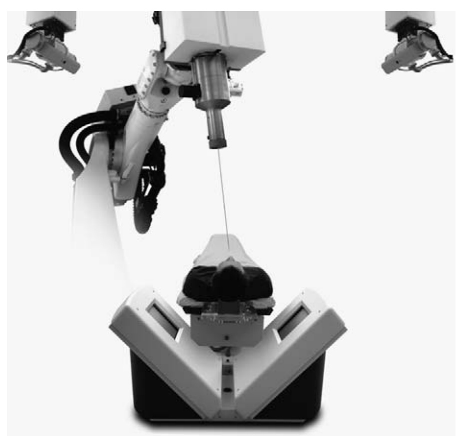

Fig. 1. The CyberKnife radiosurgical system. Note the two amorphous silicon x-ray screens positioned orthogonally to the treatment couch. The couch can move to position the fiducials in front of the cameras.

Changes in patient position during the treatment are compensated for by adaptive beam pointing rather than controlled through rigid immobilization. This allows the patient to be positioned comfortably in the treatment room without precise reproduction of the position in the treatment planning study. Because of the spatial precision with which the CyberKnife can administer radiation, it is theoretically feasible to administer a tumoricidal radiation dose in a single outpatient treatment. By minimizing the irradiation of surrounding healthy tissue, it should also be possible to decrease the rate of complications. The design of the CyberKnife makes it intrinsically capable of treating sites anywhere in the body in either a single-fraction or multifraction manner [25].

The CyberKnife consists of a computer-controlled, compact, 6-MV LINAC that is smaller and lighter in weight than LINACs used in conventional radiotherapy [21,26,27]. The smaller size allows it to be mounted on a computer-controlled six-axis robotic manipulator that permits a much wider range of beam orientations than can be achieved with conventional radiotherapy devices (Fig. 2). The CyberKnife system use image-guided frameless robotic radiosurgery. Two ceiling-mounted 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 gathered using two amorphous silicon x-ray screens capable of generating high-resolution digital images [28]. The images are processed automatically to identify radiographic features and then registered to the treatment planning study to measure the position of the treatment site. The measured position is communicated through a real-time control loop to a robotic manipulator that aims the LINAC.

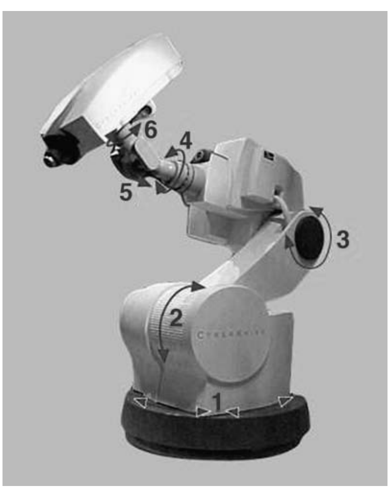

Fig. 2. The CyberKnife consists of a linear accelerator mounted on a six-axis robotic manipulator that permits a wide range of beam orientations.

The system can adapt to changes in patient position during treatment by acquiring targeting images repeatedly and then adjusting the direction of the treatment beam. If the patient moves during treatment, the change is detected during the next imaging cycle and the beam is adjusted and realigned with the target [25]. The target to be treated is identified before treatment on planning images. Between 100 and 150 beams are used to irradiate the target in a stereotactic fashion. The treatment beam can be maneuvered and pointed nearly anywhere in space. Treatment beams are also not confined to isocentric geometry, so they can be arranged in complex overlapping patterns that conform to irregularly shaped tumor volumes [3]. An analysis of the accuracy of the CyberKnife radiosurgery system found that the machine has a clinically relevant accuracy of 1.1 $\pm$ 0.3 mm using a 1.25-mm computed tomography (CT) slice thickness. Hence, the CyberKnife precision is comparable to published localization errors in other current frame-based radiosurgical systems [28].

Indications for spine radiosurgery

The indications for CyberKnife radiosurgery for metastatic spine lesions are currently evolving and will continue to evolve as clinical experience increases. This is similar to the evolution of indications for radiosurgery for intracranial metastases that occurred in the last decade. Box 1 summarizes the candidate metastatic lesions for CyberKnife spinal radiosurgery. Our indications have developed and evolved with our clinical experience of more than 200 treated spinal metastases. Unlike conventional radiation therapy, which delivers a full dose to the vertebral body and the spinal cord, the CyberKnife can deliver a single high-dose fraction of radiation 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 the main advantage to using stereotactic radiosurgery for treatment of metastatic spinal tumors.

Box 1. Candidate lesions for CyberKnife spinal radiosurgery

Well-circumscribed lesions
Minimal spinal cord compromise
Previously irradiated lesions
Radioresistant lesions that would benefit from a radiosurgical boost
Residual tumor after surgery
Recurrent surgical lesions
Lesions requiring difficult surgical approaches
Relatively short life expectancy as an exclusion criterion for open surgical intervention
Significant medical comorbidities precluding open surgical intervention
No overt spinal instability

One might imagine an infinite number of clinical scenarios in which spinal radiosurgery might be used. This new technique is an important treatment modality whose clinical role has not yet been fully defined. Box 2 summarizes some of the primary indications for spinal radiosurgery. The most frequent indication for the treatment of spinal metastases is pain, and spinal radiosurgery is most often used to treat tumor pain. Radiation is well known to be effective as a treatment for pain associated with spinal malignancies. Our clinical experience has found a greater than 90% improvement in spine pain after CyberKnife therapy. We have found CyberKnife spinal radiosurgery to be highly effective at decreasing pain in this difficult patient population. Spinal radiosurgery was also found to alleviate radicular pain caused by tumor compression of an adjacent nerve root.

A second indication would be to halt tumor progression that might lead to spinal instability or neural compromise. The ideal lesion should be well circumscribed such that the lesion can be easily outlined (contoured) for treatment planning. Our initial experience has found that many of our patients with these metastatic lesions are those who have already been irradiated with significant spinal cord doses or have had a recurrence after open surgical removal. Currently, it seems that CyberKnife radiosurgery is often being used as a "salvage" technique for those cases in which further conventional irradiation or surgery is not appropriate.

Box 2. Indications for CyberKnife spinal radiosurgery

Pain
Primary treatment modality
Prevention of tumor progression
Radiation boost
Progressive neurologic deficit
Residual tumor after surgery
Post surgical tumor progression

Other candidate lesions are those that would require difficult surgical approaches for adequate resection. Spinal radiosurgery can deliver radiation 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 candidates for open surgical intervention. We have treated patients with several radioresistant metastatic lesions (eg, renal cell, sarcoma) who have completed external beam irradiation with or without IMRT, and we have used CyberKnife radiosurgery for a boost treatment. Other patients with metastatic lesions have been treated with CyberKnife radiosurgery as their sole radiation treatment. The benefits for this treatment option include a single treatment with a minimal radiation dose to adjacent normal tissue. In addition, a much larger radiobiologic dose can often be delivered compared with external beam irradiation. With greater clinical experience, upfront radiosurgery may become more commonly used in certain cases, such as patients with a single symptomatic spine metastasis with radioresistant histologic findings.

If a tumor is only partially resected during open surgery, fiducials can be left in place to allow for radiosurgery treatment to the residual tumor at a later date. Given the steep falloff 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 perform spinal radiosurgery effectively, 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 moved 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.

There are several relative contraindications to CyberKnife spinal radiosurgery. These include any evidence of overt spinal instability and neurologic deficit resulting from bony compression of neural structures. With time and further clinical experience, these contraindications will be better understood and defined.

Overview of CyberKnife treatment

The CyberKnife spinal radiosurgery treatment consists of three distinct components: CT image acquisition based on skull bony landmarks or implanted bone fiducials, treatment planning, and the treatment itself (Box 3). 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 relation to 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.

The CyberKnife delivery treatment follows a sequential format [25]. 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 LINAC. The robotic arm then moves the LINAC through a sequence of preset points surrounding the patient. At each point, the LINAC stops and a new pair of images is acquired, from which the position of the target is redetermined. The position of the target is delivered to the robotic arm, which adapts beam pointing to compensate for small amounts of patient movement. The LINAC 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.

Box 3. Overview of CyberKnife spinal radiosurgery treatment

- Fiducials placed (lower spinal lesions only) or face mask molded (cervical lesions)
- CT image-guided simulation performed using 1.25-mm slices
- Treatment plan designed
- 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 first fitted with a noninvasive molded Aquaplast face mask (WRF/Aquaplast Corp., Wyckoff, NJ) that stabilizes the head and neck on a radiographically transparent headrest [22]. 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. Images may be acquired using the addition of intravenous contrast enhancement. Contrast is often not necessary for lesions that are completely within the bony elements, however. 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, nonenhanced CT imaging is performed with little difficulty in determining precise lesion anatomy.

The CyberKnife is able to detect and track either straight gold fiducials (Alpha-Omega Services, Bellflower, CA) or stainless steel screws (Accuray, Sunnyvale, CA) (Fig. 3). These fiducials are placed using fluoroscopic guidance by means of a percutaneous technique (Fig. 4). 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 screws are screwed directly into the posterior bony elements

Fig. 3. Gold seed fiducials, stainless steel screws, or tacks may be used for image tracking.

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

Four to five fiducial markers are usually placed: two in the vertebrae above, two in the vertebrae below, and one or two in the vertebrae at the level of the lesion. The reason for this number is that four fiducials are usually tracked during treatment to allow for maximum accuracy. Tracking more than four fiducials adds little to target accuracy. Three fiducials are required to define a full spatial transformation in all six 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. The principle is that their position 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 nonadjacent vertebral bodies, fiducials are sometimes placed between the two lesions. For example, for two lesions at T11 and L3, fiducials may be placed at T12, L1, and L2 without compromising target accuracy.

Fig. 4. Fiducials are placed percutaneously around the lesion in the bony structures using fluoroscopic guidance.

Treatment planning

The patient returns as an outpatient for the treatment planning CT. For fiducial cases, 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 [22].

Each radiosurgical treatment plan is devised jointly by a team comprising 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 (Fig. 5). The tumor dose is determined based on the histology of the tumor, spinal cord tolerance, and previous radiation quantity to normal tissue, especially the spinal cord.

The lesion is outlined based on CT imaging or from an magnetic resonance imaging fusion capability. An "inverse treatment planning" technique is used such that the tumor receives the maximum dose allowable with the restriction of the maximum spinal cord tolerance dose as well as that of other critical structures, such as small bowel and kidneys (Figs. 6 and 7).

There is no large experience to date with spinal radiosurgery that has previously developed optimal doses for this treatment technique. The dose to the tumor margin is based on tumor histology, location, and history of prior fractionated radiotherapy. Records regarding previous spinal cord irradiation are carefully considered. Many lesions have received prior external beam irradiation with significant spinal cord doses. Published reports from the Stanford CyberKnife experience indicate that spinal lesions received total treatment doses of 1100 to 2500 cGy in one to five fractions [3]. We prescribe the tumor dose to the 80% isodose line. Tumor dose at our center is maintained at 1600 to

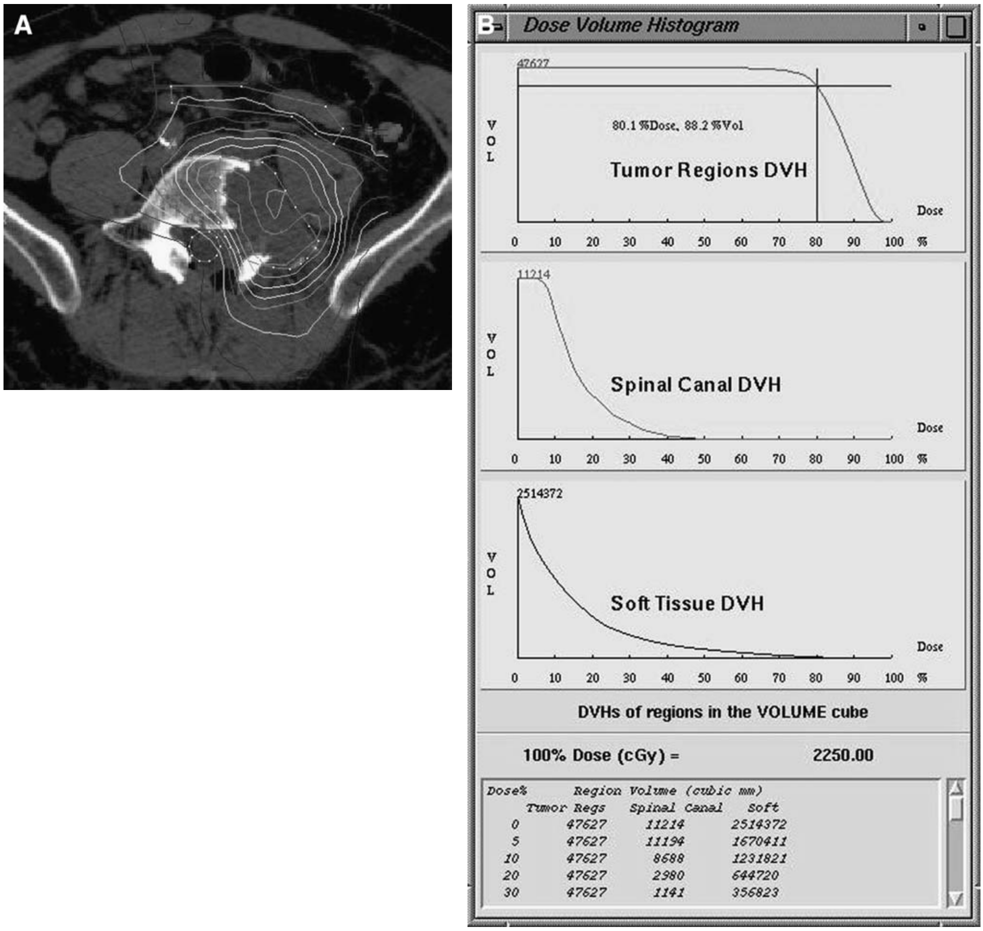

Fig. 5. (*A*) A sample treatment plan developed for an L5 metastatic hemangiopericytoma. The 80% isodose line represents the prescribed dose of 2000 cGy, the tumor volume is 50.1 mL, and 1.2 mL of the spinal canal received greater than 800 cGy. (*B*) The dose-volume histogram for the same treatment plan shows that 88.2% of the tumor volume received 80.1% of the maximum dose of 2000 cGy.

2000 cGy to the 80% isodose line contoured at the edge of the target volume. The maximum intratumoral dose (measured at the center of the target) ranges from 1750 to 2500 cGy (mean of 2000 cGy). The higher doses were for lesions situated away from critical structures. In our experience with treating spinal metastases, the mean tumor volume is approximately 30 mL (range: 1.0–190 mL). All these cases were treated in a single fraction.

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 [7]. Spinal cord tolerance related to IMRT techniques has also not yet been addressed. We must still rely on clinical data derived from external beam irradiation series in which the entire thickness of the spinal cord was irradiated. In our clinical series, no acute or delayed spinal cord toxicity has occurred with now more than 30 months of follow-up. Spinal radiosurgery was found to be safe at doses comparable to those used for intracranial radiosurgery without radiation-induced neural injury. This lack of adverse effect likely derives from a combination of the steep gradient dose fall-off and high conformality of the CyberKnife treatment as well as the relative tolerance of the spinal cord to single-fraction radiosurgery.

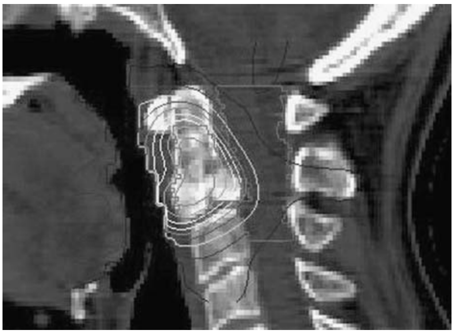

Fig. 6. Breast metastasis to the C2 body. The patient had severe pain despite external beam irradiation. The tumor was treated with 1600 cGy to the 80% isodose line. Notice the conformality of the isodose line around the spinal cord. The patient had complete pain relief within 1 month.

A limit of 800 cGy is set as the maximum spinal cord dose for treatment planning calculations. A limit of 200 cGy is set as the maximal dose to each of the kidneys. 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.

Unlike conventional radiation therapy, which delivers a full dose to the vertebral body and the spinal cord, the CyberKnife can deliver a single high-dose fraction of radiation 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 the main advantage to using stereotactic radiosurgery for treatment of metastatic spinal tumors.

Fig. 7. Large L1 metastatic renal cell carcinoma. The patient previously underwent a right nephrectomy as well as external beam irradiation. The tumor was treated with 1600 cGy to the 80% isodose line. The dose to the kidney was limited to 200 cGy. Notice the conformality of the isodose line between the spinal cord and the remaining kidney.

The doses of 1750 to 2500 cGy that we use are comparable to the total radiotherapy dose to produce a similar radiobiologic effect for fractionated radiotherapy for tumors receiving less than 1600 cGy. For those tumors that received greater than 1600 cGy, this is an increased biologically effective dose compared with standard palliation treatments. In addition, there is possibly an increased biologically effective dose to the tumor with single-fraction therapy, especially for those tumors that are relatively radioresistant.

Treatment delivery

The third component of the CyberKnife treatment is the actual treatment delivery [22]. Treatments may be performed using either 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. 8). Some patients with thoracic or lumbar lesions localized with fiducials are actually more comfortable without the alpha cradle, and only pillows are used. During the treatment, real-time digital radiographic images of the patient are obtained to track either skull bony landmarks or implanted fiducials (Fig. 9). The location of the vertebral body being treated is established from these images and is used to determine tumor location as previously described.

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 a hand or speak if he or she would like to halt the treatment temporarily. The duration of the treatment is approximately 1 to 2 hours. Many of these patients are in significant pain and are uncomfortable in the supine position for prolonged periods. No intravenous sedation is used—only oral analgesics. It is 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 the treatment resumes. Mild transient nausea may be experienced by patients

Fig. 8. Patient setup on the CyberKnife treatment couch. The patient is positioned supine with the 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.

receiving treatment to lumbar lesions. For these cases, patients are pretreated with antiemetics.

Summary

Metastatic spine tumors affect a large number of patients each year, resulting in significant pain, destruction of the spinal column causing mechanical instability, and neurologic deficits. Standard therapeutic options include surgery and fractionated external beam radiotherapy. The first option can be associated with significant morbidity and limited local tumor control. Conversely, radiotherapy may provide less than optimal pain relief and tumor control, because the total dose is limited by the tolerance of adjacent tissues, such as the spinal cord. The emerging technique of 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 more effective palliation and potentially longer survival. Spinal radiosurgery might offer improved pain control and a longer duration of pain control by giving larger radiobiologic doses. This technique also allows for the treatment of

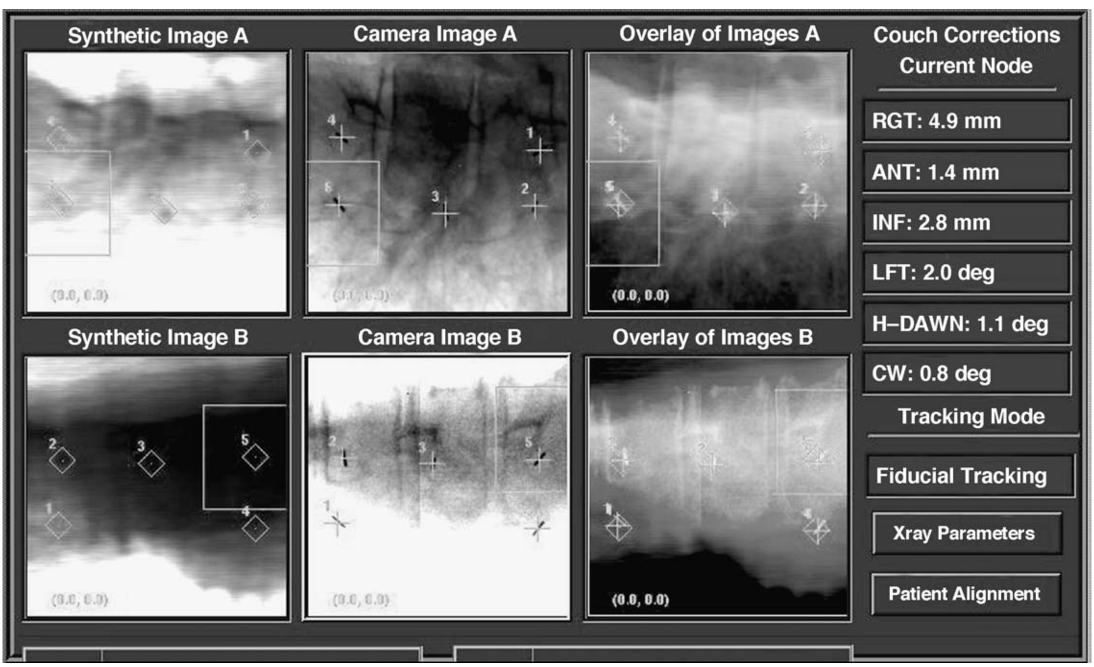

Fig. 9. All five fiducials are tracked for thoracic and lumbar lesions using real-time image guidance. The measured position as seen by both cameras is communicated through a real-time control loop to a robotic manipulator that redirects the beam to the precise intended target.

lesions previously irradiated using external beam radiation. Another advantage to the patient is that irradiation can be completed in a single day rather than several weeks, which 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. This technique allows for the treatment of lesions previously irradiated using external beam radiation. Finally, the procedure is minimally invasive compared with open surgical techniques and can be performed in an outpatient setting.

Similar to intracranial radiosurgery, stereotactic radiosurgery now has a feasible and safe delivery system available for the treatment of spinal metastatic lesions. The major potential benefit of radiosurgical ablation of spinal lesions is a relatively short treatment time in an outpatient setting combined with potentially better local control of the tumor with minimal risk of side effects. CyberKnife spinal radiosurgery offers a new and important 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. Spinal radiosurgery is likely to become an essential part of any neurosurgical spine center that treats a large number of patients with spinal metastases.

References

[1] Shiu AS, Chang EL, Ye J-S, et al. Near simultaneous computed tomography image-guided stereotactic spinal radiotherapy: an emerging paradigm for achieving true stereotaxy. Int J Radiat Oncol Biol Phys 2003;57(3):605–13.

[2] Faul CM, Flickinger JC. The use of radiation in the management of spinal metastases. J Neurooncol 1995;23:149–61.

[3] Ryu SI, Chang SD, Kim DH, et al. Image-guided hypo-fractionated stereotactic radiosurgery to spinal lesions. Neurosurgery 2001;49(4):838–46.

[4] Loblaw DA, Laperriere NJ. Emergency treatment of malignant extradural spinal cord compression: an evidence-based guideline. J Clin Oncol 1998; 16(4):1613–24.

[5] Colombo F, Benedetti A, Pozza F, et al. Stereotactic radiosurgery utilizing a linear accelerator. Appl Neurophysiol 1985;48:133–45.

[6] Hitchcock E, Kitchen G, Dalton E, Pope B. Stereotactic LINAC radiosurgery. Br J Neurosurg 1989;3:305–12.

[7] Ryu S, Yin FF, Rock J, et al. Image-guided and intensity-modulated radiosurgery for patients with spinal metastasis. Cancer 2003;97(8):2013–8.

[8] Loeffler J, Kooy H, Wen P, et al. The treatment of recurrent brain metastases with stereotactic radiosurgery. J Clin Oncol 1990;8:576–82.

[9] Auchter R, Lamond J, Alexander E, et al. A multi-institutional outcome and prognostic factor analysis of radiosurgery for resectable single brain metastasis. Int J Radiat Oncol Biol Phys 1996;35: 27–35.

[10] Sperduto P, Scott C, Andrews D, et al. Stereotactic radiosurgery with whole brain radiation therapy improves survival in patients with brain metastases: report of Radiation Therapy Oncology Group phase III study 95-08. Int J Radiat Oncol Biol Phys 2002;54:3a.

[11] Chang SD, Adler JR, Hancock SL. The clinical use of radiosurgery. Oncology 1998;12:1181–91.

[12] Kondziolka D, Patel A, Lunsford LD, Kassam AB, Flickinger JC. Stereotactic radiosurgery plus whole brain radiotherapy vs radiotherapy alone for patients with multiple brain metastases. Int J Radiat Oncol Biol Phys 1999;45:427–34.

[13] Loeffler J, Alexander EI. Radiosurgery for the treatment of intracranial metastasis. New York: McGraw-Hill; 1993.

[14] Flickinger JC, Kondziolka D, Lunsford LD, et al. A multi-institutional experience with stereotactic radiosurgery for solitary brain metastasis. Int J Radiat Oncol Biol Phys 1994;28:797–802.

[15] Milker-Zabel S, Zabel A, Thilmann C, Schlegel W, Wannenmacher M, Debus J. Clinical results of retreatment of vertebral bone metastases by stereotactic conformal radiotherapy and intensity-modulated radiotherapy. Int J Radiat Oncol Biol Phys 2003;55(1):162–7.

[16] Hamilton AJ, Lulu BL, Fosmire H, Stea B, Cassady JR. Preliminary clinical experience with linear accelerator-based spinal stereotactic radiosurgery. Neurosurgery 1995;36:311–9.

[17] Kuo JS, Yu C, Petrovich Z, Apuzzo ML. The Cyberknife stereotactic radiosurgery system: description, installation, and initial evaluation of use and functionality. Neurosurgery 2003;53(5):1235–9.

[18] Adler JR, Chang SD, Murphy MJ, Doty JR, Geis P, Hancock SL. The CyberKnife: a frameless robotic system for radiosurgery. Stereotact Funct Neurosurg 1997;60:124–8.

[19] Adler JR, Murphy MJ, Chang SD, Hancock SL. Image-guided robotic radiosurgery. Neurosurgery 1999;44:1299–307.

[20] Gerszten P, Ozhasoglu C, Burton S, Kalnicki S, Welch WC. Feasibility of frameless single-fraction stereotactic radiosurgery for spinal lesions. Neurosurg Focus 2002;13:1–6.

[21] Murphy M, Cox R. The accuracy of dose localization for an image-guided frameless radiosurgery system. Med Phys 1996;23(12):2043–9.

[22] Gerszten PC, Welch WC. CyberKnife radiosurgery for the spine. Tech Neurosurg 2003;9(3):232–41.
[23] Chang SD, Adler JR. Current status and optimal use of radiosurgery. Oncology 2001;15:209–21.
[24] Yu C, Jozsef G, Apuzzo ML, Petrovich Z. Dosimetric comparison of Cyberknife with other radiosurgical modalities for an ellipsoidal target. Neurosurgery 2003;53(5):1155–63.
[25] Romanelli P, Chang SD, Koong A, Adler JR. Extracranial radiosurgery using the CyberKnife. Tech Neurosurg 2003;9(3):226–31.
[26] Adler JR, Cox RS, Kaplan I, Martin DP. Stereotactic radiosurgical treatment of brain metastases. J Neurosurg 1992;76:444–9.
[27] Guthrie BL, Adler JR. Computer-assisted preoperative planning, interactive surgery, and frameless stereotaxy. Clin Neurosurg 1991a;38:112–31.
[28] Chang SD, Main W, Martin DP, Gibbs IC, Heilbrun MP. An analysis of the accuracy of the Cyberknife: a robotic frameless stereotactic radiosurgical system. Neurosurgery 2003;52(1): 140–7.