The role of stereotactic radiosurgery in the treatment of benign and malignant intracranial lesions is well established. Its role in the treatment of benign spinal lesions is more limited. Benign spinal lesions should be amenable to radiosurgical treatment similar to their intracranial counterparts. In this study the authors evaluated the effectiveness of the CyberKnife for benign spinal lesions involving a single-fraction radiosurgical technique.

Methods. The CyberKnife is a frameless radiosurgery system in which an orthogonal pair of x-ray cameras is coupled to a dynamically manipulated robot-mounted linear accelerator possessing six degrees of freedom, whereby the therapy beam is guided to the intended target without the use of frame-based fixation. Cervical spine lesions were located and tracked relative to skull osseous landmarks; lower spinal lesions were tracked relative to percutaneously placed fiducial bone markers. Fifteen patients underwent single-fraction radiosurgery (12 cervical, one thoracic, and two lumbar). Histological types included neurofibroma (five cases), paraganglioma (three cases), schwannoma (two cases), meningioma (two cases), spinal chordoma (two cases), and hemangioma (one case).

Radiation dose plans were calculated based on computerized tomography scans acquired using 1.25-mm slices. Planning treatment volume was defined as the radiographic tumor volume with no margin. The tumor dose was maintained at 12 to 20 Gy to the 80% isodose line (mean 16 Gy). Tumor volume ranged from 0.3 to 29.3 ml (mean 6.4 ml). Spinal canal volume receiving more than 8 Gy ranged from 0.0 to 0.9 ml (mean 0.2 ml). All patients tolerated the procedure in an outpatient setting. No acute radiation-induced toxicity or new neurological deficits occurred during the follow-up period. Pain improved in all patients who were symptomatic prior to treatment. No tumor progression has been documented on follow-up imaging (mean 12 months).

Conclusions. Spinal stereotactic radiosurgery was found to be feasible, safe, and effective for the treatment of benign spinal lesions. Its major potential benefits are the relatively short treatment time in an outpatient setting and the minimal risk of side effects. This new technique offers an alternative therapeutic modality for the treatment of a variety of benign spinal neoplasms in cases in which surgery cannot be performed, in cases with previously irradiated sites, and in cases involving lesions not amenable to open surgical techniques or as an adjunct to surgery.
in a stereotactic frame. Spinal lesions also have a fixed relationship to the spine; however, LINAC-based stereotactic radiosurgery techniques developed for spinal lesions require that an invasive rigid external frame system be directly applied to the spine and therefore are not technically practical.16

A unique image-guided frameless stereotactic radiosurgery delivery system, the CyberKnife (Accuray, Inc., Sunnyvale, CA), has been developed for use throughout the entire spine. The system consists of a lightweight LINAC mounted on a robotic arm. Real-time imaging tracking allows for the tracking of patient movement with 1-mm spatial accuracy.3,6,8,25 The CyberKnife was developed as a noninvasive means to align precisely treatment beams with targets. It differs from conventional frame-based radiosurgery in three fundamental ways.25 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. 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 on the treatment couch without precise reproduction of the position in the treatment planning study.1,3,9,25

With the ability to treat lesions outside of the skull by using fiducial tracking, a growing interest in the CyberKnife-based treatment of spinal lesions has emerged.13,23,25 Benign spinal lesions not otherwise amenable to open surgical intervention might benefit from radiosurgical therapy similar to intracranial lesions of the same histological type. 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 treatment as has been the case for intracranial lesions.

CLINICAL MATERIAL AND METHODS

Patient Population

This study involved the prospective evaluation of 15 patients with benign spinal lesions who underwent CyberKnife radiosurgery (the Dynamic Tracking System version 3.0 software was used). All patients were treated at the University of Pittsburgh Medical Center, and the protocol was approved by the institutional review board. There were six men and nine women. Tables 1 and 2 provide summaries of the histological tumor types and the characteristics of the treatment group.

The CyberKnife System

The CyberKnife consists of a computer-controlled, compact source of high-energy x-ray beams; the unit is smaller and lighter in weight than LINACs used in conventional radiotherapy.2,15,24 Its smaller size allows it to be mounted on a computer-controlled six-axis robotic manipulator, permitting a much wider range of beam orientations than can be achieved using conventional radiotherapy devices. The CyberKnife system uses image-guided frameless robotic radiosurgery. Two diagnostic x-ray cameras are positioned orthogonally to acquire real-time intraoperative images of the patient’s internal anatomy. The images are processed automatically to identify radiographic features and then registered to the treatment planning study to allow measurement of the position of the treatment site. The measured position is communicated through a real-time control loop to a robotic manipulator that aims a compact 6-mV LINAC. The system can adapt intraoperatively to changes in patient position by acquiring targeting images repeatedly and then adjusting the direction of the x-ray beam. The target to be treated is identified preoperatively on planning images, and between 60 to 100 beams are used to irradiate the target in a stereotactic fashion. The treatment beam can be maneuvered and pointed nearly anywhere in space. Because the treatment beams are also not confined to isocentric geometry, they can be arranged in complex overlapping patterns that conform to irregularly shaped tumor volumes.25

Inclusion and Exclusion Criteria

All patients were older than 18 years of age. Table 3 provides a summary of the indications for CyberKnife treatment. Exclusion criteria included three main factors: 1) evidence of overt spinal instability; 2) neurological deficit resulting from osseous compression of neural structures; or 3) previous irradiation at the tolerance dose of the spinal cord.

<table>
<thead>
<tr>
<th>Tumor Type</th>
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<tbody>
<tr>
<td>neurofibroma</td>
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<tr>
<td>paraganglioma</td>
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</tr>
<tr>
<td>schwannoma</td>
<td>2</td>
</tr>
<tr>
<td>meningioma</td>
<td>2</td>
</tr>
<tr>
<td>spinal chordoma</td>
<td>2</td>
</tr>
<tr>
<td>hemangioma</td>
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</table>

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>No. of Cases</th>
<th>Value</th>
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<td></td>
</tr>
<tr>
<td>previous open resection</td>
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<td></td>
</tr>
<tr>
<td>primary indications for radiosurgery</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>pain</td>
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<td></td>
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<tr>
<td>progressive neurological deficit</td>
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<tr>
<td>primary treatment modality</td>
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<tr>
<td>postop radiation boost</td>
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<tr>
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<tr>
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<tr>
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<td>mean tumor volume</td>
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</tr>
<tr>
<td>mean dose to 80% isodose line</td>
<td>16 Gy</td>
<td></td>
</tr>
<tr>
<td>mean volume of spinal cord/canal dose</td>
<td>0.2 ml</td>
<td></td>
</tr>
</tbody>
</table>

*TABLE 1*

Summary of histological tumor types diagnosed in 15 patients

*TABLE 2*

Pretreatment- and treatment-related data
Overview of Treatment

CyberKnife treatment consists of three distinct components: 1) CT scan acquisition based on skull osseous landmarks or implanted bone fiducials; 2) treatment planning; and 3) the treatment itself. Intracranial and cervical lesions were tracked relative to skull osseous landmarks. Thoracic and lumbar lesions were tracked relative to bone 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 vertebrae is detected as movement in the fiducials, and this movement is detected and compensated for by the CyberKnife.

All patients with cervical lesions were fitted with a non-invasive molded Aquaplast facemask (WRF/Aquaplast Corp., Wyckoff, NJ) by which the head and neck were stabilized on a radiographically transparent headrest. Computerized tomography scans were acquired using 1.25-mm-thick slices from the top of the skull to the bottom of the cervical spine. In patients harboring other lesions, fluoroscopy was used to guide the placement of four to six gold fiducial markers (Alpha-Omega Services, Inc., Bellflower, CA) into the pedicles immediately adjacent to the lesion; a standard Jamshidi bone marrow biopsy needle (Allegiance Healthcare Corporation, McGraw Park, IL) was used in these cases (Fig. 1). Three fiducials are required to define a full spatial transformation in all six degrees of target translation and rotation. The fiducial placement procedure was performed in the operating room in an outpatient setting. There were no complications associated with fiducial placement. The patient then returned as an outpatient to undergo the planning CT scanning studies. The patient was placed supine in a conformal alpha cradle during CT scanning as well as during treatment. Axial 1.25-mm-thick CT slices were acquired to include the lesion of interest as well as all fiducials.

In each case, the radiosurgical treatment plan was designed based on tumor geometry, proximity to the spinal cord, and location. Planning treatment volume was defined as the radiographically determined tumor volume with no margin. Treatment planning was performed using the Accuray treatment planning system Dynamic Tracking System (Fig. 1). The tumor dose was determined based on its histological type, spinal cord tolerance, and previous radiation quantity. An “inverse treatment planning” technique was used such that the tumor received the maximum dose allowable with the restriction of the maximum spinal cord tolerance dose, as well as other critical structures such as small bowel and kidneys.

All procedures were performed using a single fraction in an outpatient setting. The patients were placed supine on the CyberKnife table with the appropriate immobilization device. During the treatment, real-time digital x-ray films were obtained. Based on these images, the location of the vertebral body being treated is established and is used to determine the tumor location, as previously described. No intravenous anesthetic agent was used in any of these cases, and monitoring was not performed. The patient was observed intraoperatively by closed circuit television. Duration of treatment ranged from 30 to 90 minutes.

RESULTS

Treatment Planning

Table 2 provides a summary of characteristics and treatments. The tumor dose was maintained at 1200 to 2000 cGy to the 80% isodose line contoured at the edge of the target volume (mean 1600 cGy). The maximum intratumoral dose ranged from 1500 to 2500 cGy (mean 1956

| TABLE 3 |
| Criteria for CyberKnife treatment of benign spinal lesions |
| Criteria |
| well-circumscribed lesion |
| minimal spinal cord compromise |
| recurrent op lesions |
| lesion requiring difficult op approach |
| significant medical comorbidities precluding open op |

Fig. 1. Studies obtained in a 32-year-old woman with neurofibromatosis and a left L-5 neurofibroma. Upper Left: Gadolinium-enhanced axial magnetic resonance image. The patient suffered disabling, unremitting L-5 radicular pain. Upper Right: Lateral radiograph of the fiducial markers implanted in the L-4, L-5, and S-1 pedicles. Lower Left: Isodose lines of the treatment plan for the tumor. The 80% isodose represents the prescribed dose of 1600 cGy, the tumor volume is 3.2 ml, and the cauda equina received a maximum dose of 661 cGy. Lower Right: Dose volume histogram (DVH) showing that 88.2% of the tumor received 80% of the maximum 2000-cGy dose. The patient reported a significant improvement in pain within 1 month, and this has persisted at 1-year follow up.
Treatment of these lesions in the past has been limited. The role of irradiation for the fixation based on the extent of spinal column destruction spinal cord or other neural elements, decompressive sur-

improvement in pain within 1 month, and this persisted maximum dose of 2000 cGy. The patient reported a significant maximum dose of 661 cGy. The dose volume histogram
described dose of 1600 cGy that was calculated to the 80% collimator was used to treat with a single fraction to a pre-
dosage. 14 When a spinal tumor compresses the spinal cord or other neural elements, decompressive sur-

axial and radicular pain, symptoms had improved by the 1-month follow-up examination.

Patients were evaluated again at 30 days for treatment-related complications. One patient who had harbored an upper cervical lesion experienced a transient episode of parotitis, a rare but well-described complication of irradi-
aton. Another patient treated for a cervical lesion experi-

1.4,9,17,21,22,26 There is reason to believe that ra-
dosurgery involving similar doses would be equally efficacious for the treatment of benign spinal lesions.
The team from Stanford University has reviewed their experience using the CyberKnife for spinal lesions.25 Six-
teen patients harboring a variety of spinal lesions, in-
cluding histologically benign entities, underwent both stereotactic radiosurgery and hypofractionated stere-
tactic radiotherapy. The lesions were all believed to be surgically inaccessible. There were no procedure-related complications or disease progression in a minimum 6-
month follow-up period. The technique used at our instit-
tution is adapted from that reported by the Stanford team. This Phase I feasibility study will explore the feasibility of using the CyberKnife to treat metastatic lesions of the spine with large doses of radiation.

There has been no large-scale study of spinal radio-
surgery in which optimal radiation doses have been established using this technique. There has also been no pub-
lished experience regarding the tolerance of the human spinal cord to such single-fraction doses. The dose to the tumor margin was based on tumor histology, location, and history of prior fractionated radiotherapy. Re-
searchers at Stanford University have reported using the CyberKnife to deliver total treatment doses of 1100 to 2500 cGy in one to five fractions.7 In the present series, we used similar total treatment doses, all of which were delivered in a single fraction.

Unlike conventional radiotherapy that delivers a full dose to both the vertebral body and the spinal cord, the CyberKnife can deliver a high-dose single fraction of radi-
ation to the target tissue while sparing most of the adjacent spinal cord. The treatment plan can create a high gradient dose falloff to the target tissue, which should significantly reduce the possibility of radiation-induced myelopathy. This is the main advantage of stereotactic radiosurgery for treatment of many spinal tumors.

Our findings confirmed that, similar to the established stereotactic radiosurgery treatment of intracranial benign lesions, it is now feasible and effective to treat benign spinal tumors with the same modality. Stereotactic radio-
surgery may now be added to the armamentarium for the treatment of a variety of benign spinal lesions that, in the past, were not amenable to open resection or convention-
al EBRT techniques.

**CONCLUSIONS**

Spinal stereotactic radiosurgery was found to be feasible, safe, and effective for the treatment of benign spinal lesions. The major potential benefits of radiosurgical abla-
tion of spinal lesions are relatively short treatment time in an outpatient setting and the minimal risk of side effects or surgery-induced complications. This new technique offers
an alternative therapeutic modality for a variety of benign spinal neoplasms in place of open surgery, in medically inoperable patients, for lesions not amenable to open surgical techniques, or as an adjunct to surgery.

References


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