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Technical description, phantom accuracy, and clinical feasibility for fiducial-free frameless real-time image-guided spinal radiosurgery

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Object. The authors describe the technical application of the Xsight Spine Tracking System, data pertaining to accuracy obtained during phantom testing, and the initial clinical feasibility of using this fiducial-free alignment system with the CyberKnife in spinal radiosurgery.

Methods. The Xsight integrates with the CyberKnife radiosurgery system to eliminate the need for implantation of radiographic markers or fiducials prior to spinal radiosurgery. It locates and tracks spinal lesions relative to spinal osseous landmarks. The authors performed 10 end-to-end tests of accuracy using an anthropomorphic head and cervical spine phantom. Xsight was also used in the treatment of 50 spinal lesions in 42 patients. Dose planning was based on 1.5-mm-thick computed tomography slices in which an inverse treatment planning technique was used.

All lesions could be treated using the fiducial-free tracking procedure. Phantom tests produced an overall mean targeting error of 0.52 ± 0.22 mm. The setup time for patient alignment averaged 6 minutes (range 2–45 minutes). The treatment doses varied from 12 to 25 Gy to the median prescription isodose of 65% (40 to 70%). The tumor volume ranged between 1.3 and 152.8 cm^3. The mean spinal cord volume receiving greater than 8 Gy was 0.69 ± 0.35 cm^3. No short-term adverse events were noted during the 1- to 7-month follow-up period. Axial and radicular pain was relieved in 14 of 15 patients treated for pain.

Conclusions. Fiducial-free tracking is a feasible, accurate, and reliable tool for radiosurgery of the entire spine. By eliminating the need for fiducial implantation, the Xsight system offers patients noninvasive radiosurgical intervention for intra- and paraspinal tumors.

Key Words • spine • CyberKnife • radiosurgery • fiducial-free registration

Spinal radiosurgery is a relatively new method for primary or adjuvant treatment of spinal tumors. Similar to intracranial radiosurgery, spinal radiosurgery requires high dose–targeting precision. The lack of precision of conventional EBRT and the limitations of target immobilization techniques have precluded the delivery of large single-fraction doses of radiation in the vicinity of radiosensitive structures such as the spinal cord. The frameless CyberKnife radiosurgery system (Accuray Inc., Sunnyvale, CA) can be used to overcome these problems because its real-time image guidance allows target tracking even if patients move during the procedure. Continuous tracking and correction of spinal motion throughout treatment is a prerequisite for spinal radiosurgery because patients do move after the setup is complete.[11] Until recently, clinicians surgically implanted fiducials into the spine to track the movement of the lesion during treatment.[7,9,12] Fiducial placement introduces some of the surgery-related risks associated with invasive surgery, lengthens treatment time, and reduces a patient's level of comfort. It would be ideal if, instead of fiducials, the surgeon could track spinal lesions by using osseous landmarks (similar to tracking intracranial lesions based on skull anatomy). Recently, such a system was introduced (Xsight Spinal Tracking System; Accuray Inc.).[3,4] It is the aim of the present study to provide a technical description of the new fiducial-free alignment procedure, to assess targeting accuracy in end-to-end phantom tests, and to assess the tracking system's clinical feasibility for the radiosurgical treatment of tumors throughout the spine.

Abbreviations used in this paper: CT = computed tomography; DRR = digitally reconstructed radiograph; EBRT = external-beam radiotherapy; LINAC = linear accelerator; MR = magnetic resonance; ROI = region of interest; 2D = two-dimensional; 3D = three-dimensional.

Clinical Material and Methods

CyberKnife Radiosurgery

The CyberKnife robotic radiosurgery system consists of a 6-MV compact LINAC mounted on a computer-controlled six-axis robotic manipulator.[1,10,13] Integral to the

system are the orthogonally positioned x-ray cameras that acquire images during treatment. The images are processed automatically to identify radiographic features and are registered to the treatment planning study to measure the position of the treatment site in real time. The system adapts to changes in patient position during treatment by acquiring targeting images repeatedly and then adjusting the direction of the treatment beam. In contrast to a gantry-mounted LINAC, the treatment beam can be directed at the target from nearly anywhere around the patient, limited only by obstacles such as the treatment couch.

Fiducial-Free Spinal Tracking

The safety and effectiveness of fiducial-based targeting (or, in cases of high cervical lesions, targeting based on cranial anatomy) for CyberKnife treatment of the spine has been previously reported.[2,6,8,12] The new Xsight fiducial-free localization process is performed in several stages.

Image Enhancement. Pretreatment DRRs derived from CT scans and intratreatment radiographs undergo image processing to improve the visualization of the osseous anatomy (Fig. 1). The image-processing method enhances skeletal structures on the DRRs[3] and includes three steps: 1) exponential transformation of CT scans to enhance skeletal structures and suppress soft tissue; 2) DRR generation by x-ray casting and trilinear interpolation; and 3) filtering of DRRs to further enhance skeletal features.

Region of Interest. An ROI containing the maximum osseous anatomical information surrounding the target volume is selected. Selection is based on an initial user-defined position, which is refined automatically by an algorithm that seeks to maximize the image entropy within the ROI. The resulting optimal ROI typically includes one to two vertebral bodies that form the basis of patient tracking and alignment (Fig. 2).

Image Registration. Two-dimensional–three-dimensional image registration uses similar measures to compare the radiographs and DRRs, and a spatial transformation parameter search method to determine changes in patient position. In the Xsight system,[4] two orthogonal enhanced x-ray projections are used to register with a pair of enhanced DRRs, which are generated from the planning CT to solve for 3D target displacements. A mesh is then overlaid in the ROI. Local displacements in mesh nodes are estimated individually but are constrained by displacement smoothness. Nodal displacements within the mesh in the two images form two 2D displacement fields.

Three-Dimensional Tumor Localization. Three-dimensional displacements of the targets and global rotations of spinal structures within the ROI can be calculated from the two 2D displacement fields by interpolation. Three translations and three global rotations are aligned during patient setup and corrected during treatment delivery (Fig. 3).

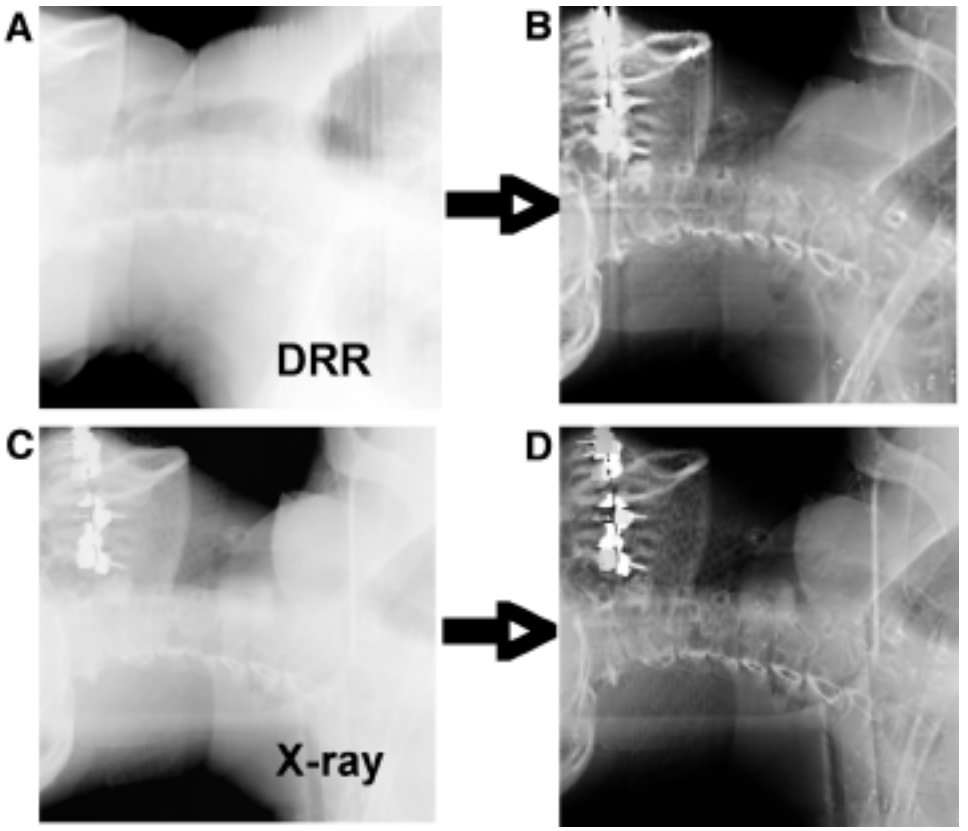

FIG. 1. Results of the image-enhancement process of the DRR (A) and the intratreatment radiograph (B). Both sets of radiographs undergo image processing based on top-hat filtering to improve the visualization of the osseous anatomy (C and D). These images were obtained in the patient in the *Illustrative Case*.

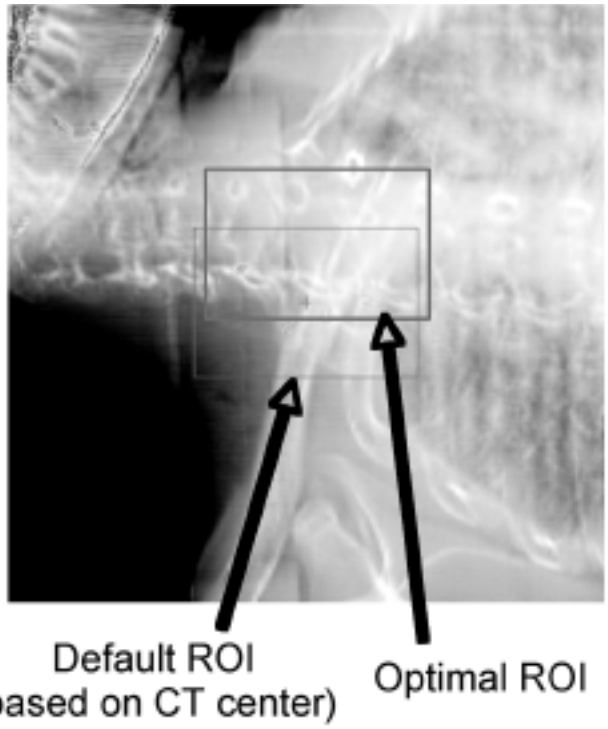

FIG. 2. Image ROI selection for spinal tracking. An ROI containing the maximum osseous anatomical information surrounding the target volume is selected based on an initial user-defined position, which is refined by an algorithm that seeks to maximize the image entropy within the ROI. The resulting ROI typically includes two vertebral bodies, which form the basis of the treatment alignment.

Phantom Tests

The accuracy of the spinal radiosurgical procedure was assessed with an anthropomorphic head and cervical spine phantom. These phantoms have cavities into which a measuring device, referred to as a ball-cube targeting tool, can be inserted. Using this device, all tracking modalities provided by the CyberKnife system can be simulated: fiducial tracking, skull tracking with six degrees of freedom, and, by using a smaller insert (mini ball-cube) anterior to the C-7 vertebra, Xsight tracking for spinal targets. The ball-cube is a precisely machined solid water cube with an acrylic ball (diameter 31.75 mm; mini ball-cube diameter 19.00 mm) in the center. This cube consists of four pieces that connect together using threaded nylon rods and nuts. Two self-developing radiochromic films (Gafchromic MD-55; International Specialty Products, Wayne, NJ) are inserted perpendicularly between those pieces. After carefully aligning the film edges with the reference edges of the ball-cube, the nuts are tightened to keep the film in position. The ball-cube is then loaded into the head phantom and a 1.0- to 1.5-mm-thick axial slice CT scan is generated. Based on the CT study, an isocentric treatment plan is calculated targeting the contoured acrylic ball. The resulting dose distribution is centered on the spherical target. A 20-Gy dose was prescribed to the 70% isodose line. While DRRs are generated, the phantom is positioned on the treatment table using a standard thermoplastic mask.

By comparing real-time images with the reference images, the couch correction offset is minimized and the treatment is delivered as planned. The exposed films are removed from the phantom and analyzed immediately after radiation delivery. The films are scanned using a calibrated optical scanner, and the difference between the center of the dose distribution and the center of the film is

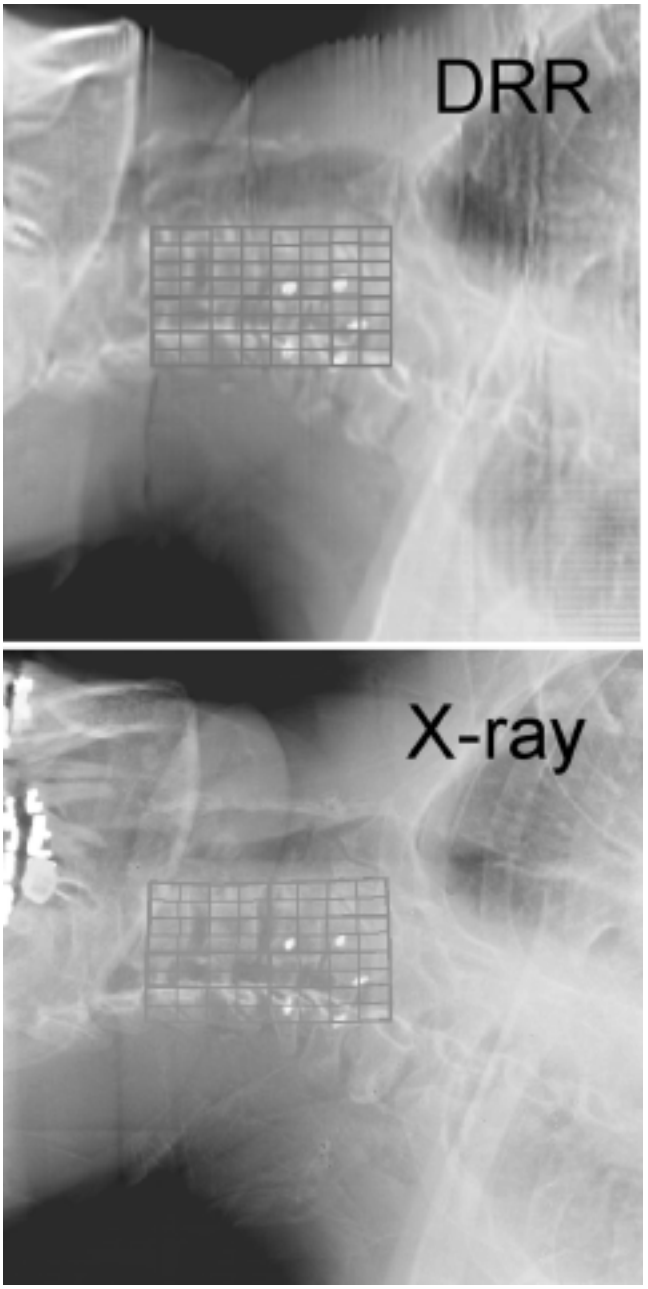

FIG. 3. The hierarchical mesh tracking procedure. Registration is performed using a hierarchical mesh technique in which the calculation is made at a series of discrete points within the ROI. The process is iterative, with additional registration points added at each step to improve the spatial resolution of the result. This approach generates a deformable registration model, which can account for nonrigid changes in the patient posture between pre- and intratreatment imaging. The deformation is apparent in the mesh in the x-ray panel.

measured in three directions (anteroposterior, left–right, and inferosuperior) using a software tool. The total targeting error is then calculated as the length of the distance vector. This test includes the uncertainties arising from all stages of treatment, from CT scan to radiation delivery. Additional details of this procedure have been provided by Yu, et al.[14] The end-to-end test was conducted 10 times.

Patient Population

A consecutive series of 42 patients underwent 50 spinal radiosurgical procedures between August 1, 2005, and February 20, 2006, in which the fiducial-free tracking system was used. In all patients, the Karnofsky Performance Scale score was 50 or greater. In patients with metastatic disease, a biopsy sample obtained at the primary site was histologically confirmed. Patients were also included when they harbored recurrent surgical lesions (that is, local recurrences after surgery), lesions requiring difficult surgical approaches, or previously irradiated lesions precluding further EBRT. Only patients with a life expectancy of at least 6 months were selected for spinal radiosurgery. Evidence of spinal instability precluded inclusion in the study. There were 25 male and 17 female patients who ranged in age from 2.5 to 81 years (mean 55 years). Table 1 summarizes the characteristics of the treatment group and Table 2 classifies the tumors into histological type.

The first clinical follow-up examination was performed 1 week after radiosurgery to analyze the patient's status, particularly the pain level. Clinical evaluations and CT and/or MR imaging studies were conducted 1, 3, and 6 months after treatment. If the patient could not come to the clinic because of his/her physical disability, data were collected over the telephone. Each evaluation included clinical investigation and evaluation of pain status using a 10-point pain scale (with scores being compared with those obtained the day of treatment). Changes in prescribed analgesic medication were recorded. Only pain that could reasonably be attributable to the tumor was used for analysis.

Treatment Procedure

Planning and delivery of treatment were performed on an outpatient basis. After consultation, the planning CT study was performed with the patient placed in a supine position without vacuum bags or alpha cradles. The images were acquired at 1.5-mm slice thickness including the lesion, as well as 5 cm above and below. In most cases, axial T_1-weighted Gd-enhanced MR images of the lesion were fused with the CT scans for better soft-tissue discrimination. Treatment planning with Multi Plan software (version 1.4.0; Accuray Inc.) was performed by a team of neurosurgeons and specialized radiation physicists. The tumor dose was based on the tumor histological type, spinal cord tolerance, and history of radiotherapy. Treatment doses were equivalent to those used for cranial radiosurgery. An inverse treatment planning technique ensured that the tumor received the maximum dose and placed restrictions on the maximum dose to the spinal cord. Because the beam directions are not confined to a common isocenter, the system can produce complex dose distributions, resulting in beam patterns that wrap around the spine and minimize exposure to the cord. A limit of 800 cGy was set as the maximum spinal cord dose for extramedullary lesions. All treatments were performed in a single fraction. Patients were positioned on the treatment table without any immobilization device (Fig. 4). Pillows for patient comfort were used as they had been during the planning CT session. Patients with significant pain received orally administered analgesic agents, but no further intravenous sedation was required. Each patient returned for radiosurgery within 1 week of treatment planning. After treatment, clinical follow-up examination was performed to determine if any immediate adverse effects had been caused by the therapy, according to the aforementioned follow-up time schedule.

The mean values are presented as ± standard deviations.

TABLE 1

Summary of histories and characteristics in 42 patients with 50 lesions

Characteristic	No. of Cases
levels treated	
cervical	7
thoracic	15
lumbar	23
sacral	5
previous EBRT	11
previous op	10
multiple lesions treated	8
primary indication for radiosurgery	
pain	15
primary treatment modality	15
progressive neurological deficit	9
radiation boost	3

TABLE 2

*Histological tumor types**

Tumor Type	No. of Cases
metastatic lesions (total)	42
renal cell	19
MPNST	3
lung	3
hemangioblastoma	3
sarcoma	3
neuroendocrine carcinoma	3
breast	3
melanoma	2
stomach	1
prostate	1
medulloblastoma	1
ependymoma Grade III	2
benign lesions (total)	6
neurinoma	2
chordoma	2
meningioma	1
pilocytic astrocytoma	1
overall total	50

*MPNST = malignant peripheral nerve sheath tumor.

Results

Phantom Tests

As determined by a series of 10 completely independent

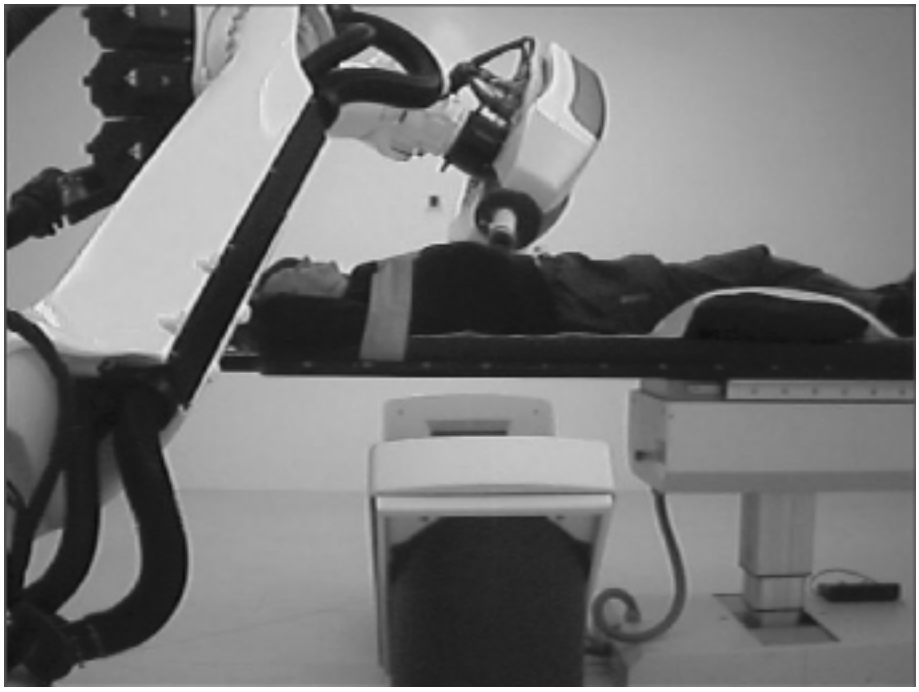

FIG. 4. Photograph of patient position during spinal radiosurgery for a lumbar lesion. The patient lies on the treatment couch without any vacuum bags or fixation devices. A cushion is placed under the legs for comfort. The pretreatment CT scan was obtained with the patient in the same position.

end-to-end tests involving a 1.5-mm CT slice thickness, the mean total targeting error of our specific CyberKnife system was 0.52 ± 0.22 mm. The results of the individual tests are listed in Table 3.

Clinical Data

We treated 50 spinal lesions (seven cervical, 15 thoracic, 23 lumbar, and five sacral) in 42 patients. The tumor volume ranged from 1.3 to 152.8 ml (mean 29.8 ml). Ten patients had previously undergone surgery—three because tumor resection was incomplete and three because follow-up imaging revealed tumor progression at the site of resection. Repeated surgery was denied either by the referring surgeon or by the patient. Eleven lesions had received previous EBRT 12 to 40 weeks before radiosurgery; in these patients, additional conventional irradiation was precluded because of previous doses to the spinal cord. The follow-up period ranged from 1 to 7 months.

All tumors were treated in a single fraction of 12 to 25 Gy to the 65% isodose line (Table 4). The fiducial-free tracking procedure was effective in all cases, even without patient-immobilization devices. The mean setup time for patient alignment on the treatment couch was 6 minutes (range 2–45 minutes). Fourteen of 15 patients treated for lesion-related pain as the primary indication for radio-

TABLE 3

*Results of end-to-end phantom tests**

Test No.	Lt Error	Ant A/L	Sup Error	Ant A/S	Mean Ant Error	Total Targeting Error
1	0.55	0.64	−0.68	0.34	0.49	1.00
2	−0.34	0.14	0.09	0.61	0.37	0.51
3	0.06	0.02	0.03	0.50	0.26	0.27
4	0.15	0.65	0.01	0.41	0.53	0.55
5	0.31	0.16	−0.08	0.29	0.23	0.39
6	−0.14	−0.21	−0.60	−0.12	−0.16	0.64
7	−0.33	0.11	0.17	−0.03	0.04	0.37
8	−0.13	0.09	0.15	−0.34	−0.13	0.23
9	−0.65	−0.27	−0.28	−0.42	−0.34	0.78
10	−0.45	−0.03	−0.12	−0.21	−0.12	0.48
						0.52 ± 0.22

*All dimensions are recorded in millimeters. Abbreviations: A/L = anterior/left; Ant = anterior; A/S = anterosuperior, Sup = superior.

surgery experienced a significant pain reduction during the 1st week of treatment. There were no cases of symptom exacerbation, radiation-induced myopathy, hemorrhage, neurological changes, or required hospitalization immediately after treatment. Additionally, short-term adverse events did not occur in any of the patients who received conventional fractionated radiotherapy before radiosurgery. One patient underwent surgery 2 months after treatment for lumbar segmental instability unrelated to radiosurgery.

TABLE 4

Summary of radiosurgery treatment characteristics

Characteristic	Mean	Min	Max
prescription dose (Gy)	18	12	25
isodose (%)	65	40	70
treatment volume (cm^3)	33.2	1.3	152.8
conformality index	1.09	1.25	2.41
homogeneity index	1.45	1.22	2.1
coverage (%)	92.5	71	99.7
vol spinal cord >8 Gy (cm^3)	0.69	0.2	2.2
no. of beams	142	75	330

Illustrative Case

History. This 56-year-old woman was transferred to our hospital for progressive gait disturbances accompanied by strong neck pain, which had been treated with morphine for 8 weeks. Incomplete surgery for a C-5 non–neurofibromatosis Type 1 malignant peripheral nerve sheath tumor had been performed 6 months prior to admission. After surgery, the patient underwent a 40-Gy course of conventional fractionated radiotherapy covering the whole spinal canal.

Examination. Cervical MR imaging upon admission revealed a large contrast-enhancing mass compressing the spinal cord anteriorly at C-5 (Fig. 5).

Treatment. Spinal radiosurgery was chosen because the conventional therapies failed to achieve local tumor control, and the patient rejected a second surgery via an anterior approach. The patient underwent a single-fraction 13.5-Gy-dose procedure prescribed to the 80% isodose (Figs. 6 and 7). A small collimator (5 mm) and a large number of beams (311 total) were used to achieve maximum dose conformality and the lowest possible dose to the spinal cord. Figure 8 *(upper)* shows 3D translational motion and the individual components (rotation angles) of orientation during the first path of treatment (45 minutes). Small movements made by the patient caused automatic corrections of the beam direction. A larger movement at node 22 required an automatic couch correction. The duration of treatment was 2.5 hours and was well tolerated by the patient.

Posttreatment Period. One week after treatment, morphine medication was reduced by 50%, and after 2 weeks, it was completely withdrawn. At 4 weeks after treatment, MR imaging demonstrated a reduction in tumor volume of approximately 70% (Fig. 5). The patient died 5 months after radiosurgery of progressive systemic disease. There were no additional neurological deficits after the radiosurgery procedure.

Discussion

Spinal radiosurgery demands high precision. Because it has been well documented that patients move during treatment, it is important continually to detect and correct for motions of the spine throughout the procedure. Because skeletal structures such as vertebrae move independently, clinicians using the CyberKnife have had to implant fiducials into the spine to track the movement of the lesion during treatment, and this introduced some of the risks and discomfort associated with invasive surgery. The introduction of Xsight enables the continuous tracking of spinal lesions based on anatomical landmarks instead of sur-

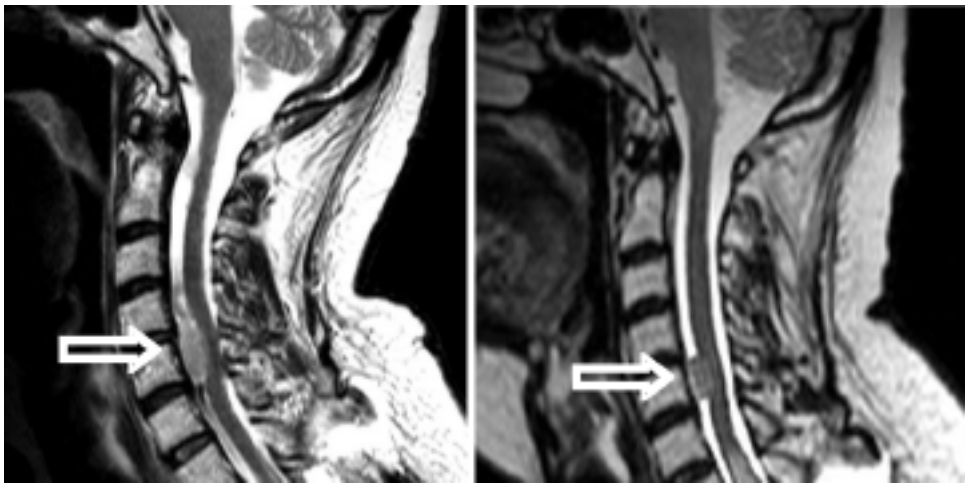

FIG. 5. *Left:* Sagittal T_2-weighted MR image obtained in a patient undergoing surgery and conventional radiotherapy for a malignant peripheral nerve sheath tumor at the C-6 level *(arrow)*. The recurrent tumor was compressing the spinal cord anteriorly. Instead of repeated surgery, CyberKnife radiosurgery was performed using fiducial-free tracking. *Right:* Sagittal image acquired after spinal radiosurgery. The tumor has shrunk significantly *(arrow)* and the anterior cord compression has been eliminated.

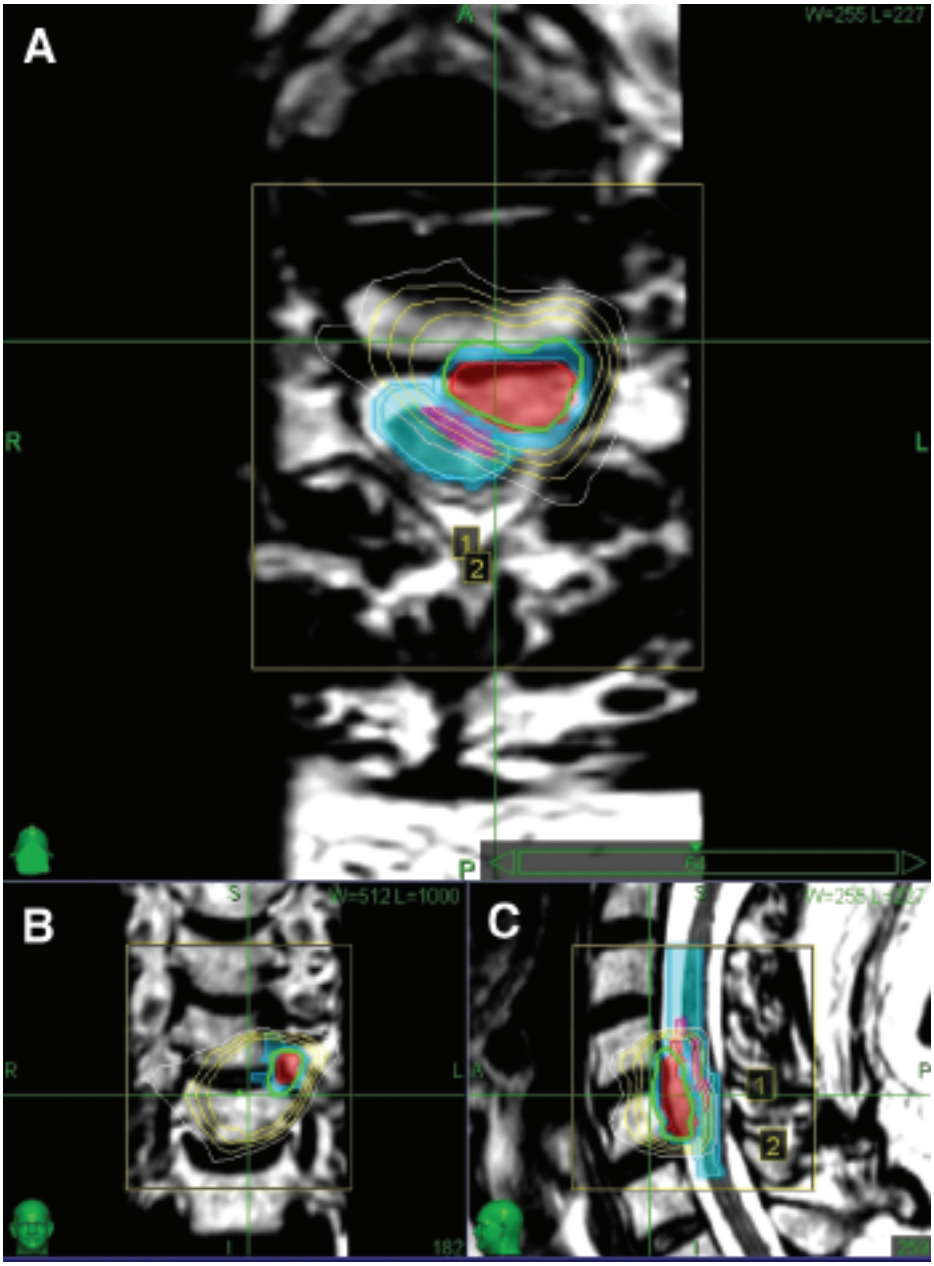

FIG. 6. Axial (A), coronal (B), and sagittal (C) views of a treatment plan. Note the sharp dose gradient near the spinal cord. The thick green line represents the prescribed isodose, and the blue and pink shaded regions adjacent to the treated volume represent dose constraints placed around the spinal cord.

gically implanted fiducials. Until now, however, data concerning the technical accuracy in a clinical setting of this new fiducial-free spinal tracking procedure and its first clinical results were lacking.

Fiducial-Free Tracking

Prior to the introduction of the Xsight system, alignment of each treatment beam to the target volume usually required the localization of implanted fiducial markers (typically, four to six steel screws placed in vertebrae near the lesion).[9,12] A comparison of the marker locations on pretreatment DRRs to their locations in intratreatment orthogonal radiographs allowed the calculation of the rigid-body six-dimensional (three translation and three rotation) offset between the target volume position during treatment planning and during treatment delivery. This offset was used to adjust the orientation of the robotic manipulator on which the LINAC is mounted to maintain the planned alignment of each beam to the target volume. This imaging-and-alignment process was repeated between beams to compensate for patient motion during treatment. The total clinical accuracy of this system for treatment of the spine, a measurement of the cumulative geometrical uncertainty associated with pretreatment imaging, treatment

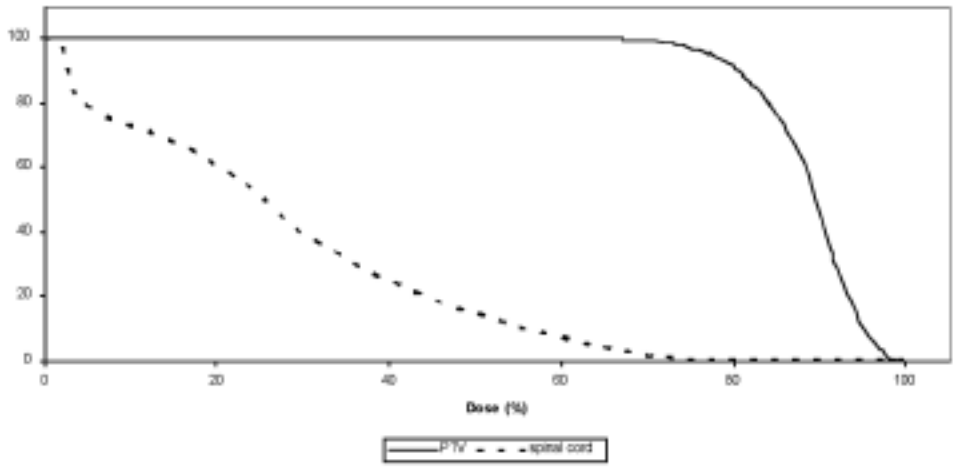

FIG. 7. Cumulative dose–volume histogram showing the planning target volume (PTV) and spinal cord coverage. The spinal cord was completely spared at the 80% dose prescription level.

planning, intratreatment imaging, and treatment delivery, has been assessed to be less than 1 mm.[14]

The main advantages of the new fiducial-free system are twofold. 1) Nonrigid deformation is accounted for, potentially improving the treatment accuracy in cases in which the patient's body poses have changed. 2) Fiducial marker insertion is not required, thereby eliminating the risks of complication and increasing convenience for both the patient and clinician. An additional advantage is that the possibility of fiducial marker migration is removed (although, with spinal screws the risk of this migration is low).

Phantom Tests

Our end-to-end tests using Xsight resulted in a mean total clinical accuracy (total targeting error) of 0.52 ± 0.22 mm. Achieving submillimetric accuracy in radiosurgical procedures necessitates quality assurance procedures that cover the entire "treatment chain," from imaging and treatment planning to dose delivery. The end-to-end test is designed to verify that the CT scanner and each of the components included in the CyberKnife system (robot, radiography, target location algorithms, and couch control system) yield the highest precision to meet the overall specified targeting accuracy of less than 1 mm. Phantom tests, however, can only measure the physical accuracy of the individual setup and do not take into account factors such as a patient's movement. This inherent problem is true for most of the published results of system accuracy tests.

The total accuracy of the CyberKnife system for spinal treatments has been reported in two studies, in both of which the investigators used implanted fiducial markers instead of osseous anatomy for beam targeting, and used a film-based phantom test method that was similar to ours. Ryu, et al.,[12] reported a total clinical accuracy of 1.0 to 1.2 mm. They used an earlier version of the robotic manipulator, whose positioning accuracy was poorer than the current system (± 0.5 mm compared with ± 0.2 mm). They also used an earlier version of the tracking software. Fiducial-based accuracy was measured with a more recent CyberKnife system by Yu, et al.[14] They performed 16 tests and reported a total clinical accuracy of 0.7 ± 0.3 mm. The similarity to the measures obtained in the present study demonstrates that anatomy-based targeting has comparable or even superior accuracy to that obtained using fiducial markers in rigid phantoms.

Clinical Feasibility

Radiosurgical procedures were well tolerated by our patients. Single-dose treatment was chosen because clinical and in vitro studies have overwhelmingly demonstrated its high efficacy and low morbidity rate for intracranial tumors. Similar to the approach of Gerszten, et al.,[5] we based our spinal treatment regimens on experience in intracranial radiosurgery. Although the follow-up period is too short to allow for conclusive clinical evaluations, the results of the present study showed that fiducial-free tracking spinal radiosurgery was feasible for cervical, thoracic, lumbar, and sacral regions of the spine. Treatments were performed without using an alpha cradle or other immobilization device, which is a significant advantage for patient comfort during treatment. Patients were placed in a supine position with a cushion under the legs for more comfort during CT scanning and treatment. A second significant finding is that spinal radiosurgery produced rapid pain reduction (within 7 days of treatment) in 14 of the 15 patients treated for pain. This finding agrees with that of Degen, et al.,[2] and Gerszten, et al.[8] Spinal radiosurgery may offer improved pain control by allowing larger radiobiological doses than standard fractionated radiotherapy, which is limited by the tolerance of adjacent tissues.

In two patients, spinal transpedicular screw fixation was performed before radiosurgery. The fiducial-free tracking algorithm was still able to find enough corresponding osseous points for image registration; however, we advocate placing the spinal instrumentation after radiosurgery whenever possible because steel artifacts may hamper the precise delineation of the lesion on CT and MR images.

We sought to achieve a steep dose gradient to the lesion

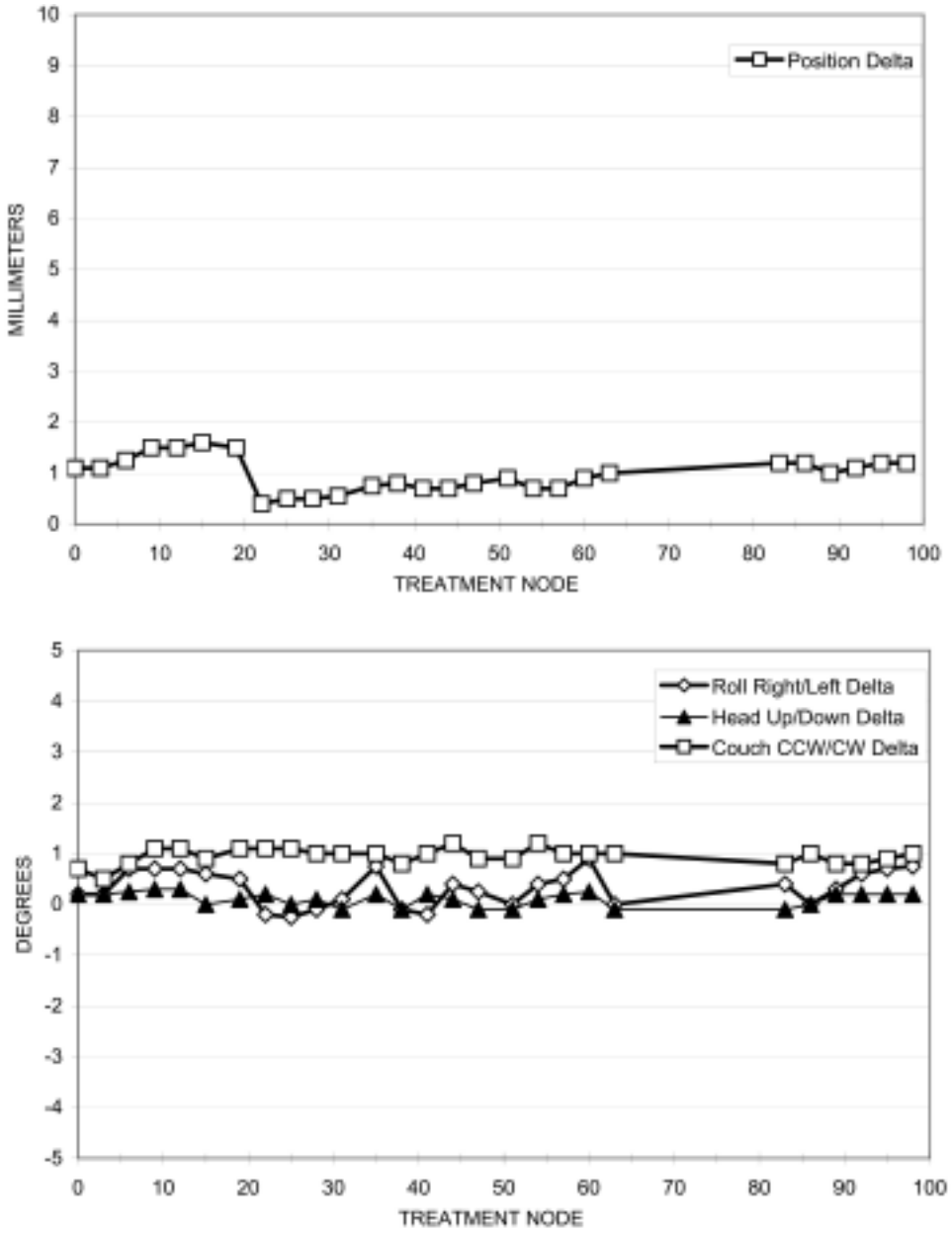

FIG. 8. Three-dimensional translational motion in millimeters *(upper)* and the individual components (rotation angles) of orientation in degrees *(lower)*, plotted as a function of treatment node during the first path of treatment. The patient's position and orientation are recorded every three nodes. At Node 22 (~ 17 minutes into the procedure), because the patient's movements caused a left–right roll error, an automatic couch correction was necessary. The smaller corrections (≤1.8 mm) until the end of the path were made automatically by the robot. CCW/CW = counterclockwise/clockwise.

in a single fraction, restricting the dose to the spinal cord to a maximum dose of 8 Gy. No short-term side effects were noted in association with this approach. This dose limit was exceeded in two of the six patients with a history of surgery. These two patients presented with significant spinal cord compression (Fig. 5), and repeated open surgical resection was thought to be unfeasible. The tumors in these patients received up to 14 Gy to a limited volume of the myelon. Fortunately, this did not result in early adverse events. Myelopathic symptoms improved in both patients. In addition, 11 patients underwent conventional radiation 12 to 40 weeks before radiosurgery. None of these patients suffered radiation-related toxicity after CyberKnife treatment. A more prolonged follow-up period is needed to analyze whether these doses lead to adverse radiation reactions. Tumor control rates could not be reported in the present study because of the short follow-up period. It was the aim of our paper to describe the fiducial-free tracking system and indicate its feasibility in the treatment of lesions all along the spine.

Conclusions

Fiducial-free spinal tracking is a feasible, accurate, and reliable tool for spinal radiosurgery of cervical, thoracic, lumbar, and sacral lesions. It eliminates the need for implantation of radiographic markers, or fiducials, in the delivery of radiosurgery treatments for spinal tumors. Fiducial-free spinal radiosurgery, therefore, has a significant advantage for outpatient spinal radiosurgery in terms of time, cost of treatment, and quality of life of the patient.

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References

1. Adler JR Jr, Chang SD, Murphy MJ, Doty J, Geis P, Hancock SL: The Cyberknife: a frameless robotic system for radiosurgery. **Stereotact Funct Neurosurg 69:**124–128, 1997
2. Degen JW, Gagnon GJ, Voyadzis JM, McRae DA, Lunsden M, Dieterich S, et al: CyberKnife stereotactic radiosurgical treatment of spinal tumors for pain control and quality of life. **J Neurosurg Spine 2:**540–549, 2005
3. Fu D, Kuduvalli G: Enhancing skeletal features in digitally reconstructed radiographs, in Reinhardt JM, Pluim JP (eds): **Medical Imaging 2006: Image Processing.** San Diego: The International Society for Optical Engineering, 2006, Vol 6144 (Abstract 61442M)
4. Fu D, Kuduvalli G, Maurer CR Jr, Allision JW, Adler JR Jr: 3D target localization using 2D local displacements of skeletal structures in orthogonal x-ray images for image-guided spinal radiosurgery. **Int J CARS 1 (Suppl 1):**198–200, 2006
5. Gerszten PC, Burton SA, Ozhasoglu C, Vogel WJ, Quinn AE: Cyberknife radiosurgery: single-fraction treatment for spinal tumors, in Mould RF (ed): **Robotic Radiosurgery.** Sunnyvale, CA: CyberKnife Society Press, 2005, Vol 1, pp 171–186
6. Gerszten PC, Germanwala A, Burton SA, Welch WC, Ozhasoglu C, Vogel WJ: Combination kyphoplasty and spinal radiosurgery: a new treatment paradigm for pathological fractures. **J Neurosurg Spine 3:**296–301, 2005
7. Gerszten PC, Ozhasoglu C, Burton SA, Vogel W, Atkins B, Kalnicki S, et al: Evaluation of CyberKnife frameless real-time image-guided stereotactic radiosurgery for spinal lesions. **Stereotact Funct Neurosurg 81:**84–89, 2003
8. Gerszten PC, Ozhasoglu C, Burton SA, Vogel WJ, Atkins BA, Kalnicki S, et al: CyberKnife frameless stereotactic radiosurgery for spinal lesions: clinical experience in 125 cases. **Neurosurgery 55:**89–99, 2004
9. Gerszten PC, Ozhasoglu C, Burton SA, Welch WC, Vogel WJ, Atkins BA, et al: CyberKnife frameless single-fraction stereotactic radiosurgery for tumors of the sacrum. **Neurosurg Focus 15 (2):**E7, 2003
10. Kuo JS, Yu C, Petrovich Z, Apuzzo ML: The CyberKnife stereotactic radiosurgery system: description, installation, and an initial evaluation of use and functionality. **Neurosurgery 53:**1235–1239, 2003
11. Murphy MJ, Chang SD, Gibbs IC, Le QT, Hai J, Kim D, et al: Patterns of patient movement during frameless image-guided radiosurgery. **Int J Radiat Oncol Biol Phys 55:**1400–1408, 2003
12. Ryu SI, Chang SD, Kim DH, Murphy MJ, Le QT, Martin DP, et al: Image-guided hypo-fractionated stereotactic radiosurgery to spinal lesions. **Neurosurgery 49:**838–846, 2001
13. Welch WC, Gerszten PC: Accuray CyberKnife image-guided radiosurgical system. **Expert Rev Med Devices 2:**141–147, 2005
14. Yu C, Main W, Taylor D, Kuduvalli G, Apuzzo ML, Adler JR Jr: An anthropomorphic phantom study of the accuracy of Cyberknife spinal radiosurgery. **Neurosurgery 55:**1138–1149, 2004

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