Prospective evaluation of a dedicated spine radiosurgery program using the Elekta Synergy S system

Clinical article

PETER C. GERSZTEN, M.D., M.P.H.,¹,² JOSEF NOVOTNY JR., PH.D.,²,³ MUBINA QUADER, PH.D.,²,³ VALERIE C. DEWALD, R.T.(T),²,³ AND JOHN C. FLICKINGER, M.D.¹,³

Departments of ¹Neurological Surgery and ²Radiation Oncology, University of Pittsburgh Medical Center, and ³University of Pittsburgh Cancer Institute, Pittsburgh, Pennsylvania

Object. Cone beam CT (CBCT) image guidance has recently been adopted for the delivery of spine radiosurgery. In 2007, the authors’ institution began a dedicated spine radiosurgery program using the Elekta Synergy S system, which incorporates CBCT technology. In this study, the authors prospectively evaluated the Synergy S platform as a dedicated spine radiosurgery delivery system, including an evaluation of the accuracy of patient positioning using this technology, as part of a quality assurance program.

Methods. One hundred sixty-six spine and paraspinal lesions were treated using the Elekta Synergy S 6-MV LINAC with a beam modulator and CBCT image guidance combined with a HexaPOD couch that allows correction of patient positioning in 3 translational and 3 rotational directions. Stratifying the lesion by location, there were 28 cervical, 69 thoracic, 48 lumbar, and 21 sacral lesions. The most common histological types for the metastatic lesions (136 cases total) were breast, lung, sarcomas, and renal cells. The most common benign tumors (30 cases total) included 10 schwannomas, 5 neurofibromas, and 5 meningiomas. Twenty-eight lesions (17%) were intradural. To measure intratreatment patient movement, 3 quality assurance CBCTs were performed and recorded at separate times: immediately before treatment started; at the first third of the procedure; and at the second third of the procedure. The positioning data and fused images of the planning CT and CBCT were analyzed to determine intrafraction patient movements. From each of 3 quality assurance CBCT images, 3 translational and 3 rotational coordinates were obtained.

Results. The prescribed dose to the gross tumor volume, delivered in a single fraction, ranged from 12 to 20 Gy (mean 16 Gy) in this cohort. This dose was delivered by between 7 and 14 coplanar intensity-modulated radiation therapy beams (mean 9 beams). The gross tumor volumes ranged from 1.2 to 491.7 cm³ (mean 39.2 cm³). Mean treatment time including setup was 64 minutes. At the first third of the treatment, the magnitude of the 3D translational vector (X, Y, Z) was 1.1 ± 0.7 mm. Similarly, the 3D translational vector at the second third of the treatment was 1.0 ± 0.6 mm. The means ± SDs of the rotational angles were 0.2° ± 0.4°, 0.4° ± 0.5°, and 0.3° ± 0.5° along yaw, roll, and pitch, respectively, at the first third of the treatment, and 0.2° ± 0.3°, 0.4° ± 0.5°, and 0.4° ± 0.5°, respectively, at the second third of the treatment.

Conclusions. Single-fraction spine radiosurgery performed using the Synergy S platform and incorporating CBCT image guidance was determined to be feasible, accurate, and safe. This technique provides an overall translational position accuracy of < 2.0 mm. (DOI: 10.3171/2010.8.GKS10949)

Key Words • spine radiosurgery • spine tumor • cone beam computed tomography

Since that time, a substantial body of literature has offered descriptions on the use of large-fraction conformal radiation delivery to spinal lesions using a variety of technologies. A recent systematic review of the literature found that spine radiosurgery is both safe and effective and provides a durable symptom response and local control for even radioresistant tissues, regardless of whether prior fractionated radiotherapy was performed. Such outcomes closely mirror the clinical success that has been achieved using intracranial radiosurgery.
Spine radiosurgery using the Synergy S system

Recent technological developments, including imaging technology for 3D localization and pretreatment planning, the advent of IMRT, and a higher degree of accuracy in achieving target dose conformation while sparing normal surrounding tissue, have made possible radiosurgical treatment of vertebral body lesions close to the spinal cord and cauda equina. Multiple studies have demonstrated the feasibility and clinical efficacy of spine radiosurgery for both primary and secondary malignancies. Others have demonstrated the effectiveness of protons for spinal and paraspinal tumors. To provide the accuracy of dose delivery necessary for extracranial radiosurgery, current radiosurgery techniques must use some form of image-guided robotic technology to alter the position and trajectory of the beam delivery system or micromultileaf collimated beams designed by inverse planning to generate IMRT. Regardless of which delivery system is used, in all cases, the treatment plan must tightly conform the prescribed radiation dose to the tumor target while featuring deep dose gradients at the edge of the target and immediate surrounding normal tissue.

Cone beam CT image–guidance technology has been adopted for radiosurgery setup and delivery by a variety of radiosurgery delivery systems. Following an extensive experience with spine radiosurgery using non-CBCT technologies, our facility began a dedicated spine radiosurgery program using the Elekta Synergy S system (Elekta AB). In this paper, we describe a prospective evaluation of our spine radiosurgery program using Synergy S to determine the feasibility of using this technology for spine radiosurgery applications.

Methods

Beginning in 2007, 166 spine and paraspinal lesions in 108 patients underwent radiosurgery treatment delivered using an Elekta Synergy S 6-MV LINAC (Elekta AB) with a beam modulator (Fig. 1). In a plane orthogonal to the LINAC, the CBCT image guidance system was mounted on the gantry. The accelerator was also equipped with a HexaPOD couch (Medical Intelligence) that allows the target to be visualized at the precise time of treatment while the patient is in position on the treatment couch. The cone beam imaging system is located in a position orthogonal to the LINAC beam. The robotic couch is adjusted in 3 translations and 3 rotations to ensure that the radiation is directed precisely to the target.

The positioning deviations for all patients during the radiosurgery treatments were prospectively quantitatively evaluated and recorded. An extravertebral extension of the tumor also was targeted when clinically indicated. The initial patient setup was performed based on the patient’s

### TABLE 1: Characteristics of 166 treated cases

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>No. of Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>previous external beam irradiation</td>
<td>103</td>
</tr>
<tr>
<td>primary indications for radiosurgery treatment</td>
<td>44</td>
</tr>
<tr>
<td>primary treatment modality</td>
<td></td>
</tr>
<tr>
<td>tumor progression after prior conventional radiotherapy</td>
<td>81</td>
</tr>
<tr>
<td>adjuvant postsurgical therapy</td>
<td>41</td>
</tr>
<tr>
<td>level treated</td>
<td></td>
</tr>
<tr>
<td>cervical</td>
<td>28</td>
</tr>
<tr>
<td>thoracic</td>
<td>69</td>
</tr>
<tr>
<td>lumbar</td>
<td>48</td>
</tr>
<tr>
<td>sacral</td>
<td>21</td>
</tr>
<tr>
<td>intradural</td>
<td>28</td>
</tr>
<tr>
<td>mean gross tumor vol in cm³ (range)</td>
<td>39.2 (1.2–491.7)</td>
</tr>
<tr>
<td>mean max tumor dose in Gy (range)</td>
<td>16 (12–20)</td>
</tr>
</tbody>
</table>
body marks followed by a CBCT image for target localization, and any subsequent position adjustment was based on CBCT and treatment planning CT image registration results. To verify the initial patient setup and ensure the accuracy of patient positioning during treatment, 3 quality assurance CBCT studies were performed during the procedure (Fig. 2). The first quality assurance study was conducted immediately before treatment started, the second at the first third of the procedure, and the last at the second third of the procedure. This strategy was used to monitor patient movement after the initial setup had taken place. The positioning data and fused images from the planning CT study and the CBCT studies during treatment were analyzed to determine intrafraction patient movements. From each of 3 quality assurance CBCT studies, 3 translational and 3 rotational coordinates were obtained. In all cases, even very small deviations in patient positioning observed after the initial CBCT study were always corrected.

Results

The radiosurgery procedure was successfully completed in all patients. The prescribed dose to the gross tumor volume for the cohort was 12–20 Gy (mean 16 Gy). Seven to 14 coplanar beams (mean 9 beams) using IMRT were used to deliver the total dose to the target volume. The gross tumor volume ranged from 1.2 to 491.7 cm³ (mean 39.2 cm³). The mean treatment time for the entire radiosurgery procedure, including the initial patient setup, was 64 minutes.

At the first third of the procedure, the mean translational variations ± SDs were 0.5 ± 0.5, 0.5 ± 0.5, and 0.5 ± 0.5 mm in the lateral (X), longitudinal (Y), and anteroposterior (Z) directions, respectively. The magnitude of the 3D vector (X, Y, Z) was 1.1 ± 0.7 mm. Similarly, variations at the second third of the procedure were 0.5 ± 0.5, 0.5 ± 0.5, and 0.5 ± 0.5 mm along the X, Y, and Z directions, respectively, and the 3D vector (X, Y, Z) was 1.0 ± 0.6 mm. The mean ± SD measurements for the rotational angles were 0.2° ± 0.4°, 0.4° ± 0.5°, and 0.3° ± 0.5°, respectively, along yaw, roll, and pitch at the first third of the treatment and 0.2° ± 0.3°, 0.4° ± 0.5°, and 0.4° ± 0.5°, respectively, at the second third of the treatment. The overall translational position accuracy was determined to be < 2.0 mm.

Positioning deviations were further compared as a function of treatment site, immobilization device used, and total treatment time. Positioning deviations did not differ when a comparison was made by treatment segment of the vertebral column (that is, cervical, thoracic, or lumbar). However, for patients with tumors located in the cervical spine, more difficulties with setup and patient positioning were observed, and the overall treatment time was also typically longer than for other patients. Positioning deviations were independent of the immobilization device used and the total treatment time. No evidence of acute or subacute radiation-induced spinal cord toxicity was observed in this series (median follow-up 15 months).

Illustrative Case

Figure 3 demonstrates a case example of a 35-year-old man who worked full time. He presented with right proximal leg pain. Magnetic resonance imaging and a subsequent CT-guided biopsy revealed an intradural hemangioblastoma at the L-1 level on the right side. The

<table>
<thead>
<tr>
<th>Tumor Type</th>
<th>No. of Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>breast</td>
<td>33</td>
</tr>
<tr>
<td>lung</td>
<td>20</td>
</tr>
<tr>
<td>sarcoma</td>
<td>16</td>
</tr>
<tr>
<td>renal cell</td>
<td>15</td>
</tr>
<tr>
<td>schwannoma</td>
<td>10</td>
</tr>
<tr>
<td>thyroid</td>
<td>7</td>
</tr>
<tr>
<td>melanoma</td>
<td>7</td>
</tr>
<tr>
<td>colon</td>
<td>7</td>
</tr>
<tr>
<td>meningioma</td>
<td>5</td>
</tr>
<tr>
<td>neurofibroma</td>
<td>5</td>
</tr>
<tr>
<td>chordoma</td>
<td>4</td>
</tr>
<tr>
<td>prostate</td>
<td>4</td>
</tr>
<tr>
<td>other</td>
<td>33</td>
</tr>
</tbody>
</table>

Fig. 2. Cone beam CT images obtained during patient setup and positioning for treatment, showing extremely high spatial resolution of both bone structures and soft tissue, making possible the setup of sites with submillimeter targeting errors. Sagittal (left) and axial (right) CBCT images displaying an overlay match of the planning CT and the CBCT, obtained with the patient on the treatment couch at the time of radiosurgery.
Spine radiosurgery using the Synergy S system

The patient was referred for radiosurgery to avoid the risks and the recuperation process associated with open resection. The gross tumor volume (17.2 cm$^3$) was treated with 15 Gy to the edge of the tumor, which was delivered in a single fraction. The patient reported complete resolution of pain within 1 month with no evidence of tumor progression at the 18-month follow-up imaging session. He did not miss a single day of work.

**Discussion**

Stereotactic body radiosurgery has emerged as a new treatment option in the multidisciplinary management of tumors located within or adjacent (paraspinal) to the vertebral bodies or spinal cord. Stereotactic radiosurgery provides an option to deliver high-dose radiation per fraction, and therefore, a high biological equivalent dose, in 1–5 fractions. The aims of stereotactic body radiosurgery for spinal tumors are to improve existing rates of clinical response and tumor control and to reduce the retreatment rate by increasing the biological equivalent dose. A systematic literature review concluded that a strong recommendation can be made, albeit based on low-quality evidence, that radiosurgery should be considered over conventional fractionated radiotherapy for the treatment of solid-tumor spine metastases in the setting of oligometastatic disease and/or a radioresistant histological type in which no relative contraindications exist. Spine radiosurgery has become an integral part of the multidisciplinary management of malignant and benign lesions of the spine at our institution.

The feasibility, safety, and clinical efficacy of a stereotactic intensity-modulated beam technique to treat spinal and paraspinal tumors using online treatment field imaging to ensure the precision of tumor targeting (image-guided IMRT) has been reported. Extracranial radiosurgery requires the delivery of precisely shaped radiation beams. In LINACs, electrons are accelerated to high energies and either exit as electrons or are aimed at a hard metal target designed to produce high-energy x-rays or photons. The latter are used in radiosurgery. In the Synergy S LINAC, a rotatable gantry allows 360° rotation of the source to allow for multiple beam directions. The total number of beams, the beam angles, or directions are selected to provide the best coverage of the target volume while sparing dose-limiting structures. For instance, a lower thoracic tumor will generally be treated with beams angled off the kidneys to avoid delivering a significant dose to this normal tissue structure. The beam is further modified by using collimators within the machine treatment head. These collimators attenuate the primary beam and therefore precisely define the treatment field size. The field size can be continuously adjusted by using multiple collimator leaves, which are continuously moving to shape the beam (multileaf collimator). In radiosurgery, these leaves are very small in size, allowing for the accurate delivery of radiation to extremely small field sizes (micromultileaf collimator). Each beam of radiation can be envisioned as being divided into many small beamlets, each of which can be modulated into varying intensities using multileaf collimators: this is referred to as IMRT.

**Fig. 3.** Representative case of a 35-year-old man with an intradural hemangioblastoma located at the L-1 level on the right side. Coronal (A) and axial (B) images of the treatment plan. C: Eleven coplanar beams were used. D: The dose–volume histogram of the radiosurgery plan. Details of this case are found in the Illustrative Case section.
Cone beam x-ray imaging is a relatively new volumetric imaging technique that uses a gantry-mounted kilovoltage source and detector. By making a full gantry rotation, the kilovolt system acquires several hundred projection images. Other systems use megavoltage cone beam imaging. These are converted into CT-like axial slices in a process similar to the reconstruction used by conventional CT scanners. The cone beam scans provide extremely high spatial resolution of both bone and soft-tissue structures, making possible the setup of sites with submillimeter targeting errors. The Elekta Synergy S was the first digitally controlled LINAC optimized for image-guided radiation therapy that enables the acquisition of a high-definition 3D volume image at the time of treatment with the patient in the treatment position. The machine combines a LINAC with a fully integrated onboard 3D volume imaging system that allows the target to be visualized while the patient is on the treatment couch at the precise time of treatment. The robotic couch makes any necessary adjustments in 3 translations and 3 rotations of the patient’s position to ensure that the radiation beam is directed precisely to the target. Our center previously reported an evaluation of the setup accuracy of spine radiosurgery using CBCT image guidance with the same Synergy S platform in a subset of patients with spinal implants.

Conclusions

Management of target localization has always been a central issue in the delivery of spine radiosurgery. Many stereotactic body radiosurgery systems today have adopted kilovoltage CBCT technology over megavoltage CBCT technology for radiosurgery image guidance. However, little work has been done to date to evaluate specifically kilovoltage CBCT in such a large cohort of patients. This prospective evaluation of a large cohort of patients undergoing spine radiosurgery using a dedicated Synergy S platform demonstrates that the use of CBCT image guidance for patient setup in single-fraction spine radiosurgery is feasible, safe, and highly accurate.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author contributions to the study and manuscript preparation include the following. Conception and design: Gerszten. Acquisition of data: all authors. Analysis and interpretation of data: Gerszten. Drafting the article: Gerszten. Critically revising the article: Gerszten, Novotny, Quader, Dewald. Reviewed final version of the manuscript and approved it for submission: all authors. Statistical analysis: Flickinger.

References

Spine radiosurgery using the Synergy S system


Accepted August 20, 2010.
Address correspondence to: Peter C. Gerszten, M.D., M.P.H., Department of Neurological Surgery, UPMC Presbyterian, Suite B-400, 200 Lothrop Street, Pittsburgh, Pennsylvania 15213. email: gersztenpc@upmc.edu.