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Robotics and Radiosurgery – The Cyberknife

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Cyberknife · Image-guided · Robotics · Stereotactic radiosurgery

Abstract
The Cyberknife is a dedicated image-guided robotic radiosurgical device. While clinical results with intracranial lesions are comparable to frame-based radiosurgical techniques, recent experience demonstrates the potential to broadly expand the scope of radiosurgery to many extracranial sites.

The Cyberknife

Although radiosurgery is an effective tool for ablating intracranial tumors and arteriovenous malformations, rigid cranial fixation is associated with patient discomfort, limited treatment degrees of freedom, and an inability to treat extracranial targets. The Cyberknife was developed by Accuray, Inc. (Sunnyvale, Calif., USA) to address these limitations.

The Cyberknife combines advanced technologies and robotics to deliver frameless conformal radiosurgery [1]. The first is a lightweight (130 kg) 6-MV LINAC, designed for radiosurgery and mounted to a highly maneuverable robotic manipulator capable of positioning and pointing the LINAC with a mean total radial error of <0.6 mm [2]. The second innovation is real-time image guidance, which eliminates the need to use skeletal fixation for either positioning or rigidly

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immobilizing the treated lesion. Two fixed amorphous silicon detectors, illuminated by x-ray sources and arranged orthogonally with respect to the patient, comprise the imaging hardware. They provide a stationary frame of reference for locating the patient's anatomy that in turn has a known relationship to the reference frame of the robot and LINAC. This imaging system acquires digital radiographs of skeletal features or previously implanted fiducials associated with the treatment site, and uses image registration techniques to determine the target's coordinates with respect to the LINAC/manipulator. The robot utilizes these coordinates to aim the LINAC beam. When a target moves, this process detects the change and corrects beam pointing in near real-time.

Frameless Targeting

The Cyberknife determines the location of the skull, spine, or other radiographic landmarks in the coordinate frame of the radiation delivery system by comparing digitally reconstructed radiographs (DRRs) derived from the treatment planning CT with projection x-rays acquired by the real-time imaging system. A computer algorithm measures both anatomic translation and rotation by iteratively changing the position of the anatomy in the DRR until an exact match of the radiographs and DRRs is achieved [3]. Once skeletal position is determined, the coordinates are relayed to the robotic manipulator, which adjusts the pointing of the LINAC, and radiation is delivered. Once the LINAC moves to a new position, the process is repeated. Despite this flexibility, total system error for the Cyberknife is <1.2 mm [1, 4].

Treatment Planning

Kinematics restrict conventional radiosurgical systems to isocentric-based treatments in which all beams converge on a common point in space. In contrast, the Cyberknife enables the delivery of more complex treatments whereby beams originate at arbitrary positions in the workspace, and target arbitrary points within the treated lesion. During the actual patient treatment, the LINAC stops at each of approximately 100 equally spaced nodes, at each of which, the beam can be aimed anywhere within a volume around the center (non-isocentric beams). Optimization techniques are used to determine a dose weighting of beams that satisfy dose constraints specified by the surgeon. Total treatment time depends on the complexity of the plan and delivery paths, but is generally comparable in length to standard radiosurgery with a few isocenters. Since skeletal fixation is not required, fractionation is possible with negligible patient discomfort.

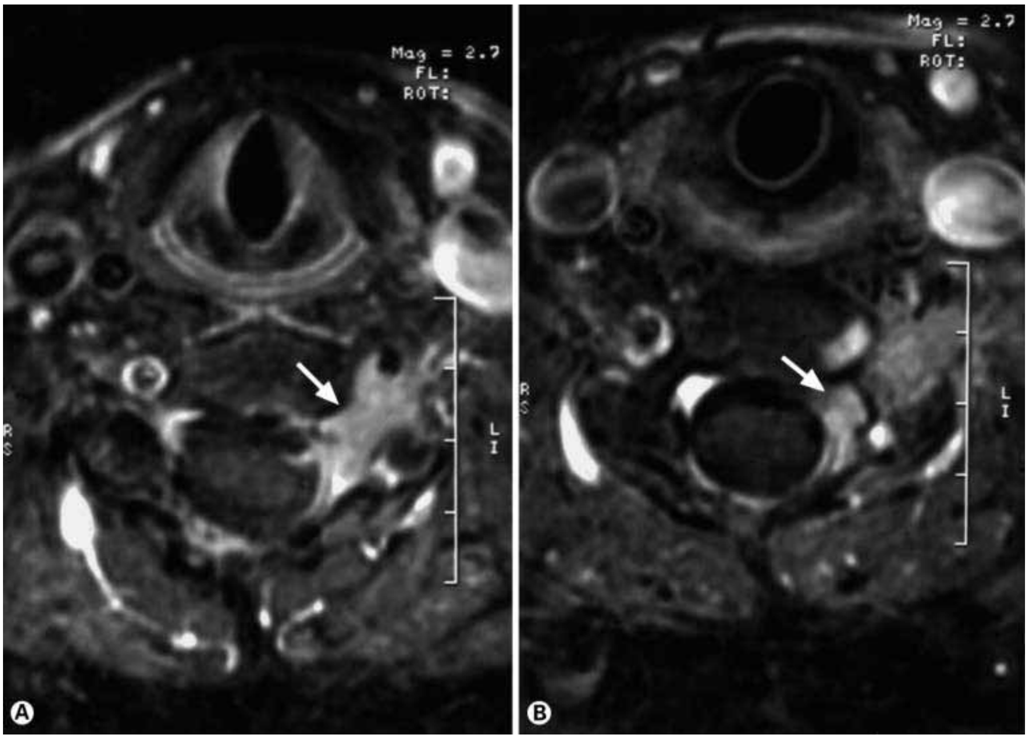
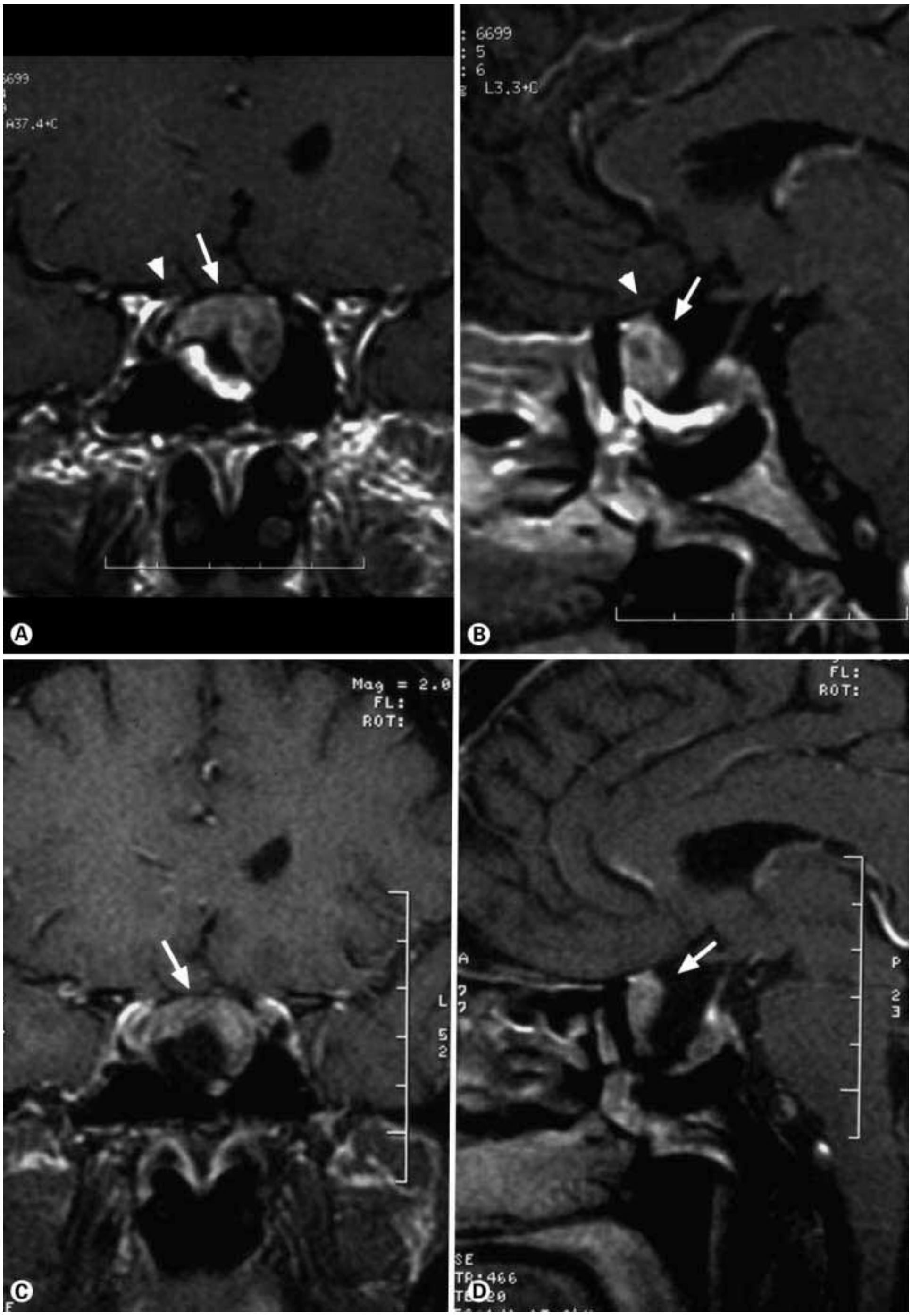
1 

Fig. 1. A 71-year-old female presented with neck pain and numbness in her left arm. One year after resection of a C6 spinal meningioma, a T1 contrast-enhanced sagittal MRI showed tumor recurrence (arrow) extending out the neural foramen (**A**). The patient was treated with Cyberknife radiosurgery using 20 Gy delivered in one fraction. At 6 months, the tumor (arrow) was smaller on MRI (**B**) and the patient remained clinically unchanged.
Fig. 2. A 63-year-old presented with bilateral temporal hemianopsia. A pituitary adenoma was discovered and the patient underwent transsphenoidal surgical resection. Four years later, MRI imaging showed a recurrent tumor (arrow) adjacent to the optic nerve (arrowhead), as shown on coronal (**A**), and sagittal (**B**) MR contrast-enhanced images. The patient was treated with the Cyberknife using 2 fractions for a total of 18 Gy. At one year follow-up the tumor (arrow) was smaller on both coronal (**C**) and sagittal (**D**) MRI contrast images, and the patient's vision remained normal.

Clinical Experience

As of July 1, 2001, over 350 intracranial tumors and AVMs and 31 spinal lesions have been treated at Stanford University (fig. 1, 2), with another 1,500 intracranial and 25 spinal lesions treated at other Cyberknife centers worldwide [1, 4]. The results with treatment of intracranial lesions closely parallel that



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described for other radiosurgical techniques [5]. Meanwhile, the 31 spinal lesions that have been treated at Stanford (hemangioblastomas, AVMs, spinal metastases, ependymomas, schwannomas, meningiomas, and chordomas) demonstrate the Cyberknife's unique ability to administer accurate radiosurgical treatment throughout the cranial-spinal axis. Such spinal treatments utilize percutaneously implanted fiducials to direct the radiosurgery beams. Treatment dose in these cases ranged from 11 to 25 Gy using one to five fractions. Although these initial doses were deliberately chosen to be conservative, no tumor demonstrated progression on follow-up MR imaging nor were any complications observed. More recently the Cyberknife has been used to treat over 35 tumors of the lung and pancreas, thereby demonstrating the feasibility of also treating extraneural targets. Ongoing larger studies will better quantify the benefits of such extracranial radiosurgery.

Conclusion

The Cyberknife provides state-of-the-art robotic radiosurgery with the potential to treat anywhere in the body. Homogenous irradiation of non-spherical targets tumors and the ease of fractionation are added benefits of this technology.

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