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The Cyberknife: A Frameless Robotic System for Radiosurgery

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Abstract
The Cyberknife is a unique instrument for performing frameless stereotactic radiosurgery. Rather than using rigid immobilization, the Cyberknife relies on an image-to-image correlation algorithm for target localization. Furthermore, the system utilizes a novel, light-weight, high-energy radiation source. The authors describe the technical specifications of the Cyberknife and summarize the initial clinical experience.

Radiosurgery is an ablative technique that combines principles of stereotactic localization with multiple cross-fired beams from a highly collimated high-energy radiation source. This noninvasive procedure is an effective alternative to conventional neurosurgery and cranial irradiation for selected intracranial tumors and arteriovenous malformations. Because all existing stereotactic methods rely on rigid target fixation, patient discomfort, limited treatment degrees of freedom, and an inability to treat extracranial lesions are major drawbacks. Additionally, the fixed isocenter designs of current systems result in significant inhomogeneity of dose when treating nonspherical tumors. To address these limitations, a novel technology that uses a lightweight high-energy radiation source, a robotic

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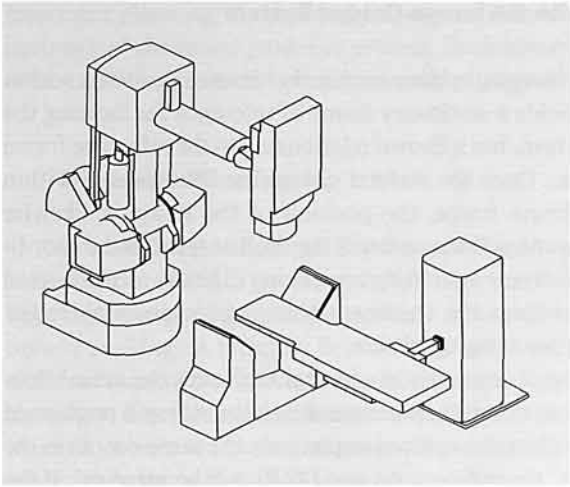

Fig. 1. Schematic of the Cyberknife presently installed at Stanford.

delivery system, and noninvasive image-guided localization, was developed by Accuray, Inc. (Sunnyvale, Calif., USA). This instrument, the Cyberknife™ (fig. 1), has been used to treat patients with intracranial and spinal tumors.

Technical Characteristics

The Cyberknife combines two advanced technologies to deliver conformal radiosurgery doses without a frame. The first is a lightweight (285 lb.) 6-MV linear accelerator (Linac), designed for radiosurgery and mounted to a highly maneuverable robotic manipulator. This manipulator can position and point the Linac with 6 degrees of freedom and 0.3 mm precision. The second innovation is real-time image guidance, which eliminates the need to use skeletal fixation for either positioning or rigidly immobilizing the target. This system acquires radiographs of skeletal features associated with the treatment site, uses image registration techniques to determine the treatment site's coordinates with respect to the Linac/manipulator, and transmits the target coordinates to the manipulator, which then directs the beam to the treatment site. When the target moves, the process detects the change and corrects beam pointing in near real time. Two diagnostic fluoroscopes, illuminated by x-ray sources 365 cm away and arranged orthogonally with respect to the patient, comprise the imaging hardware.

Target Localization with the Image-Guided System

The components of the imaging system are fixed at known positions within the treatment room, and provide a stationary frame of reference for locating the patient's anatomy, which, in turn, has a known relationship to the reference frame of the manipulator and Linac. Once the skeletal system has been located within the imaging system's coordinate frame, the position of the lesion is likewise known. The Cyberknife determines the location of the skull or spine in the coordinate frame of the radiation delivery system by comparing digitally reconstructed radiographs (DRRs) derived from the treatment-planning images with radiographs acquired by the real-time imaging system.

DDRs are produced using a computer model that replicates the actual fluoroscope geometry and optics, so that if the patient's skeletal anatomy is positioned in the coordinate frame of the treatment room in precisely the same way as in the treatment-planning CT study, the radiographs and DRRs will be identical. If the positioning is not the same, the system calculates differences using either of two different computational algorithms. One algorithm uses a large database of precomputed DRRs to simulate the full range of possible positions during treatment. The acquired radiographs are correlated with each of the precomputed DRRs to obtain a measure of similarity. The degree of correlation is used to interpolate to the most probable actual position of the cranium or spine in the imaging reference frame. DRRs are computed prior to the beginning of treatment; an array processor computes the correlation in near-real time during treatment. This algorithm makes accurate measurements of the translational position but cannot determine all rotational effects. Consequently, a non-invasive head restraint maintains the patient's head orientation when using this algorithm.

An alternative algorithm [1] currently in development 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. This algorithm does not require the database of precomputed DRRs or the array processor, and eliminates the need to fix the patients' orientation.

Once skeletal position is determined, the coordinates are relayed to the manipulator, which adjusts the pointing of the Linac, and radiation is delivered. The speed of the imaging process allows the system to detect and adjust to changes in target position in near real time (less than a second). The Linac is then moved to a new position, where the process is repeated.

The Cyberknife's dose placement accuracy has been measured in a series of tests that simulate both intracranial and spinal treatment scenarios [2]. The mean total radial error observed was 1.6 mm, with a mean positioning error along each coordinate axis of ± 0.9 mm. This accuracy incorporates all sources of error in the treatment process, including uncertainties in target localization during

treatment planning, the pointing precision of the robotic arm, and the positioning accuracy of the image guidance process. Such precision compares favorably with what can be achieved by using stereotactic frames [3].

Treatment Planning

Conventional radiosurgical systems are limiting in that their restrictive kinematics allow only for isocentric based treatments. Since the resulting region of high dose is spherical [4–6] treatment of nonspherical lesions is problematic. Sphere packing, as typically done with standard radiosurgical devices, results in some measure of both overtreatment in normal tissue and undertreatment within the target. The Cyberknife, however, enables the delivery of more complex treatments in which beams originate at arbitrary points in the workspace, and target arbitrary points within the lesion.

Treatment planning with this system occurs in steps. First, regions of interest are delineated on CT or MR images, and the amount of radiation that each can tolerate is specified. Next, the system uses the contour data to create a three-dimensional representation of the tumor geometry, and based on this, defines an initial set of beam configurations such that the beams aim from random orientations at points that are evenly spaced over the surface of the tumor. Approximately 300 equally spaced points (nodes) are defined on the surface of this sphere. Finally, optimization techniques are used to determine dose weighting of the beams to satisfy the specified dose constraints. If the constraints cannot be satisfied in the context of initial beam selection, information gained during optimization is used to select a new set of beam configurations more likely to satisfy the constraints. This iterative process of beam selection and optimization continues until the system finds a feasible set of beams and weights, or until it reaches a maximum number of iterations. The Cyberknife then calculates the dose distribution and presents the plan for review. If satisfactory, treatment is delivered. Otherwise, additional constraints are specified and integrated into a solution.

During the actual patient treatment, the Linac stops at each node. The target is taken to be near the center of a sphere of 80-cm radius, which is fixed with respect to the patient's anatomy. The beam is not constrained to point at the center of the sphere, but can be aimed anywhere within a volume around the center. This allows delivery of nonisocentric beams which are aimed at points within the target that are not at the center of the sphere. Treatment planning consists of selecting from among the fixed nodes and developing a dose distribution involving beams from each of the selected nodes. Total treatment time depends on the complexity of the plan and delivery paths, but is comparable to

standard Linac treatments. Since skeletal fixation is not required, fractionation is possible with minimal patient discomfort.

Clinical Experience

As of May 1997, 30 patients with malignant intracranial tumors have been treated (all single-fraction doses between 12 and 18 Gy). Outcome in terms of radiographic and clinical response closely parallels that achieved with standard radiosurgery, although follow-up is limited. Treatment of spinal tumors has been limited to 2 hemangioblastomas. A 3-fraction, 21 Gy treatment dose was administered to both tumor edges with a 33% and 70% reduction in size respectively (1 year follow-up).

Conclusion

The Cyberknife provides state-of-the-art radiosurgery. Early results with intracranial metastatic tumors and unresectable spinal hemangioblastomas are promising in themselves, but also demonstrate the technical feasibility and practicality of image-guided stereotactic radiosurgery. Homogeneous irradiation of tumors with complex shapes and the delivery of fractionated therapy are added benefits of this system. Despite the flexibility, overall accuracy parallels invasive stereotactic frames. While currently limited by protocol to treatment of malignant intracranial lesions and benign spinal tumors, this technology is being adapted to treat nonneural extracranial tumors as well.

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