Cyberknife Radiosurgery – A New Treatment Method for Image-guided, Robotic, High-precision Radiosurgery

a report by
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Cyberknife Radiosurgery – Overview

Cyberknife technology is based on radiosurgical principles that have been in clinical practice for 30 years. Radiosurgery is the precise application of a high (tumour-destructing) dose of radiation in a precisely defined target volume, while protecting the surrounding healthy tissue. During radiosurgery, many radiation beams from different directions intersect in the tumour region, where they accumulate. The surrounding healthy tissue receives only a small amount of the total dose. Until recently, the Gamma Knife system was the standard instrument for neurosurgical applications, and some centres use linear accelerators (linacs) for clinical radiosurgical procedures. These systems, which are used mostly in conventional radiation oncology, have to be readjusted for every radiosurgical treatment. They must also undergo physical testing, because radiosurgical applications demand significantly higher quality and precision requirements than conventional radio-oncological applications. However, Gamma Knife and conventional linacs share the same necessity of applying an invasive stereotactic ring on the patient's head in order to achieve the desired accuracy of ±1mm. The revolutionary development of the Cyberknife technology, combining integrated image-guided and robotic technology, has led to a paradigm shift in radiosurgery.[1,2]

Advantages of Cyberknife Radiosurgery

With Cyberknife technology, an invasive stereotactic head frame is no longer required in order to obtain the highest possible accuracy for brain treatments. Non-invasive and pain-free radiosurgical treatment is now available to patients. In addition, if feasible, the treatment can be divided into several stages,[2] which makes it even safer to treat larger lesions or those in highly sensitive areas. Apart from standard neurosurgical indications (i.e. acoustic neurinomas, meningeomas, brain metastases), radiosurgical applications are currently evolving to include extracranial indications. It is now possible to treat tumours of the spine, pancreas, lung and liver safely and effectively with radiosurgical techniques in cases where the tumours are well delineated from the surrounding healthy tissue. In selected cases, this could replace a surgical procedure. Because of the physiological breath-dependent organ movement, until now it has not been possible to apply high-radiation doses to body lesions. The newest development in Cyberknife radiosurgery is a breath-triggered realtime movement-correction system, which makes it possible to apply radiosurgical doses to these lesions. The Cyberknife moves according to the tumour's movement. Infrared cameras follow the breath excursions and send information online to a robot, which steers the linac into position.[6] Anaesthesia or dedicated body stereotactic frames, as used with conventional radiation devices to suppress respiration, are no longer necessary. Cyberknife treatment is designed for outpatient treatment, which significantly enhances the quality of life of cancer patients. A hospital stay or rehabilitation is not needed in most cases. Treatment time is dependent on tumour location and size and the organs at risk. A full course of radiosurgery lasts between 60 and 90 minutes.

Technology

The Cyberknife technology is a composition of two main parts: the radiation source, which is a lightweight and compact photon device (6 MeV linac, dose rate 4 Gy/minute) coupled with a robotic arm capable of moving in six degrees of freedom (Kuka GmbH, Augsburg, Germany). The robot can achieve 1,200 positions during treatment. It is linked to a computerised localisation system consisting of two X-ray generators that are fixed on the ceiling to enable orthogonal images of the target region. Images are recorded on silicon detectors that generate high-resolution digital images. Depending on the location of the target region, exact patient positioning is enabled by a five-axis patient couch. During treatment, the system automatically corrects patient movements in a range of 10 millimetres. A dedicated algorithm compensates for the system's inherent latency. For cerebral and spine indications, co-registration of the acquired X-ray images of the bone structures with the digitally reconstructed images from the planning computed tomography (CT) – digitally reconstructed radiographs (DRRs) – is performed. DRRs are matched with the X-ray images during treatment (see *Figure 1*).

Dynamic Patient Correction

Moving target volumes can be monitored, and irradiation dynamically adapts to the movement accordingly. After fiducial markers are applied percutaneously, internal organ movement is defined by the X-ray image-guided system. Simultaneously, external light-emitting diodes, which are fixed on the breast of the patient, measure the breath excursions. The software calculates the organ movement, taking into account the internal and external target volume. Systemically performed X-ray image updates are the basis for iterative corrections of the correlation model.[5,6]

Frameless Stereotaxy – Accuracy

Academic studies at the European Cyberknife Center Munich, Germany, and Stanford University, US, have shown that frameless Cyberknife technology is as precise as the conventional frame-based systems. Phantom studies achieved total accuracy results (including imaging, planning and treatment) of 0.42±0.4mm.[3,4]

Treatment Schedule

An individual head mask is used for brain treatments. This helps to stabilise the patient's head during treatment. For lesions in moving organs such as the lung, liver and pancreas, small (5mm) metal markers are implanted percutaneously in the vicinity of the lesion. They are used as landmarks for image registration and are detected automatically by the X-ray camera system. Image registration for brain treatments is performed without external fiducials and uses bony scull structures. All treatments are performed on the basis of CT and magnetic resonance imaging. The frameless technology allows the planning of images days before radiation application. Dose planning is performed using an inverse dose planning algorithm whereby the

Figure 1: The Cyberknife System with Major Components Such as the Treatment Couch, X-ray Detectors (Silicon Detectors), X-ray Cameras at the Ceiling, Robot and Compact Linear Accelerators

dose prescription to the target volume is defined by the tolerance dose to the organs at risk. During treatment, the patient is awake and is monitored by a video camera system. During treatment, the robot moves to 100 defined virtual points that are distributed homogeneously above the target. From each of these points, the robot can be directed to each point inside the treatment area (non-isocentric radiation). Complex optimisation techniques weight the individual beam in such a way that a high dose of radiation is directed to the tumour, taking into account the specific limitations of the organs at risk. The stereotactic X-ray system records images during treatment and compares them with the generated DRRs of the planning CT, providing the highest possible precision during treatment.

Medical Indications

The European Cyberknife Center Munich is a co-operative institution with the University Hospital of the University of Munich. Principally, well-circumscribed tumours with a clear border to the surrounding healthy tissue are suitable for Cyberknife radiosurgery. Currently, main indications are tumours of the brain and spine (see *Figure 2*). The efficacy of Cyberknife radiosurgery for body lesions is presently being evaluated. More than 150 spine tumours have already been treated in the Munich centre using the new fiducial-free, image-guided tracking system. Single-session spinal radiosurgery is effective for local control and tumour-associated pain syndromes.[3]

Future Perspectives

New research activities are focusing on the full potential of robotic techniques for radiosurgical applications. One of the primary goals is the introduction of realtime image guidance of tumours in soft tissue without the implantation of fiducials.[7] This would require a fast, fully automated analysis of X-ray imaging during treatment. The technology is currently undergoing phantom tests. In addition, research activities are being carried out in order to optimise the inverse planning algorithm and to take into account the relative organ movement during respiration. ■

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Figure 2: Metastasis from Renal Cancer in the Lateral Aspects of the Lumbar Vertebra L2

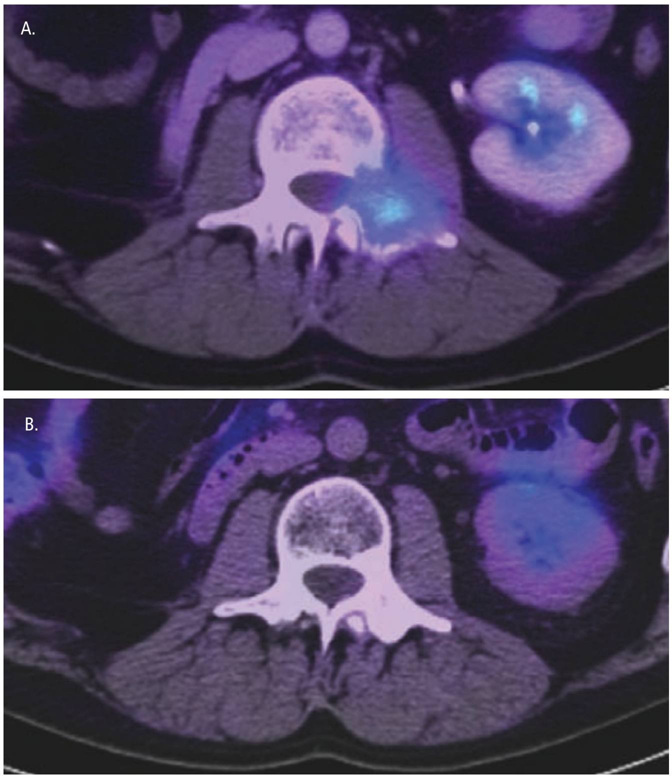

Image A shows the lesion on axial positron emission tomography and computerised tomography taken before spinal radiosurgery. Image B was taken six months later. Complete remission of the metastasis and re-calcification of the pedicle tissue is obvious.