Cyberknife technology is based on radiosurgical principles which are in clinical practice since 30 years. Radiosurgery is the precise application of a high (tumor destructing) dose of radiation in a precisely defined target volume protecting the surrounding healthy tissue. During radiosurgery many radiation beams from different directions intersect in the tumor region where they accumulate to a total dose. Surrounding healthy tissue only receives a small fragment of the total dose. Until recently the Gamma Knife system was the standard instrument for neurosurgical applications. Some centers use linear accelerators (LINAC) for clinical radiosurgical procedures. These mostly in conventional radiation oncology used systems have to be readjusted for every radiosurgical treatment and must undergo physical testing because radiosurgical applications demand significantly higher quality and precision requirements as for conventional radiooncological indications. However, Gamma Knife and conventional LINACs share the same necessity to apply an invasive stereotactic ring on the patient’s head to achieve the desired accuracy of +/- 1 mm. The revolutionary development of the Cyberknife technology combining integrated image guided and robotic technology lead to a paradigm shift in radiosurgery (1).

Advantages of Cyberknife radiosurgery

With Cyberknife technology an invasive stereotactic head frame is no longer required to obtain highest possible accuracy for brain treatments. This offers to the patient for the first time a real non-invasive and pain free radiosurgical treatment. Moreover, if feasible, the treatment can be divided in several stages (2 – 5) which makes it even safer to treat lesions in highly sensitive areas or larger lesions (2,3,4,5). Apart from standard neurosurgical indications (i.e. acoustic neurinomas, meningiomas, brain metastases) radiosurgical applications are currently evolving to extracranial indications (Fig. 1). It is nowadays possible to treat tumors of the spine, the pancreas, the lung and the liver safe and effectively with radiosurgical techniques in case they are well delineated from the surrounding healthy tissue. In selected cases this could replace a surgical procedure. Because of the physiologic breath dependent...
organ movement it was up to now not possible to apply high radiation doses to body lesions. The newest development in Cyberknife radiosurgery is a breath triggered real time movement correction which makes it possible to apply radiosurgical doses to body lesions (6,7). The Cyberknife is moving according to the tumor movement: infrared cameras follow the breath excursions and send this information online to the robot which steers the LINAC in the correct position. Anaesthesia or dedicated body stereotactic frames as used with conventional radiation devices to suppress respiration are no longer affordable. Cyberknife treatment is designed for outpatient treatment which significantly enhances the quality of life for cancer patients. A hospital stay or rehabilitation is not needed in most cases. Treatment time is dependent on tumor location, tumor size and 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 light weight and compact photon device (6 MeV LINAC, dose rate 4 Gy/minute) coupled to a robotic arm capable of moving in 6 degrees of freedom (Kuka GmbH, Augsburg, Germany) (Fig. 2). The robot can approach 1200 positions during treatment. The robot is linked to a computerized localization system consisting of two x-ray generators which are fixed on the ceiling to enable orthogonal images of the target region. Images are recorded on silicon detectors which generate high resolution digital images. According to the location of the target region exact patient positioning is automatically done by a 5 axis patient couch. During treatment the system automatically corrects eventual patient movements in a range of 10 millimetres. A dedicated algorithm is compensating for the inherent system latency. For cerebral and spine indications a co-registration of the acquired x-ray images of the bony structures with the digital reconstructed images of the planning CT (DRRs = digital reconstructed radiographs) is performed. DRRs are continuously matched with the x-ray images during treatment.

**Dynamic patient correction**

Moving target volumes can be monitored and irradiation dynamically adapts to the movement, accordingly (6,10). After percutaneous applied fiducial makers the internal organ movement is defined by the x-ray image guided system. Parallel to that external light emitting diodes (LEDs) which are fixed on the breast of the patient measure the breath excursions (Fig. 3). The software is calculating 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.

**Frameless stereotaxy — accuracy**

Academic studies at the University Stanford and Los Angeles, USA and San Bertolo hospital in Vicenza, Italy showed that frameless Cyberknife technology is as precise as the conventional frame based systems (8). Phantom studies achieved all over accuracies (including imaging, planning, treatment) of 0.42 ± 0.4 mm (Fig. 4).

**Treatment schedule**

For brain treatments an individual head mask is done. This helps to stabilize the head of the patient during treatment. For lesions in moving organs like lung, liver or pancreas small (5 mm) metal markers are percutaneously implanted in the vicinity of the lesion (Fig. 5). They are used as landmarks for image registration and are automatically detected by the x-ray camera system. Image registration for brain treatments is performed without external fidicials; image registration is performed using bony skull structures (Fig. 6). All treatments are performed on the basis of CT and MRI imaging. The frameless technology allows...
to perform planning images days before radiation application. Dose planning is performed using an inverse dose planning algorithm where the dose prescription to the target volume is defined by the tolerance dose to the organs at risk (9). During treatment the patient is awake and monitored by a video camera system. During treatment the robot is moving to 100 defined virtual points in space which are distributed homogeneously above the target. From each of these points the robot can be directed to each direction inside the treatment volume (non-isocentric radiation). Complex optimization techniques weight the individual beam in such a way that a high dose of radiation is directed to the tumor taking into account the specific limitations of the organs at risk. The stereo X-ray system is constantly recording images during treatment and compares these with the generated DRRs of the planning CT providing the highest possible precision during treatment.

**Medical indications**
The European Cyberknife Center Munich is a cooperative institution with the University Hospital of the University Munich. Principally, well circumscribed tumors with a clear border to the surrounding healthy tissue are suitable for Cyberknife radiosurgery. Currently, main indications are tumors of the brain and spine. The efficacy of Cyberknife radiosurgery for body lesions is presently being evaluated.

**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 real time image guidance of tumors in soft tissue without the implantation of fiducials. This would require a fast fully automated analysis of X-ray imaging during treatment. This technology is currently undergoing phantom tests (10,11). Furthermore, research activities are done to optimize the inverse planning algorithm and to take into account the relative organ movement during respiration.

**Literatur**
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