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CyberKnife System [Target Tracking/Motion Management]: Pre-Treatment Imaging, Image Fusion and Treatment Planning Technique

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Abstract: In order to control motion, the CyberKnife uses continuous X-ray and optic image guiding to send out a plethora of precisely targeted, non-coplanar radiation beams. The delivery of stereotactic body radiation therapy has been greatly improved by this method, which allows for the focused delivery of tumour dose while sparing surrounding normal tissue. Covering topics such as pretreatment patient setup, treatment planning, and treatment delivery, this chapter gives an overview of the CyberKnife system from the perspective of a particular institution. It also covers capabilities like as target monitoring and motion management. The original idea of the CyberKnife was to create a more advanced focused stereotactic radiosurgery technology. Many technical advancements have been made to the CyberKnife since its developer, Dr. John Adler, treated the first patient with it in 1994 at Stanford University Medical Centre. Technical advancements have made it possible to treat tumours in different places, including tumours that migrate, expanding the original treatment window from brain tumours to other types of tumours.

Keywords: CyberKnife System, Motion Management, Treatment Imaging, Image Fusion.

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Introduction

The present CyberKnife system is composed of an image guiding system and a robotic manipulator provided with a linear accelerator. The Cyberknife is built to offer real-time and inevitable X-ray or optical image direction to provide hundreds of separately targeted nonparallel radiation beams coming from diverse solid angles. This makes it possible to deliver very dense or concentrated target dose on the tumour while at the same time sparing the dose to the neighbouring healthy tissues. During the process of administering treatment the motion of the target is monitored by the robotic arm with the help of an image guidance system and changes the position if necessary [1-3]. For the stereotactic body radiation treatment (SBRT), this new form of robots with the image guiding system represents a revolution in the clinical practice. Following establishing the emphatic outcome of CyberKnife in frameless intracranial SRS by single or many fractions; it acted rapidly for anything more than intracranial SBRT treatment. For instance, the locally published data show excellent 2-year OS rates ranging from 62-97% in patients with medically inoperable peripheral NSCLC and from 97-100% in operable patients. It has also been revealed that cases with low toxicity have been witnessed, and improved quality of life due to cyber knife sbrt treatment. After the later publication of 5-year outcome results of the first 5-year outcomes of placebo showing biochemical progression-free survival rate of 93% in low-risk patients, there has been increased use and exploration of Prostate SBRT with CyberKnife. Overall, the clinical outcome of CyberKnife SBRT has been established in primary and metastasized liver tumours particularly in patients with low- and intermediate-risk prostate cancer and these are consistent with previous report with low toxicity, negligible effect on quality of life, excellent preservation of erectile function as well as biochemical control. Further positive outcomes of CyberKnife SBRT in the pancreatic cancer management are that 78% of the patients displayed local tumor control within 24 months, and their median life expectancy improved to 20 months. After the installation of CyberKnife in June 2006 at our institution more than 1500 patients have been managed in the subsequent 5 years. Here, based on this background, the CyberKnife system is described in its entirety including target tracking and motion management. We then proceed to discuss CyberKnife-delivered SBRT in more details as a result of patient preparation, treatment planning, and administration.

Blade System CyberKnife

Currently, the linear accelerator is capable of delivering radiation at the rate of 1000 MU min, being a magnetron driven 6 MV X band accelerator. The small structure of the robotic arm as observed means that it can set itself in that location which is desirable. Thus, attain the collimation, the twelve circular collimators of diameters ranging between 0.5 and 6 cm are used. It has a submillimeter accuracy in end-to-end phantom tests, where phantom is an imitation or model, usually of the human body. The robot can change the relation between the beam and targets in place compared to the repositioning of the patient where it can be less accurate and time-consuming. This allows for a relatively low level of restriction of normal breathing and of the general bodily movement. A motion tracking optic and a stereotactic X-ray imaging system enables the cyber knife to give real time picture guiding. CyberKnife has a capability of real-time intrafractional image guidance in contrast to many presently available systems that use image guidance at the time of patient initialization only [5-7]. To faster decide about the position of the patient and the localization of the target in the irradiation field tracking software systems obtain orthogonal X-ray images during the treatment, and compare them with digitally reconstructed radiographs that has been generated and stored beforehand [8, 9]. For the treatment's purposes, the patient's chest area may be spot with some optical markers. Optical guiding is used for the position of tumours that move with respiration, and the system has three CCD cameras for this purpose; their position is monitored during therapy.

Figure 1. CyberKnife setup parts. A six-jointed robotic arm carries a small linear accelerator and may freely move around the patient. Nearly "real-time" target imaging is achieved by positioning two kilovoltage x-ray sources orthogonally. Using light-emitting diodes attached to the patient's chest, the infrared Synchrony camera can track the patient's chest wall's movement.

Target Monitoring and Control

In contrast to conventional linear accelerators in which the patient expects to be positioned on the treatment table, the robotic arm translates most positioning changes, which applies to all CyberKnife target tracking. Most of the CyberKnife treatment couches are not movable and are configured at the start of the treatment regimen. Throughout the delivery of the treatment, the robotic arm will alter the configuration of the linac head if any motion is detected including the patient or the tumour [10, 11]. Classification of target tracking systems in the CyberKnife system is done based on the anatomic regions, tumours, and tumour motions. Some of the current special modes of tracking and targeting currently in use are Synchrony respiratory motion tracking, Xsight Lung tracking, six-dimensional (6D) skull tracking, InTempo for prostate motion, Lung Optimised Treatment (LOT), and fiducial marker tracking for special therapeutic uses.

Tracking the Spine

For targets that pertain to the spine or are near it, fixed in the relation to the spinal skeleton, the Xsight Spine tracking system is used. This is done in accordance to the bone features of the spine which create a positional alignment. An image registration is a non-rigid one and types of image processing and alignment correspond to features of the skeletal structures. Besides the femurhead[12,13], sacrum, iliac crest, and shoulder, Xsight Spine can track tumours that are adjacent to other bones. During extracranial lesion treatment, Xsight Spine can also be incorporated into the patient’s setup. Phantom and clinical studies have demonstrated submillimeter accuracy with the help of Xsight Spine tracking.

Using Fiducial Markers

Targets in soft tissue and the lungs can be identified and we can apply automatic correction for targeting issues that arise due to displacement and motion whereby the position of the fiducial markers is tracked. When the targets do not move because of breathing, then fiducial tracking alone is sufficient. Targets that move with respiratory motion are managed using fiducial tracking and an additional respiratory tracking technique called Synchrony, which is described later. I close with the observation that, in both cases, the treatment target and alignment geometry are portrayed by fiducial markers. Additional information about this alignment method of LDS 90 is explained elsewhere [15, 16].

Fiducial tracking which is described below is a procedure in which radiopaque fiducial markers are put in or adjacent to the lesion being treated.

Monitoring the Aerobic System

In the case of tumours that are presented as mimicking the respiratory movement, there is the use of Synchrony as the tracking method. For instance, in Synchrony, the action of the target is followed by radiation beams in real-time. In patients receiving a Synchrony treatment, the fiducial or tumor position is checked using radiographic imaging simultaneously with respiratory motion captured by an optical tracking system. In the process of developing a model for predicting motion, the synchronised position of the tumor with the data on respiratory motion is used. It reviews, in real-time, data related to respiratory motion; the position of the tumor during the administration of radiation beams is expected in the course of treatment and with aid of robotics treatment moves in tandem with the mobility of the tumor. The adaptability of the system enables the motion predictive model to be updated throughout the treatment session based on the change in the patient's breathing pattern. This technique helps in ensuring that the patients 'air passages' are not blocked throughout the procedure [16]. Synchrony's precision has been backed by multiple papers such as the end-to-end phantom testing which documented the model to have a submillimeter precision and clinical analysis to the model's goodness of fit.

Enhanced Care for the Lungs

The goal of the LOT lung therapy alternatives is to reduce or do away with the requirement for implanted fiducials. For XLT to work, both X-rays must clearly show the tumour. When the tumour isn't always apparent in both pictures, LOT expands XLT's capabilities to those circumstances. This typically happens when the tumour is situated on top of other structures that attenuate X-rays, including the spine or the heart. The LOT tracking system is based on the idea of defining an internal target volume (ITV) for the untrackable component of motion. The stereoscopic X-ray imaging system allows for direct tracking of the inferior/superior component of tumour motion with a single imager. This is typically the primary component of motion for lung tumours, since the two imagers share the same axis. When a tumour is only visible on a single image, tracking the predominant component of motion allows for a relatively minimal amount of partial ITV to compensate for the remaining component of motion [17, 18]. Treatment is based on spine tracking if the tumour is not apparent on both images; otherwise, a full intraoperative video (ITV) is necessary. One of the features of LOT is a simulation software that lets you put a patient on the couch during the planning phase and run through a series of treatment simulations to find out which tracking method will be most effective. If the tumour can be seen on both photos, XLT is the way to go. Based on the patient's unique clinical circumstances, the doctor can decide whether to implant fiducials or use the LOT option if the tumour is evident on just one or no images at all.

Assessment and Preparation for Treatment

Establishing and Maintaining Fiducial Bonds

Radiopaque fiducial markers are implanted in or near the intended volume as a first step in the treatment management process for treatments that need fiducial tracking. There are several options for fiducials and implantation techniques. For percutaneous implantation under imaging guidance, the most frequent fiducials are cylindrical gold markers with dimensions of 0.8-1.2 mm in diameter and 3-6 mm in length. These markers can be preloaded into 17- or 18-gauge needles. Bronchoscopic implantation provides precise insertion of fiducials in the lung while reducing the risk of pneumothorax. The Visicoil (Core Oncology, Santa Barbara, CA) and the gold anchor fiducial are two examples of newer alternatives to traditional fiducials that have just entered clinical usage. There is less risk of fiducial migration and pneumothorax with these preloaded 22-gauge needles that contain gold anchor fiducials. Despite this, there is still no consensus on the ideal amount of fiducials required for tracking. For prostates and significant extracranial lesions (*5 cm or more), we insert four fiducials at the Philadelphia CyberKnife centre [19, 20]. To lessen the occurrence of pneumothorax in lung patients undergoing fiducial implantation, Wu et al. (2007) suggested inserting a single fiducial into the tumor's centre and calculating the margin to offset the linear displacement of the tumor's edge due to rotation.

Pre-Treatment Imaging

Dosimetry calculations and the creation of DRR pictures for target tracking are often accomplished with pre-treatment imaging, which often involves non-contrast CT imaging. Additional imaging modalities including MRI and PET/CT are frequently obtained with thin slices, depending on the indications. Brain tumour patients often get T1 contrast MRI, AVM patients undergo angiography, while c-spine and prostate patients undergo T2 MRI. To aid in the contouring of tumours and essential structures, these supplementary images are co-registered with planning CT. To better define targets and identify organs at risk, CT scans with intravenous (IV) or oral (PO) contrast are frequently performed, depending on the location of the target. While the majority of patients are scanned head-first while lying down on the table, the CyberKnife can accommodate fiducial tracking, which allows for scanning while the patient is either prone or feet-first. A thermoplastic mask is placed on the head rest plate to immobilise patients undergoing treatments to the brain, head, and neck. Patients can be immobilised in a device like a Vac-lok cushion for all other body-site treatments. Immobilisation may have some benefits, but there's also a chance that the patient may be less comfortable and more likely to move around while wearing the device [21–23]. We recommend utilising a Vac-lok cushion exclusively for upper body targets, as it allows for consistent patient shoulder posture and the CyberKnife does real-time motion monitoring. Patients frequently report discomfort when using immobilisation devices for the majority of our body treatments. Because of this, we usually just put the patient on a cushion. Typically, a rapid spiral multiple slice CT scanner is used to obtain 3D pictures with contiguous thin slices (1-2 mm). A 4-slice CT scanner is the very minimum that should be utilised. For extracranial scans, it is ideal to have a scanner with 64 slices or more processing speed, if one is accessible. It is important for the patient to remain centred on the CT field of view during imaging, which should ideally encompass the whole patient's circumference. A complete CT scan of the skull is required for 6D skull tracking. An adequate CT scanning volume, beginning approximately 20 cm above the target and continuing 20 cm below it, is ideal for extracranial patients because it enables precise planning of non-coplanar beams. Extracranial lesion patients should also undergo scans with normal inspiration-hold and expiration-hold computed tomography (CT) [24–27]. In addition to the expiratory CT, which is utilised for planning purposes, the inspiratory CT is combined with the expiratory CT to estimate the excursion of the target and adjacent organs caused by respiratory motion. This fusion is based on vertebral body match. As a result, the dose to the organs in danger can be more accurately estimated, and the best tracking method and treatment margins can be determined. By providing a reference for treatment quality control and allowing for "lock on" of the fiducial or tumour at different respiratory phases, the target's pattern of respiratory motion can also aid in therapy administration.

Combining Images

For SBRT or radiosurgery to be successful, precise target and critical structural definitions are required. This can only be achieved with precise multimodality picture fusion and high-quality thin-slice image capture. With the CyberKnife, you can combine up to five supplementary sets of images from different imaging modalities with the main CT set. Primary and secondary pictures must be in DICOM format, which stands for Digital Imaging and Communications in Medicine. Compatibility with XA (3DRA), CT, MR, PET, and other secondary image sets is supported. The CyberKnife may fuse photos using a variety of techniques, including mutual information, manually adjusted points, or detected feature spots in both sets of images. According to the feature-point-based approach, fusion is carried out by comparing primary and secondary pictures depending on the three or more feature points that the treatment planner has defined [28, 29]. Patients with prostate cancer often undergo this procedure, which involves using implanted gold fiducial markers as feature points in CT and rapid echo T2 MRI. Anatomical mismatch outside the area of interest can be avoided by defining a partial volume that solely encompasses the area of interest. When the partial volumes are similar, local fusion can be done. Because of the way it breathes while fusing the spine, this is great for preventing chest wall mismatch. With manual fusion, you may visually check the correctness of the merged images and make any necessary adjustments to the fusion process. If the treatment planner is going to use manual fusion, they need to make sure the fusion is good in all three views—axial, sagittal, and coronal. To ensure accurate fusion, it is necessary to assess not only tumour match but also specific anatomical markers, such as the basilar artery or sulcus in brain instances. A variety of fusion procedures should be employed according to the intended use of the fused images [30, 31]. Take brain CT and MRI scans as an example; they need to be fused globally in order to map out a lesion's exact location. To the contrary, a local spinal fusion of expiration CT and inspiration CT can be helpful in estimating the respiratory motion of a peripheral lung tumour or in confirming that the fiducial moves in accordance with the tumour.

Fiducial point fusion is used to examine the relative position of the tumour and fiducial in different respiratory phases if the fiducial is placed outside of the lung tumour.

Therapy Routines

Exclusively for CyberKnife treatment planning, the MultiPlan system provides a task-oriented, step-by-step approach to treatment planning. After the pictures are loaded and fused, the workflow moves on to contour the volumes of interest, choose the right tracking mode, centre the image, and set dose limitations. This optimises the treatment plan, which can be done using forward or inverse planning approaches. The first step in using MultiPlan for dosimetric planning is to import a sequence of 3D CT scans. These images will serve as the foundation for the DRRs, which are reference images used for treatment tracking. To estimate the respiratory motion [32, 33] of the volume of interest or, if needed, to generate the ITV or to facilitate visualisation of the target volume and nearby organs at risk (OARs), additional 3D images can be fused onto the planning CT. These images can come from a variety of sources, including a second CT study acquired at a different respiratory phase, a contrast CT, MRI, angiography, PET, or other modalities. From a set of predetermined source positions, or "nodes," the treatment planning procedure optimises the group of beams that will be utilised for therapy. A virtual sphere with the image tracking centre at its centre contains the widely dispersed nodes. For intracranial treatment, the radius of this roughly spherical device ranges from 800 to 850 mm. For procedures performed outside of the skull, this treatment area is more elliptical, with a radius of 800 to 1,000 mm. "Paths" are the sets of preconfigured nodes. Both the intracranial and extracranial pathways include approximately 130 and 110 nodes, respectively; the latter has around 20 fewer nodes as it approaches the apex. Depending on the number of collimator sizes and the optimisation algorithm performed, the system will generate many candidate beams per node. For details on the possible algorithms, see below. Consequently, there are 1,200 to 6,000 beams that could be considered as candidates. In typical clinical layouts, you can find a range of 50 to 250 beams.

Treatment Planning Technique

Thus, using CyberKnife it is possible to perform both isocentric and non-isocentric planning of the tumor treatment. Dosage cloud that is oval or spherical is generated when all the radiation beams in the isocentric treatment planning feature the same isocenter. Similar to gamma knife (Elekta AB, Stockholm, Sweden) and conventional LINACs, the CyberKnife has isocentric treatment planning. In these systems, the mechanical centre of the gantry with respect to the collimator defines the isocenter. The CyberKnife’s dosimetric isocenter is not affected by any mechanical device centre and can be located by the treatment planner at any CT position. You may also define several isocenters, this means you can specify weight for each of them and place them in different coordinates. While in delivering the next set of beams to another isocenter, the CyberKnife robotic arm may move of the Linac from one node to another without shifting the patient, unlike the Gamma Knife. Before moving to the next node, it makes sure to deliver all beams from the current node to any number of isocenters. It also appeared that CyberKnife might adapt the weighting of the individual beams, while Gamma Knife indeed applies forward planning to give each of the beams of the same isocenter the same MU. This also makes it easier to have better dose conformality to the tumour. Because the doses decay very quickly around the isocentre, isocentric treatment plans are dosimetrically superior and this optimisation advantage is specially relevant to two kind of radiotherapies which are SBRT and SRS. Isocentric treatment planning on the other hand only allows the distribution of shapes of the dose cloud to be spherical or oval. Therefore, isocentric treatment is applied only to the small targets, for example, the trigeminal neuralgia or the smaller lesions in the brain, liver or lungs, and several larger lesions with an ovoid shape. For the purpose of delivering the conformal dosage cloud of the majority of targets with a non-standard shape, it is suggested to utilize the non-isocentric targeting. As opposed to the isocentric approaches to treatment the CyberKnife non-isocentric method aims each beam at a different part of the tumour. Unlike conventional linac, the CyberKnife is built to free itself from the limitations arising from the position of the gantry isocenter and instead of the CyberKnife is designed to shoot radiation beams from a range of positions determined during the planning phase. In the planning process before optimisation, the planning system optimises thousands of candidates of beam inside the tumour volume based on the shape of the tumor. An optimised treatment plan with the dose cloud being conformed to assume the shape of the tumor is usually produced by the treatment planning that includes selecting and weighting of beams. Nonisocentric plans not only consider conformity, but also create the high dose isodose line to exclude the key structures in the area, thus decreasing the MU of the radiation beam passing through them. Quite convincingly encouraging these observations, non-isocentric treatment plans have been selected as the primary method of CyberKnife planning.

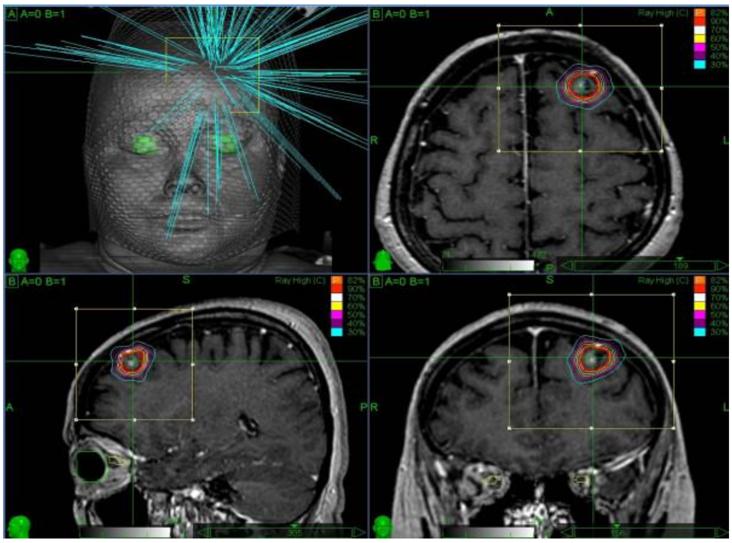

Figure 2. Axial, coronal, and sagittal views show the treatment plan and the geometry of the Cyberknife beam.

Optimisation with Simplex

One common way to solve optimisation issues using linear algebra is simplex optimisation. Prior to doing simplex optimisation, the treatment planner must establish a number of objective parameters. These parameters may include the minimum and maximum dose to the tumour, the maximum dose that can be delivered to important structures, and a weighting factor that can take values between zero and one hundred. In optimisation, a goal parameter's relevance decreases as its weighting factor drops (to zero, in extreme cases). Conversely, optimisation will be actively pushed to reach a target when the weight factor is high (up to 100) for that parameter. The "target function" will be a combination of the goal parameters, weight factors, tumour and critical structure volumes of interest, and minimal total MU used for optimisation. By expressing the optimisation issue as a matrix equation, simplex optimisation finds the optimal combination of candidate beams that maximise the objective function. It is a linear optimizer. Simplex has a reputation for being efficient, and it can potentially promise to discover the global optimum under specific conditions. By modifying the weighting factor, simplex makes it easy to strike a compromise between conserving vital structures and covering tumours in practice. Treatment planners can also manually add a point of constraint to the CT and assign a dose to that spot. The shape of the dose cloud can be readily adjusted by the treatment planner using this capability. Nevertheless, getting the hang of the simplex algorithm can be challenging for first-timers, especially when it comes to adjusting the weight factors and objective parameters. Additionally, it is a one-stop optimisation that necessitates re-optimization for any changes to the planning parameters, and it does not let the user change the optimisation target while optimisation is underway. Also, there's a cap of 1,200 potential optimisation beams, and it doesn't work with the IRIS collimator. When dealing with small brain, lung, or liver lesions that are close to no important structures, simplex optimisation is usually the way to go. When planning a prostate procedure with a uniform dosage distribution, Simplex is ideal.

Administration of Therapy

The first step in administering therapy is getting the patient into the exact same posture on the treatment table as during CT simulation. This includes employing the identical immobilisation and support device to mimic the patient's original position. The comfort of the patient should be prioritised. Both the patient's comfort and their ability to remain motionless throughout therapy can be enhanced with this. With the use of the in-room laser, therapists physically adjust the couch position until the patient is in a position where the target is near the imaging centre. Prior to adjusting The next step in patient alignment is to take X-ray images. This can be done with the help of an image guiding system or by visually comparing the X-ray image's anatomy to the DRR image. As part of this procedure, the therapist remotely adjusts the treatment table to ensure proper alignment. The next step is to take more X-rays to verify the image guiding system has locked onto the correct anatomy and to update the patient's position. Furthermore, in order to set up the initial Synchrony model before treatment starts, the Synchrony technology needs approximately 8 photos taken at different phases of respiration for tumours that move with respiration. We follow the patient-set-up method suggested by Wu et al. (2007) while administering extracranial fiducial tracking. In this method, the tracking centre is established using expiration-hold CT coordinates, specifically (X1, Y1, and Z1). The first step in alignment is to centre the patient's spine at (X2, Y2, and Z2) and use spine tracking to bring the patient into proper alignment. Once the patient is properly aligned with the spinal setup, the patient is transferred from the spinal setup to the treatment position using a precalculated couch shift of (X1-X2, Y1-Y2, and Z1-Z2). In addition to realigning the patient's anatomy, the process also helps the therapist find the fiducials on the X-ray pictures. It is helpful to rule for fiducial migration before therapy starts since the fiducials should be in the centre of the shifted X-ray image when captured at patient exhale. The robot follows the predetermined path by moving successively across the nodes after therapy begins. By using an optimised path traversal algorithm, the robot can avoid nodes that do not require therapy beam delivery. At every active node, the robot will adjust the Linac's position and rotation automatically by utilising the most up-to-date patient transitional and rotational data derived from image guidance. This compensates for any slight movement of the target. The therapy will automatically pause so the operator can reposition the patient if image guidance detects a target movement greater than the manufacturer's or clinical limit. By default, image guiding will capture one set of X-ray images for each beam. However, this can be adjusted by the user. When objects in motion, such the robotic arm or Linac, obstruct the imaging zone, we skip taking that picture and instead use the data from the one before it to track our movements. Moreover, a "safe zone" specified by the user according to patient size and couch position, or a touch sensor on the Linac, will cause the robot to pause and display a "e-stop" warning until the user either clears the area or overrides the stop. A plan will be made to resume treatment at a later date in the event that it is interrupted. The entire treatment duration incorporates the time spent imaging, travelling between nodes by robot, and machine beam-on time. It also takes a few minutes after patient setup to construct the initial Synchrony model for Synchrony treatment .

CONCLUSION

When it comes to SBRT delivery, the CyberKnife provides a comprehensive integrated solution. Clouds of highly radioactive material that precisely mimic the form of the target are produced by the robot-mounted linear accelerator. Even when the target is in motion, precise tracking may be achieved with continuous image guiding throughout treatment. The radiation dose cloud can be more sharply reduced when delivered by numerous non-coplanar beams, reducing the likelihood of harm to surrounding normal structures. The CyberKnife offers a novel strategy for SBRT in clinical settings, as shown by the increasing amount of SBRT papers.

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