Gamma Knife Radiosurgery: Current Technique

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Professor Lars Leksell first coupled an orthovoltage x-ray tube with his first generation guiding device to focus radiation on the Gasserian ganglion to treat facial pain. He subsequently investigated cross-fired protons as well as x-rays from an early generation linear accelerator (LINAC) for radiosurgery. Leksell and Larsson finally selected Cobalt-60 as the ideal photon radiation source and developed the Gamma Knife® 1,6. The first Gamma Knife created a discoid-shaped lesion suitable for neurosurgical treatment of movement disorder surgery and intractable pain management.

Clinical work with the Gamma Knife began in 1967 in Sweden. In 1975, a series of surgical pioneers at the Karolinska Hospital, Stockholm began to utilize a re-engineered Gamma Knife (spheroidal lesion) for the treatment of intracranial tumors and vascular malformations. Units 3 and 4 were placed in Buenos Aires and Sheffield England in the early 1980's.

Lunsford introduced the first clinical 201-source Gamma Knife unit to North America (the fifth gamma unit worldwide). Lunsford first performed Gamma KnifeÒ radiosurgery in August 1987 at University of Pittsburgh Medical Center. In the United States, based on the available published literature, a cautious approach was adopted while waiting for increased scientific documentation 7. The encouraging results of radiosurgery for benign tumors and vascular malformations led to an exponential rise of radiosurgery cases and sales of radiosurgical units. In recent years metastatic brain tumors have become the most common indication of radiosurgery. Brain metastases now comprise 30-50% of radiosurgery cases at busy centers.

THE EVOLUTION OF GAMMA KNIFE TECHNOLOGY

Models A, B and C

There have been numerous changes to the Gamma KnifeÒ since the original 1967 design. In the first models (Model U or A) 201 Cobalt sources were arranged in a hemispheric configuration. These units presented challenging Cobalt-60 loading and reloading issues. To facilitate reloading, the unit was redesigned so that sources were arranged in a circular configuration (Model B, C and 4C) (Fig 1).

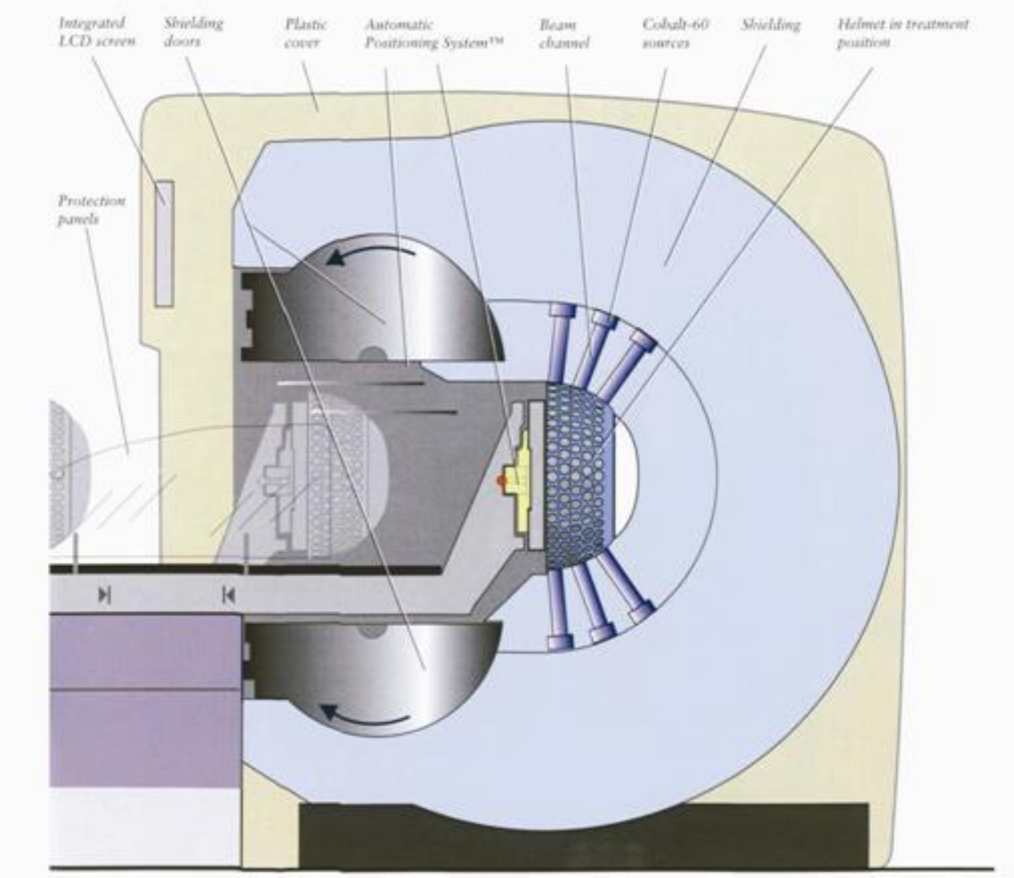

Figure 1: Schematic diagram of the Leksell Gamma Knife 4C

Gamma Knife radiosurgery usually involves the use of single or multiple isocenters of different beam diameters to achieve a treatment plan that conforms to the 3-dimensional volume of the target. The total number of isocenters may vary depending upon the size, shape, and location of the target. Each isocenter has a set of three Cartesian (X, Y, Z) stereotactic coordinates corresponding to its location in three-dimensional space as defined using a rigidly fixed stereotactic frame. When multiple isocenters are used, the stereotactic coordinates will need to be set individually. In 1999, the Model C Gamma Knife was introduced and first installed in the United States at the University of Pittsburgh Medical Center in March 20003. This technology combined dose planning advances with robotic engineering. The unit incorporated an automatic positioning system (APS) with submillimetric accuracy, used to move the frame to each coordinate. This technology obviates the need to manually adjust each set of coordinates in a multiple-isocenter plan.

The robot eliminates the time spent removing the patient from the helmet, setting the new coordinates for each isocenter and repositioning the patient in the helmet. This has significantly reduced the total time spent to complete the procedure and also increased accuracy and safety2,4,9-11. The other features of the Model C unit include an integral helmet changer, dedicated helmet installation trolleys, and color-coded collimators. In 2005 the fourth generation Leksell Gamma Knife® model 4C was introduced. The first unit was installed at the University of Pittsburgh in January of 2005. The model 4C is equipped with enhancements designed to improve workflow and provide integrated imaging capabilities. The imaging enhancements available with the Leksell GammaPlan®, offers image fusion capability. These images can also be exported to a CD-ROM, so the referring physician can receive pre- or post-operative images for reference and follow-up. The planning information can be viewed on both sides of the treatment couch. The helmet changer and robotic Automatic Positioning System® are faster and reduce total treatment time.

LGK PERFEXION

The newest iteration of Gamma Knife technology is the PERFEXION unit. Beginning in 2002, an invited group of neurosurgeons, radiation oncologists and medical physicists was asked by the manufacturer to define specifications for a new Leksell Gamma Knife system. The group agreed on five critical features for a new system: 1) best dosimetry performance, 2) unlimited cranial reach, 3) best radiation protection for patient and stuff, 4) full automation of the treatment process, 5) patient and staff comfort, and 6) similar radiation dose profiling as prior units. The new unit was first installed in 2006, and was first used at our center in September 2007 (Fig 2).

Figure 2: Leksell Gamma Knife PERFEXION.

The radiation unit was redesigned. A total of 192 60Co sources were arranged in a cylindrical configuration in five concentric rings. This differs substantially from the previous hemispherical arrangements and results in different source to focus distances for each ring varying from 374 to 433 mm. The primary and secondary collimators have been replaced by a single large 120 mm thick tungsten collimator array ring (Fig 3). Consequently no collimator helmets are needed for the PEREFXION system 5,8.

Three collimators are available for the PERFEXION system. The 4 mm and 8 mm collimators remain, and a new 16 mm collimator replaces the prior 14 mm and 18 mm collimators. The tungsten collimator array is subdivided into eight identical but independent sectors, each containing 72 collimators (24 collimators for 4 mm, 24 collimators for 8 mm, 24 collimators for 16 mm). The collimator size for each sector is changed automatically by moving 24 sources over the selected collimator set. Each sector with 24 sources can be moved independently into five different positions: 1) sector in home position when system is standby, 2) 4 mm collimator, 3) 8 mm collimator, 4) 16 mm collimator, and 5) sector off position (defined as the position between the 4 and 8 mm collimators providing blocking of all 24 beams for that sector)(Fig 3). Sector movement is performed by servo-controlled motors with linear scales located at the rear of the radiation unit.

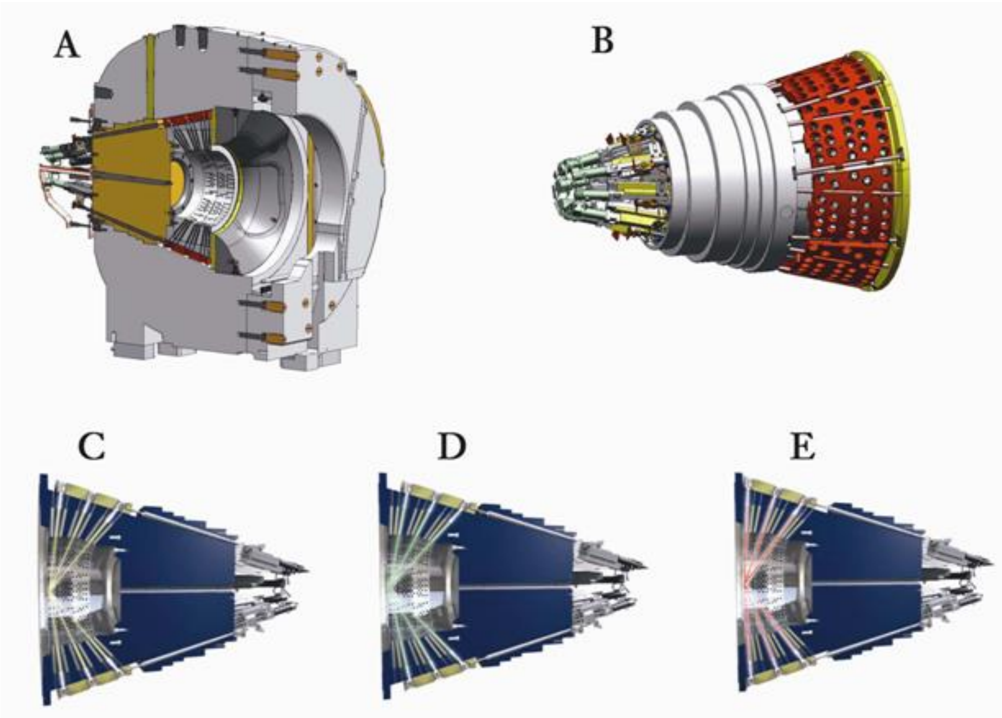

Figure 3: Diagrams of the PERFEXION Gamma Knife radiation unit and collimator system. A) Cross section of the Leksell Gamma Knife PERFEXION radiation unit. B) Each sector holds 24 60Co sources and can be moved independently on other sectors to the desired position to define collimator size or block groups of beams. C) Sector position in 4 mm collimator. D) Sector position in 8 mm collimator. E) Sector position in 16 mm collimator.

The radiation cavity has been increased by more than 300% compared to previous models. However, due to an improved collimation system (120 mm tungsten ring), the average distance from source to focus is very close to previous models. This results in similar output for the prior 18mm and new 16 mm administrations. The increase in the volume of the radiation cavity to more than three times allows for a greater mechanical treatment range in X/Y/Z. It is (160/180/220mm) for the PERFEXION system compared to (100/120/165mm) for other gamma knife models. This provides virtually unlimited cranial reach, so crucial in the care of patients with multiple brain metastases5. To date, we have seen no problems related to potential helmet collisions.

The Automatic Positioning System (APS) used in the C units was replaced by the Patient Positioning System (PPS).
Rather than just the head, the whole couch moves into pre-selected stereotactic coordinates.

This provides better patient comfort and allows complete of the majority of radiosurgeries in one single run. Docking of the patient into the PPS is done by means of an adaptor that attaches to the standard stereotactic Leksell G frame with three clips. The adapter is then directly docked to the PPS. The patient can be attached in three different positions, with gamma angles of 70, 90 or 110 degrees reflecting neck flexion or extension. The gamma angle is the only treatment parameter that requires manual set up. The PPS has repeatability better than 0.05 mm.

The redesigned hardware of the PERFEXION unit has had significant impact on the planning software Leksell GammaPlan PFX (LGP PFX), a new version of the LGP running on a PC platform with the Linux operating system. There are in principle three possible approaches in the treatment planning: 1) use of classical combinations of 4, 8, and 16 mm isocenters (shots), 2) use of composite shots containing combinations of 4, 8 16 mm or blocked sectors and 3) dynamic shaping using blocked selected sectors to protect volumes defined as critical structures (Fig 4). The most revolutionary change in the treatment planning is the ability to generate a single isocenter composed of different beam diameters. Such a composite shot design allows an optimized dose distribution shape for each individual shot. The setup of any sectors, combinations of different collimators, or blocking takes only minimal time (a few seconds done automatically).

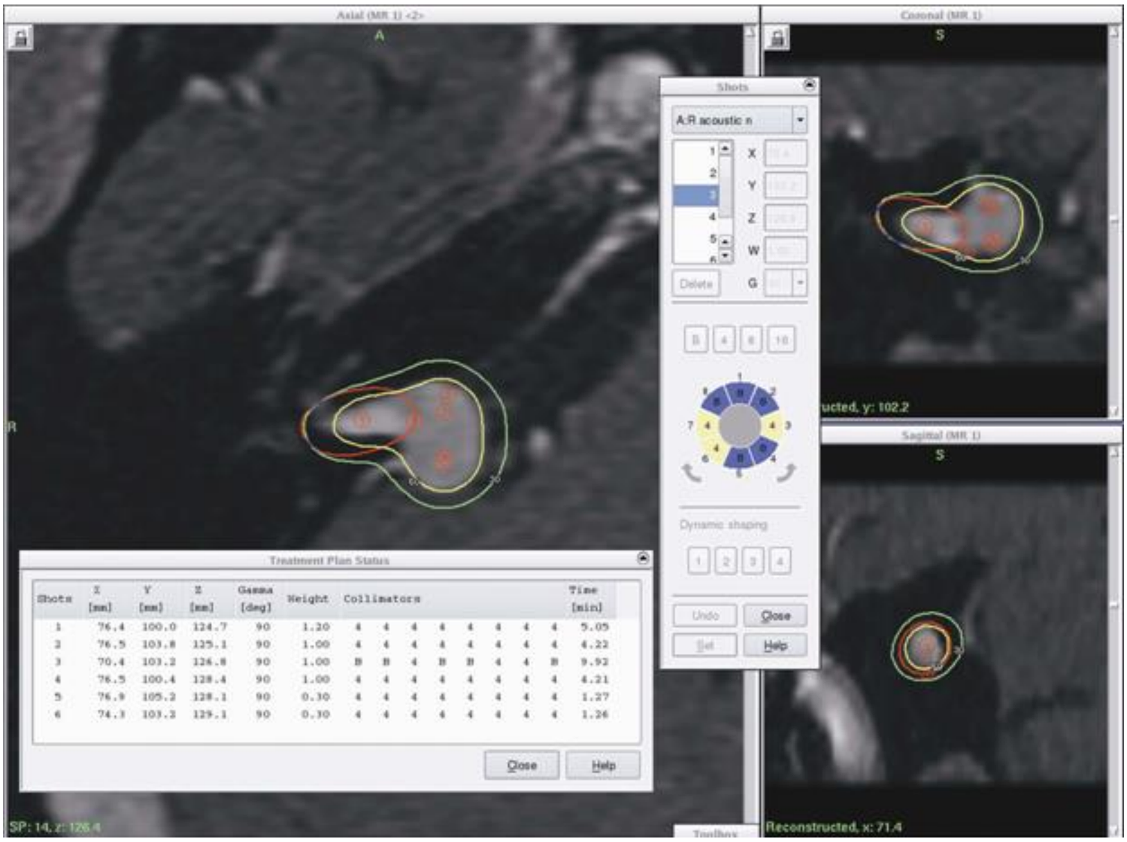

Figure 4: Example of the treatment plan with composite shots for the Leksell Gamma Knife PERFEXION. Multiple 4 mm collimators were used to design dose plan for a vestibular schwannomas. Sector blocking was used in one shot to achieve high conformity and sharp dose fall.

The new PERFEXION system provides further improvements in patient and staff radiation shielding. The sectors are always in the off position (blocked) during patient transportation in the treatment position, transition into new stereotactic coordinates, pause or emergency interrupt. These results in significantly (about 5-10 times) lower extracranial irradiation to the patient compared to models B and C. Our preliminary comparison study shows that for a patient with ten brain lesion, the total time saved is about 1.5-2.0 hours compared to other systems. The new Leksell Gamma Knife PERFEXION provides excellent dosimetry performance, unlimited cranial reach, enhanced radiation protection for patient and staff, full automation of the treatment process and better patient and staff comfort compared to previous models (Table 1). Thus, the PERFEXION unit provides the potential to increase the spectrum of treatable indications including multiple brain metastasis, access to the upper cervical spine, and other pathologies of the head and neck. The use for the lower to mid-cervical spine will require the development of a new fixation device.

THE RADIOSURGERY PROCEDURE

In the following sections we discuss the basic technical steps of gamma knife radiosurgery using LGK 4C and PERFEXION.

Daily Quality Assurance

Gamma Knife quality assurance testing is performed by an authorized medical physicist every morning. The purpose of Daily Quality Assurance is to assure proper system function in standard treatment conditions plus verify all safety and emergency functions. The medical physicist ensures that all system tests required by Nuclear Regulatory Commission (NRC) regulations are performed and functioning properly. These tests include the permanently mounted radiation monitor inside the treatment room and it's remote indicator, hand held radiation monitor, patient viewing and communication systems, door interlock, timer termination of exposure, treatment pause and emergency stops, test of all required beam status indicators and alarm indicators, availability of the release rods for the emergency removal of a patient and function of the helmet hoist used for collimator helmet exchange. A test run simulating the standard treatment procedure is performed and also includes check of automatic positioning system accuracy test. There are other monthly and annual checks, as well as preventive maintenance of the Leksell Gamma Knife.

Daily Quality Assurance for PERFEXION system is very similar to 4C system as described above. The test run includes a sector positioning check verifying proper function of automatic collimator set up. The patient docking device function is tested together with overall system accuracy (including patient positioning system and sector positioning) by a diode test tool and focus precision check. The same monthly and annual tests are performed as for 4C system.
Application of the stereotactic frame

For Gamma Knife radiosurgery, appropriate stereotactic frame placement is an initial critical part of the procedure. Prior to frame placement, the radiosurgery team should review the preoperative images and discuss optimal frame placement strategy. An effort should be made to keep the lesion as close to the center of the frame as possible. The possibility of collision by the frame base ring, the posts/pins assembly, or the patient's head with the collimator helmet during treatment should also be considered prior to the frame application. Steps to avoid a possible collision should be taken during frame placement. These collisions should be minimal with the LGK PERFEXION.

The frame is shifted lower or higher on the head, to the left or right, or anteriorly or posteriorly, using the ear bars attached to the sides of the base ring. The anterior posts are positioned low along the supraorbital region to avoid collision of frontal post/pin assembly with the collimator helmet. For radiosurgery planning, a higher gamma angle (1200-1400) is used, if a collision is detected at the default angle of 900. While shifting frame laterally, it is important to make sure that there is enough space on the contralateral side to allow positioning of the fiducial box on the base ring of the frame. The MRI or CT fiducial should be tried on frame prior to sending the patient to MRI unit. If the fiducial box does not fit on to the frame due to excessive shifting of the frame, the frame will have to be repositioned.

Frame adaptor and Frame cap fitting check

The frame adaptor (which attaches the frame to the table) is checked for fit. If the frame is shifted too anteriorly and the back of head ring is too close to the neck adaptor may not fit and consequently treatment can not be carried out. Tight fitting of the adaptor may cause neck discomfort to patient especially during a long treatment.

The frame cap check provides information about geometry of all stereotactic frame parts including posts and screws and also information about patient head geometry to the treatment planning system. This information is needed for the prediction of potential collisions or close contact with the gamma knife unit collimator system. If frame cap does not fit then the exact post and screw measurements must be given to the treatment planning system.

Techniques of Stereotactic Imaging

Imaging is crucial in radiosurgery. Magnetic resonance imaging (MRI) is the preferred imaging modality. CT is used when MR imaging is not possible. Angiograms are used in conjunction with MRI for arteriovenous malformation radiosurgery.

Since 1993, MRI has been used for stereotactic radiosurgery planning in almost all eligible cases using a 1.5 Tesla unit. In addition, arteriovenous malformations are imaged also by biplane angiography. At our institution high-resolution, a gadolinium enhanced 3-D localizer (T2* images) image sequence is used first to localize the tumor in axial, sagittal, and coronal images. Using the axial images, the fiducials can be measured and compared to the opposite side to exclude the possibility of MR artifacts and confirm that there is no angulation or head tilt. The average time for this sequence is approximately 1.5 minutes. For stereotactic imaging of most lesions, a 3D-volume acquisition using Fast Spoiled-Gradient Recalled Acquisition in Steady State (GRASS) sequence at 512 x 256 matrix and 2 NEX (number of excitations) covering the entire lesion and surrounding critical structures is preferred. To define the radiosurgery target, this volume is displayed as 1 or 1.5 mm thick axial slices. The FOV (field of view) is kept at 25 cm x 25 cm in order to visualize all fiducials. The approximate imaging time for this sequence is 8 minutes. We generally prefer 3-D Spoiled-GRASS sequence for most lesions. Additional sequences are performed when more information is needed.

Pituitary lesions are particularly difficult to image especially if there has been prior surgery. A half dose of paramagnetic contrast is usually given to image pituitary adenomas. For residual pituitary tumors, after trans-sphenoid resection, a fat suppression SPGR sequence is recommended in order to differentiate tumor from the fat packed in the resection cavity. For cavernous malformations, an additional VEMP (Variable Echo Multi Planar) imaging is obtained to define the hemosiderin rim. For thalamotomy planning, an additional fast inversion recovery sequence is performed to differentiate thalamus from the internal capsule. Brain metastases patients receive a double dose of contrast agent and the entire brain is imaged by 2 mm slices to identify all of the lesions. Before removing the patients from the MR scanner, the images must be checked for accuracy.

When using CT imaging, it is advisable to use short posterior posts to avoid metallic artifacts from the posts and pins. Care should also be taken in deciding the optimal place for the pins since they cause artifacts on CT. With modern CT scanners 1, or 2 mm thick slices (depending upon the size of the lesion) without any gap can be obtained quickly. Angiography is the gold standard for AVM radiosurgery planning. It should be used in conjunction with MR or CT imaging. The orthogonal images (instead of oblique or rotated) are preferred but are not necessary. For AVM nidi that are not properly visualized in orthogonal planes a rotation of up to 100 in two dimensions or aspects can be used without compromising the accuracy of radiation delivery. Before removing the angiography catheter the images should be reviewed to make sure that all the fiducials are seen on the images. Digital subtraction techniques, despite a potential radial distortion error, have proven satisfactory spatial accuracy.

Determination of Target Volume(s)

Target determination is an important step in order to make a conformal plan. Target volume can be outlined using the LGPâ software (manual or semiautomatic mode). Although experienced surgeons can create conformal dose plans without outlining the target, the target outline allows for a more quantitative assessment of the plan.

For new centers especially where physicists assume the initial responsibility for planning, target definition and outlining by the surgeon or oncologist becomes an important step. The surgeon’s input is required to define radiosurgery targets for patients with AVMs, tumors and functional neurosurgery as used by some centers.

By defining the target volume and volumes of critical structures better evaluation and quantification of the treatment plan can be done. Various parameters such as dose volume histograms for the target volume and critical structures plus conformity indexes can be obtained.

Techniques of Conformal Dose Planning

In the process of treatment planning, several strategies can be used. The Model C allows treatment using robotic automatic patient positioning system (APS mode), manual positioning (trunnion mode) or mixed treatment (some isocenters in APS mode and some in trunnion mode). Most users will select shots and directly place them over the target. Beginners can also use the inverse dose-planning algorithm (WizardÒ) to create a plan and then optimize it manually. The conformal dose planning is enhanced by the use of multiple small collimators.

Three different approaches in the treatment planning can be applied when using LGK PERFEXION. The first is to use the same strategy as described for 4C system above. Since only 4, 8 and 16 mm collimators are available only combination of these three different collimators can be used to cover the entire target volume. The second approach is to use dynamic shaping that is new feature in the treatment planning introduced for the PEREFXION system. This automatic procedure will provide solutions to block selected sectors to protect volumes defined as critical structures. Different levels to reduce dose delivered to critical structures can be selected. The treatment planning system then automatically calculates which sectors should be blocked for each individual shots. One should be aware that each blocking will significantly increase total exposure time. The third approach is to use single isocenters composed of different beam diameters or blocked sectors. Any pattern of sectors including 4, 8, 16 mm collimators and blocks can be generated. This can help significantly for shaping dose distribution especially for irregular volumes.

Radiation Administration during Stereotactic Radiosurgery

The Model 4C Gamma knife allows radiation delivery using trunnion mode (manual patient positioning) or APS mode (Robotic positioning) or a combination of the two (mixed treatment). In trunnion treatment, the x, y, and z of each isocenter are set manually and triple-checked to avoid errors.

The APS plan is transferred directly from the planning computer to control computer. The operator selects the run (a combination of isocenters of same beam diameter) that matches the collimator helmet on the Gamma Unit. The APS is moved to the dock position and the patient's head frame is fixed into the APS. The accuracy of the docking position is checked. The system prompts the user to perform clearance checks first for all those planned isocenters in which the pins, posts, frame or patient's head would be less than 12 mm away from the inner surface of the collimator helmet (even though they may not match with the collimator size which is being used for first run). The clearance check is performed by moving the patient to those positions under APS manual control and by visual check of collision with the collimator helmet. After the clearance check, the system prompts the surgeon to carry out position checks. In the position checks, all the isocenters using the same helmet are checked, one by one, by moving the patient's head to these positions using APS manual control to make sure patient will handle all head position changes with sufficient comfort. All personnel then leave the room, and the radiosurgical dose is administered. The APS moves the patient to all planned positions, one by one, until the isocenters using that size collimator helmet are completed. The team monitors the patient and the coordinates of different isocenters on the control computer. If other runs using a different gamma angle but using the same helmet are planned, then the patient is taken out, next run is selected, APS is moved to the dock position and patient's head is again fixed in the APS using the planned angle (720, 900, 1100, or 1250).

Radiosurgery with the LGK PERFEXION is a fully automated process for all aspects of the procedure including set up of the stereotactic coordinates, set up of different sector positions defining collimator size or blocked beams and set up of exposure times. All treatment data are exported to the operating console. The only manual part of the procedure is the positioning of the patient's head in the docking device and adjustment of the couch height for optimal comfort. After confirmation of the patients' identity, most PERFEXION radiosurgeries are administered in one single run (95%). Rarely a clearance check is needed. For this, a special test tool simulating the shape and dimensions of the inner collimator is attached and rotated around patient's head. Once radiosurgery begins, the team monitors the patient and the set up of coordinates, exposure times and sector set up of different isocenters on the control computer of operating console. The system allows audio-visual communication with the patient during irradiation and the process can be interrupted at any time if needed.

Conclusion

In the past two decades, we have witnessed dramatic improvements in stereotactic radiosurgery technologies. Gamma knife radiosurgery now offers better image-handling features, faster and more compact software platforms that make the calculations almost real time, automated and robotic patient positioning thus reducing the potential for human error, inverse treatment planning, and expanded indications.

Tables

Table 1: Technical Specifications of Different Leksell Gamma Knife Units

Comparing parameter	Leksell Gamma Knife PERFEXION	Leksell Gamma Knife 4C	Leksell Gamma Knife B
Accuracy			
Radiological accuracy	< 0.25 mm	< 0.50 mm	< 0.50 mm
Positioning accuracy	< 0.20 mm	< 0.30 mm	< 0.50 mm
Positioning repeatability	< 0.05 mm	< 0.20 mm	< 0.25 mm
Radiation safety			
Room shielding required around back wall, 180 degrees	0 cm Standard concrete	10 cm Standard concrete	10 cm Standard concrete
Room shielding required around front wall, 180 degrees	< 50 cm Standard concrete	< 50 cm Standard concrete	< 50 cm Standard concrete
Body dose to patient lower than other devices	10-100 times lower	2-20 times lower	2-20 times lower
Treatment planning			
Mechanical treatment range X/Y/Z	160/180/220 mm	100/120/165 mm	100/120/150 mm
Shape of accessible volume	Cylindrical	Spherical	Spherical
Effective target dose rate	> 3.0 Gy/min	> 3.0 Gy/min	> 3.0 Gy/min
Composite shot	Yes	No	No
Dynamic shaping	Yes	No	No
Workflow			
Typical treatment time	20 min	50 min	80 min
Approximate patient set up time	2 min	10 min	10 min
Stereotactic coordinates set up time	3-5 s	30-40 s	7-10 min
Collimator size set up time	< 3 s	7-10 min	7-10 min
Collimator blocking set up time	< 3 s	10-20 min	10-20 min
Composite collimator set up time	< 3 s	N.A.	N.A.

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