

Latest Developments in Gamma Knife Radiosurgery: Gamma Knife Model C and Gamma Plan 4C

Gamma Knife Radyocerrahisinde son Gelişmeler: Gamma Knife Model C ve Gamma Plan 4C

ABSTRACT

A wide application field, high precision and low complication and high success rates make Gamma Knife radiosurgery a standard treatment modality in neurosurgery. During Gamma Knife radiosurgery, 201 cobalt 60 sources are arranged in a hemispheric shape in such a manner that all the gamma rays are focused at the center to create a cumulative radiation field. The total energy of the rays is therefore transmitted precisely to the target with preservation of normal brain tissue. The Leksell Gamma Knife has undergone numerous refinements, additions and modifications since 1967. Additions and refinements in Gamma Knife radiosurgery are still continuing parallel to developing technology. We present the new Gamma Knife (Model C) and the latest version of Gamma Plan (Gamma Plan 4C) in use at the Department of Neurosurgery of Gazi University School of Medicine, the 207th Gamma Knife Radiosurgery center in the world. Gazi University Gamma Knife Center is the first center using Gamma Plan 4C in the world. Information on new developments in Gamma Knife radiosurgery is presented instead of the indications and results.

KEY WORDS: Automatic Positioning System, Gamma Knife, Gamma Plan 4C, stereotactic radiosurgery

ÖZ

Geniş uygulama alanı, keskinliği, düşük komplikasyon ve yüksek başarı oranı Gamma Knife radyocerrahisini nöroşirürjinin standart tedavi yöntemlerinden biri haline getirmiştir. Gamma Knife'da 201 adet kobalt 60 kaynağı yarı küre şeklinde organize edilerek, gamma ışınlarının merkezdeki tek noktada kumulatif radyasyon alanı oluşturması sağlanır. Bu sayede ışınların toplam enerjisi, normal beyin dokusu korunarak keskin biçimde hedefe iletilir. 1967 yılından bu yana Leksell Gamma Knife üzerinde birçok değişiklikler yapılmıştır ve ilerleyen teknolojiye paralel olarak halen geliştirilmektedir. Gazi Üniversitesi Tıp Fakültesi, Beyin ve Sinir Cerrahisi Gamma Knife Merkezi, dünyada 207. merkez olarak kurulmuş olup, Gamma Plan 4C'yi dünyada ilk kullanan merkez olma özelliğini taşımaktadır. Bu makalede yazarlar, Gazi Üniversitesi Tıp Fakültesi, Beyin ve Sinir Cerrahisi, Gamma Knife Merkezinde kullanılmakta olan Gamma Knife Model C ve Gamma Plan'ın son versiyonu olan Gamma Plan 4C'nin özelliklerini ve üstünlüklerini sunmaktadırlar. Gamma Knife'in endikasyon ve sonuçlarını vurgulamaktan çok, bu alandaki son gelişmeleri sunmak amaçlanmıştır.

ANAHTAR SÖZCÜKLER: Gamma Knife, Gamma Plan 4C, Otomatik Pozisyonlandırma Sistemi, stereotaktik radyocerrahi

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INTRODUCTION AND HISTORY

Two hundred and one cobalt 60 sources converge and focus on a specific point during stereotactic space Gamma Knife Surgery (GKS). As a result, the target receives a high dose, with a steep fall-off in the dosage gradient peripherally. The principal is to create a high radiation effect on the target while sparing the surrounding structures. As the energy of each ray is very weak, the rays do not cause a significant biological effect on the normal brain tissue that they pass through.

The first applications of Gamma Knife® were performed at the Karolinska Institute (Sweden) by Swedish neurosurgeon Lars Leksell and professor of biophysics Borje Larsson in the early 1950's. They irradiated the Gasserian ganglion of a patient suffering from tic douloureux with a stereotactic frame adapted to a conventional X-ray machine.

The prototype of the modern Gamma Knife was produced and used at the same Institute in 1967. It was called Model A or U and there were 179 sources of cobalt 60 in this machine (Figure 1). Since imaging techniques were insufficient, Gamma Knife Surgery (GKS) was mostly used in functional neurosurgery at that time (4, 13, 14, 15, 17).

Thanks to further developments in computer and imaging technologies, GKS was improved and Model B was produced. Model B was installed first in Bergen in Norway (Figure 2). This model is still used in more than 100 centers around the world, and also in the first center in Turkey. Model B makes three-dimensional, complex treatment planning possible by using modern imaging techniques (Computed Tomography (CT), Magnetic Resonance



Figure 1: Professor Lars Leksell and the first Gamma Knife



Figure 2: Gamma Knife Model B

Imaging (MR) and Digital Subtraction Angiography (DSA)).

After approval by the FDA (Food and Drug Administration) in 1988, GKS was accepted as a dedicated neurosurgical treatment tool and spread all over the world (17). There were only 5 centers using GKS in the world in 1988 but this number has now reached 217. It is estimated that more than 250,000 patients have been treated with GKS until 2004. Another leading factor of this progress is the efficiency of GKS in treating arterio-venous malformations (AVM).

The use of a shielding system (plugs) is a very important step in GKS. This system blocks the beams passing through eloquent and sensitive structures such as the optic tract and brain stem. Safe treatment with low complication rates can thus be achieved.

Gamma Knife evolved parallel to technological developments and Model C was produced in 1999 (Figure 3). This model was designed both to reduce the treatment time for radiosurgery and to prevent human errors (1). The most important feature of this model is the Automatic Positioning System (APS) (Figure 3). This system carries the target to the focus automatically according to the treatment plan with very high precision. APS provides fast, safe, more accurate and very precise treatment planning (2, 7, 15, 18, 19). Model C can also work without APS. Easy use of the new helmet transport system, color-coded collimators and occlusive plugs are the other advantages of this model.

"Gamma Plan" is the computer software used in treatment planning in GKS and is the most intelligent part of the system. Gamma Plan 4C is currently the most advanced such system. Today there are only three centers using this system and



Figure 3: Gamma Knife Model C

Gazi University Gamma Knife Center was the first among these. This software is capable of using Positron Emission Tomography (PET) images and involves an integrated electronic Schaltenbrand / Wahren stereotactic brain atlas. It fuses the anatomical structures in the electronic Schaltenbrand / Wahren stereotactic brain atlas images to the patient's images. The third important feature of the software is the capability to use frameless images with the guidance of the frame-based images.

GAMMA KNIFE MODEL C

Gamma Knife Model C consists of 6 major separate units. APS is the main difference of Model C from the previous models. The well-known five units of the system are also briefly described below.

1. Treatment unit: This unit consists of 201 hemispherically-arranged cobalt 60 sources.

2. Collimators: These are used to define the volume of the radiation field that the beams constitute. For instance, while the 4 mm collimator produces 0.07 ml of active radiation field, the 18 mm collimator produces 6 ml active radiation field (18). There are four different collimator sizes (4, 8, 14, 18 mm) that are chosen according to the lesion's shape, size and localization. The hemispheric tool containing the 201 collimators is called the "helmet" (Figure 4).

3. Patient Couch: This is the bed that the patient lies on and which automatically moves in and out of the treatment unit.

4. Leksell Stereotactic Frame: This is used to define the coordinates of any structure in the

cranium. It also ensures immobility of the patient's head during the imaging and treatment procedures. The frame is attached to the skull under local anesthesia by four head pins. The Leksell frame must be placed so that the target is located as close to the center of the frame (x:100, y:100, z:100) as possible. Sometimes lesions placed in frontal poles, occipital poles or lateral poles cannot be centralized and treatment cannot be performed in these situations (Figure 5).

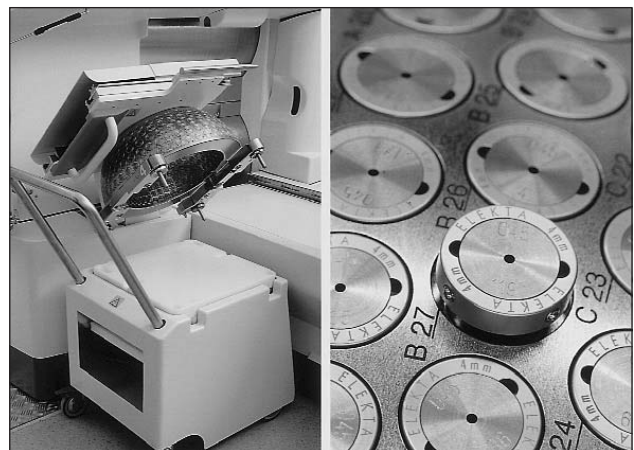


Figure 4: Left: the helmet and the helmet changing procedure Right: 4 mm collimators placed on the helmet

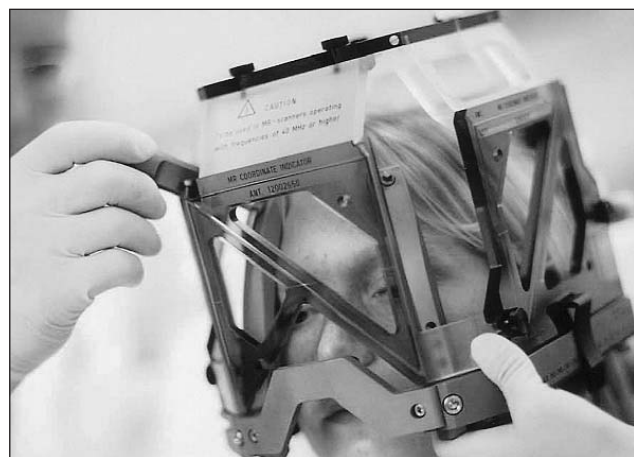


Figure 5: Leksell stereotactic frame and MR indicator box

5. Planning System (Gamma Plan): After the application of the frame, images are transferred to the planning system. By the help of fiducials (indicators with coordinates already installed in the software), the coordinates of the target are recognized by the computer. The operator defines and introduces the target to the computer by drawing the margins of the lesion. The lesion is then covered with shots. These shots produce isocenters

that can roughly be defined as active radiation fields (Figure 6). Gamma Plan also predicts any collisions (hit) of the patient's head and the frame to the helmet before the treatment and warns the operator. Once the treatment plan is completed, the plan is exported via the network to the treatment control console computer. After positioning the patient on the couch, a second check is carried out by the operators called 'collision and position check run'.

6. Automatic Positioning System (APS): GKS usually involves multiple isocenters to achieve a treatment plan that conforms to the irregular three-dimensional volumes of most lesions. The APS moves the patient's head to the target coordinates defined in the treatment plan. In other words, this system adjusts the stereotactic coordinates of isocenters automatically. Robotic movement is performed by the six positioners (each directing one axis; X, Y, Z) located on the left and right side of the head (Figure 7). In the APS, the movements and coordinates are checked by another system 10 times a second, thus providing a high degree of accuracy and safety. Coordinate adjustment was performed manually with the system called "Trunnion" in previous models. Operators had to enter the treatment room and adjust the coordinates manually for every shot in Model B. The robot eliminates the time spent for removing the patient from the helmet, setting up the new coordinates for each isocenter

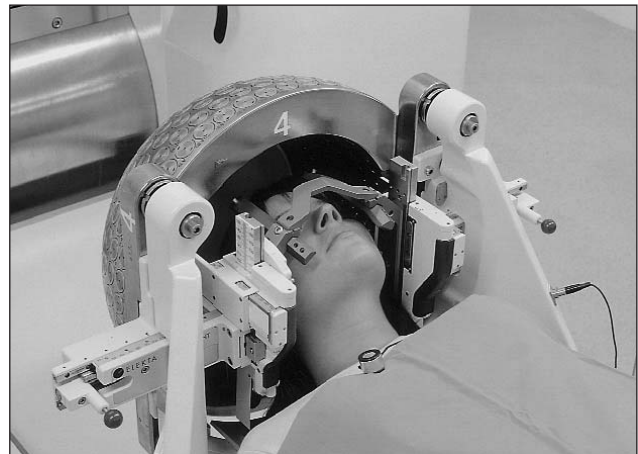


Figure 7: Patient mounted on the APS (located near both sides of the head)

using the same beam diameter, and repositioning the patient in the helmet. The time required to complete the treatment is therefore reduced significantly. Since the aim of stereotactic radiosurgery is to design and implement a treatment plan in which the prescription isodose line covers the target with a minimal excess volume and a sharp dose fall-off outside the target volume, the shortened treatment time helps to create a more precise three-dimensional plan by using multiple small isocenters (1, 2, 7, 15, 18). A sharp dose fall-off outside the target volume means high selectivity and lower complication rates. In stereotactic radiosurgery, the term "conformality" is used to define how much or what percentage of the target is covered by the isodose line and "selectivity" is used to define how well the isodose line fits the target shape. Horstmann et al compared patients with vestibular schwannoma who were treated with and without APS. They reported that APS provides more conformal and selective treatment plans (2) In a similar study, Regis et al reported that the total treatment time was reduced by %53 and that conformity and selectivity were improved from 95% to 97% and 78% to 84% respectively in the treatment of vestibular schwannomas (18). Model U and C were compared in the treatment of cavernous sinus meningiomas (7). Kuo et al reported higher conformality, shorter treatment time (approximately 1 hour) and lower radiation dose in the optic chiasm (3.8 Gy and 5.3 Gy respectively) with Model C (7). Another important advantage of APS is the elimination of errors in setting stereotactic coordinates manually. Flickinger et al found an error rate of 8% in setting the



Figure 6: A picture from the monitor at the beginning of the treatment plan. The red line indicates the target and the yellow line shows 50% isodose (50% of the maximum dose) line produced by 3 shots. The yellow line indicates the active radiation field for the target. The green line shows the border that receives 20% of the maximum dose and it is generally used to observe the dose that the important structures receive. The coordinates of the third shot can be followed on the right box.

coordinates (for errors between 0.25 and 0.5 mm) before the second check. This number was reduced to 1 in 1392 after checks by two independent observers (3). APS sets the coordinates more accurately than the manual procedure since the system is sensitive to 0.1 mm. Model C and APS also provide lower radiation dose delivery to the operators and the extracranial regions of the patient (5). The patient couch automatically withdraws the patient 28 cm from the radiation focus between the shots to minimize unplanned radiation delivery. Kondziolka et al measured the sternal and gonadal dose fall-offs for trunnion and APS by using phantom. They reported lower radiation fall-off in sternal and gonadal regions with APS for the same treatment (5). As the operators enter the treatment room less frequently in Model C, they do not receive significant radiation (1). There are two limiting factors for APS use: extreme coordinate locations and patients with broad shoulders and short necks. Far lateral lesions (>40 mm from the midline of the frame) and inferior targets (lower than the level of pons) may not be reached in some cases (5). Treatment cannot be performed in these situations. APS positioners are located on each side of the head and just above the shoulders. Sometimes it may not be possible to place the patient's head to the APS because the broad shoulders can hit the positioners. We prefer to treat the patient with the trunnion mode in such cases.

GAMMA PLAN 4C

Gamma Plan is the software used in treatment planning. The latest version is Gamma Plan 4C and it has important advantages to previous versions. The latest technological developments are used in this software. Gazi University Gamma Knife Center is the first center to use Gamma Plan 4C in the world and there are currently only three centers using this software.

The three main features of Gamma Plan 4C are listed below:

1. Planning with stereotactic PET images (Figure 8).
2. Integrated electronic Schaltenbrand / Wahren stereotactic brain atlas (Figure 9).
3. Capability to use frameless images.

Another feature of the software is the system called "wizard". The last two versions have the wizard that is used to cover the target with shots

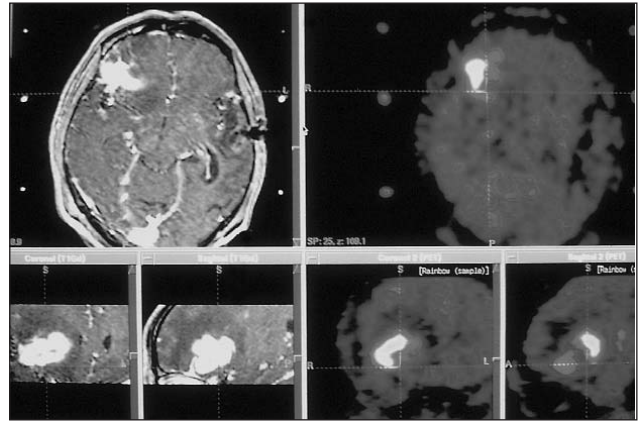


Figure 8: A treatment plan with PET and MR images.



Figure 9: Atlas structures applied on the patient's MR images.

automatically. We think that this system cannot be used alone for planning but it can help the operator in some conditions.

PET is used to evaluate the extent and degree of anaplasia and the prognosis via the metabolic activity of the tumor. It has limited use for determining anatomical details. Efficiency of PET images in stereotactic brain biopsies is the background of the contribution of PET images to stereotactic radiosurgery (8, 9, 10, 11). Integration of PET to neurosurgical procedures may contribute to a better management of brain tumors, either by optimizing their delineation or by targeting the aggressive areas of heterogeneous tumors (Figure 8). MR and CT do not provide sufficient data for the true margins of invasive tumors. They also have limited use in the differential diagnosis of tumor recurrences and radionecrosis in some cases. These cases constitute a big problem for the surgeon since target definition is vital for stereotactic radiosurgery. The contribution of PET images can be helpful for

better planning in such cases. In 2004, Levivier et al treated 57 patients with GKS using MR and PET images at the same time. The authors integrated PET because the tumor margins were not well-defined in MRI. They found 86% abnormal PET uptake and this information altered the MRI-defined tumor significantly in 69% of the targets (12).

The integrated electronic Schaltenbrand / Wahren stereotactic brain atlas is the second important feature of the Gamma Plan 4C (Figure 9). After introducing the AC-PC line to the computer and defining the midline, the software shows any structure of patient brain that the operator wants to see. The coordinates of these structures can also be obtained. GKS is accepted as a safe and effective way of treatment in functional neurosurgery (6, 16). We believe that this atlas has great advantages not only in functional stereotactic radiosurgery but also for safer treatment of tumors and AVM's that are located in basal ganglias.

The third advantage of the new version is the capability of using non-frame based images by fusing these images to frame-based images. Gamma Plan 4C enables co-registration of non-stereotactic tomographic data (MR, CT, PET) to a frame-based study for the same patient. Frame-based images act as a guide for this process. This feature helps to compare the images objectively on follow-ups and prevent unnecessary repetitions of CT, MR or PET scans.

CONCLUSION

Gamma Knife surgery has undergone numerous refinements, additions and modifications in recent years. Gamma Knife Model C and Gamma Plan 4C have significant advantages over earlier models. Efficient dose plans which allow treatment using more isocenters with smaller collimators, short treatment time, elimination of human errors in setting the coordinates, lower radiation dose for extracranial compartments and operators are the advantages of Gamma Knife Model C. Gamma Plan 4C provides more accurate target definition by using PET and the Schaltenbrand / Wahren stereotactic brain atlas.

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