Use of the Leksell gamma knife C with automatic positioning system for the treatment of meningioma and vestibular schwannoma

MARC LEVIVIER, M.D., PH.D., JOSE LORENZONI, M.D., NICOLAS MASSAGER, M.D.,
SALVADOR RUIZ, M.D., DANIEL DEVRIENDT, M.D., AND JACQUES BROTHI, M.D., PH.D.

Centre Gamma Knife of the Université Libre de Bruxelles; Department of Neurosurgery, Hospital Erasme; and Department of Radiation Therapy, Institut Jules Bordet, Brussels, Belgium

Object. The authors report their experience using the Leksell gamma knife C (GK-C) for the treatment of meningioma and vestibular schwannoma (VS).

Methods. In December 1999, the first commercially available clinical GK-C was installed at the Université Libre de Bruxelles (Erasme Hospital, Brussels, Belgium). In January 2000, the system was upgraded and equipped with the automatic positioning system (APS). Between February 2000 and February 2003, the APS-equipped GK-C was used to perform 532 radiosurgical treatments, including those in 97 meningiomas and 101 VSs.

Meningioma and VS represent 18 and 19%, respectively, of lesions in patients treated with GK-C at the authors' center. The mean number of isocenters per lesion was 9.5 (range 1–36): 18.1 (range 1–36) for meningioma and 12.8 (range 1–27) for VS. In 77.6% of the cases, the authors used a single helmet of collimators (55.5% in meningioma and 74.3% in VS). The most frequently used collimator size was 4 mm (46.7%). Whereas it was 4 mm in cases of VS (64.3%), it was 8 mm in cases of meningioma (41.6%). The APS could be used in 86% of the cases, either alone (79%) or in combination with trunnions (7%). There was a difference in the APS-based treatment success rate in meningiomas (85%) and VSs (94%). A significant difference was also noted in the conformity of the radiosurgical treatments between the two lesions.

Conclusions. The APS-equipped GK-C represents an evolutionary step in radiosurgery. It requires adjustments by the treating team for its specific limitations, which vary among indications, as exemplified by the differences inherent between meningioma and VS in this series.

KEY WORDS • gamma knife • radiosurgery • automatic positioning system • meningioma • vestibular schwannoma • benign tumor

Gamma knife surgery was originally developed by the late Leksell, and the device is now manufactured as the Leksell GK (Elekta Instruments A.B., Stockholm, Sweden). The latest model, GK-C, was introduced in 2000 and includes several new technological features. Among these is the APS, which allows robotic movements for positioning the patient's head at the isocenter.

Radiosurgery has become a widely used modality for benign extraaxial lesions, either for first-line treatment or residual/recurrent tumor after resection. Of these lesions, meningioma and VS represent the most common indications. Their management with GKS is safe and effective and has been well documented by many groups.^{2,8,15,17,20} We report on the treatment of cases of meningioma and VS in which we used the APS-equipped GK-C.

Abbreviations used in this paper: APS = automatic positioning system; GK = gamma knife; GK-C = GK model C; GKS = gamma knife surgery; PIV = prescription isodose volume; TV = tumor volume; TV_{PIV} = percentage of coverage of the TV; VS = vestibular schwannoma.

CLINICAL MATERIAL AND METHODS

In December 1999, the first commercially delivered clinical GK-C was installed at the Centre Gamma Knife, Université Libre de Bruxelles (Erasme Hospital, Brussels, Belgium). This installation followed the completion of a beta-test period with GK-C (upgraded from model B) in Krefeld, Germany.⁵ During January 2000, our unit was upgraded and equipped with the APS. In May 2001, the old APS was exchanged for a modified version (the new APS), mostly redesigned to reduce its dimensions in the part that is close to the patient's shoulders.

The technical and clinical experience reported here is based on a 3-year interval beginning when the first commercially available APS-equipped GK was fully operational in our center (February 2000–February 2003).

Use of the GK-C has been recently described by others.^{4,5,9} Briefly, a modified APS-compatible Leksell G frame (Elekta Instruments A.B.) is attached to the patient's head after administration of a local anesthetic and mild sedation (except in pediatric patients, in whom the entire procedure is performed after induction of general anesthesia). The base ring of the modified frame contains

a hole in the middle of lateral bars for bilateral attachment to the APS, as well as a groove on the anterior part of the right bar for fitting the attachment of the gamma angle. We have used combined stereotactic magnetic resonance imaging and computerized tomography scanning in all patients. No other imaging modalities were used in cases involving meningioma and VS; however, stereotactic digital angiography was undertaken to assess vascular lesions, and metabolic data obtained by conducting stereotactic positron emission tomography was used in selected cases.^{11,12} The dosimetry plan was created using Leksell GammaPlan (release 5.X), in which the wizard function was used and completed manually in most cases. Multiple isocenters or shots were required to optimize the conformity and selectivity of the radiosurgical treatment. The GK-C-based radiosurgical treatment can be performed either with the aid of APS or in manual mode by using trunnions such as those in previous models of the GK. The APS can be used in combination with the manual administration of some shots in the same patient (mixed mode). The goal of planning was always to use the APS, except when there was a period of known technical failure and when it was unavailable. In addition to technical failure, however, the APS could not be used, although available, in the following three instances (these represent the limitations of the APS): 1) when GammaPlan anticipated (and further test runs confirmed) collisions in the helmet; 2) when there was insufficient space between the patient's shoulders and the APS; and 3) when coordinate(s) of the target(s) were too extreme to be reached using the APS. In only these cases were treatments then converted to the mixed mode or trunnion mode. Once the radiosurgical plan is finalized, it is exported to the control console computer and checked by the physicist. The patient is then placed comfortably on the couch in the GK-C unit, the frame is attached to the APS (in the determined docking position), and a position and collision test run is performed by the physicist and one physician of the team. The APS-based treatment allows the administration of a series of multiple shots (called a run) in a sequential automated session, without any member of the team entering the room. The coordinates of each shot are set by the robotic functions of the APS while the patient is "defocused" from the radiation unit. Thus, it is assumed that GammaPlan should plan one run for all shots performed with the same helmet of collimators and with the same gamma angle (that is, in the same docking position), provided that the distance between two shots is not too long. When shots are performed in trunnion mode, the left and right components of the APS must be removed and replaced by the same trunnions bars used in older models of the GK. When irradiation is completed, the stereotactic frame is removed and the patient leaves the unit.

Clinical and treatment data were prospectively collected in all patients. When relevant, the data obtained in cases of meningioma and VS were compared using commercially available statistical software (version 3.02; GraphPad Prism, San Diego, CA).

RESULTS

A total of 682 lesions were treated successfully in 532 treatment sessions (some patients underwent multiple

GKS sessions, whereas others with multiple lesions sometimes underwent treatment in one session). The treatment indications are presented in Fig. 1. Meningiomas (97 lesions) and VS (101 lesions) represent 18 and 19% of the treatment-related indications, respectively.

Characteristics of Meningioma and VS

Meningiomas. There were 97 treatments for meningiomas (110 lesions [nine patients with multiple lesions, treated in one session]). Three additional patients with meningiomas were scheduled for GKS, but the treatment was aborted after frame placement and image acquisition. In two of these patients multilobular extension had developed which was considered incompatible with radiosurgery. Treatment of the third patient was postponed because of APS-related failure during the test run; it was considered that treatment could not be optimally performed using trunnions.

Forty-seven patients with meningiomas underwent GKS as their first treatment: 34 postoperative residual tumors, 15 recurrent lesions, and one that could not be removed surgically. Seventy percent of the lesions were located at the skull base (supra- or infratentorial), and 26% were located at the convexity (cerebral or cerebellar hemispheres). The mean TV was 5.07 cm³ (range 0.13–19.8 cm³). The mean prescription isodose was 13.4 Gy (range 12–16 Gy) at the 50% isodose (range 40–55%), and the mean PIV was 7.35 cm³ (range 0.23–31.5 cm³).

Vestibular Schwannomas. There were 101 VSs (16 Grade I, 29 Grade II, 42 Grade III, and one Grade IV [according to the Koos grading scale]¹⁰ and 14 evolutive postoperative residual lesions). Hearing was assessed using the Gardner–Robertson classification³: Class I hearing was present in 16 patients, Class II in 28, Class III in 41, Class IV in one, and Class V in 14. Nine patients presented with some degree of facial nerve weakness. In six of these patients, it corresponded to a postoperative deficit; the three others had not undergone previous surgery and presented with Class II facial function, according to the House–Brackmann classification.⁷

The mean volume of the treated lesions was 1.44 cm³ (range 0.01–7.5 cm³). The mean prescription isodose was 12.2 Gy (range 12–14 Gy) at 50% (range 50–55%), and the mean PIV was 1.72 cm³ (range 0.02–9.1 cm³).

Evaluation of the APS-Equipped GK-C

In the entire series, the mean number of isocenters or

Fig. 1. Pie chart showing indications for 532 GK-C treatments between February 2000 and February 2003. CNS = central nervous system.

shots used to treat a lesion was 9.5 (range 1–36). Because the GK-C can be used with helmets of collimators of four different sizes, a lesion can be treated using a single helmet or the combination of two, three, or four helmets. Overall, the mean number of helmets used per lesion was 1.2. In 77.6% of the cases, all isocenters for the treatment of a single lesion were performed using only one helmet of collimators; two helmets were used in 21.3%, and we rarely used three (0.9%) or four different helmets (0.3%) to treat a single lesion. Regardless of the number of helmets, the frequency of use of the four different helmets with respect of the size of their collimators was: 4-mm collimators (46.7%), 8-mm collimators (37.6%), 14-mm collimators (10.1%), and 18-mm collimators (5.6%).

The data varied, however, when comparing meningioma and VS. The number of isocenters used to treat a lesion was higher in cases of meningioma (mean 18.1, range 1–36) than VS (mean 12.8, range 1–27) (unpaired t-test, $p < 0.0001$). The lesions were treated using a single helmet of collimators in 55.5% of meningioma compared with 74.3% of the VS; there was a significant difference between single and multiple helmet use in meningioma and VS (Table 1; Fisher exact test, $p = 0.006$). Additionally, we used larger collimators to treat meningioma than VS (Table 2; chi-square test for independence = 33.22, 3 df, $p < 0.0001$).

For the 532 sessions, treatment was successfully completed using the APS only in 79%, APS and trunnions (mixed mode) in 7%, and trunnion only in 14%. Thus, to some extent, use of the APS alone was not possible in 21% of the treatments. In the non-APS group, its use was not possible because of technical failure and its unavailability in 35%; in the other cases, the APS could not be used, although it was available, because of its limitations (collisions in the helmet in 37.5%, incompatibility with the patient's shoulders in 10%, and coordinates outside of the APS range in 52.5% of cases).

Again, these data varied between the two lesions. Indeed, it was possible to treat VS entirely with APS only in 90%, compared with 76% in meningioma (Fisher exact test, $p = 0.009$). The reasons for using trunnions despite APS availability, also differed between lesions (Table 3). It is worth noting that some of these limitations have been solved, at least for the treatment of meningioma and VS, with the upgrade of the APS. Indeed, with the new APS, we did not encounter any more limitations due to the patients' shoulders.

Radiation Conformity

The conformity of the radiosurgical planning dose was

TABLE 1
Number of helmets of collimators used for the treatment of individual lesions

Lesion Type	No. of Lesions (%)			
	1 Helmet	2 Helmets	3 Helmets	4 Helmets
meningioma	61 (55.5)	43 (39.1)	5 (4.5)	1 (0.9)
VS	75 (74.3)	26 (25.7)		

TABLE 2
Size of collimators used for the treatment of individual lesions

Lesion Type	No. of Lesions (%)			
	4 mm	8 mm	14 mm	18 mm
meningioma	62 (37.3)	69 (41.6)	25 (15.1)	10 (6.0)
VS	81 (64.3)	43 (34.1)	1 (0.8)	1 (0.8)

evaluated using the ratio between the PIV and the TV.¹⁸ To assess further the TV that is actually covered by the PIV, we also recorded TV_{PIV},¹⁴ and we calculated a conformity index by dividing these two values (conformity index = [PIV/TV ratio]/TV_{PIV}). In meningiomas, the mean PIV/TV ratio was 1.59 (range 1.11–6.62) and the mean TV_{PIV} was 98% (range 80–100%); the mean calculated conformity index was 1.63 (range 1.15–6.62). In VS, the mean ratio was 1.28 (range 1.10–2.13), and the mean TV_{PIV} was 99% (range 92–100%); the mean calculated conformity index was 1.30 (range 1.11–2.13). We found statistically significant differences for the conformity of treatment between meningioma and VS (unpaired t-test, $p < 0.0001$, < 0.001 , and < 0.0001 , for the ratio, TV_{PIV}, and conformity index, respectively).

DISCUSSION

The GK-C represents the latest development in GKS. One of its major features is the sophisticated computer-based control of treatment parameters and process; an additional feature is robotics for the automatic positioning of the target in the irradiation unit. Indeed, the previous prototypes and models used the mechanical human-based setting of the stereotactic coordinates of each isocenter, according to the arc and target-centered principles developed by Leksell.¹³ Thus, the GK-C should allow the user to organize more sophisticated treatment plans by using an increased number of smaller shots, and to deliver the stereotactic irradiation more efficiently and with less human intervention. The world-wide clinical experience with the GK-C is still limited, although treatment parameters have changed at those centers at which earlier models of the GK were replaced by the GK-C equipped with APS.^{6,16} Although it is beyond the scope of this study to perform a metaanalysis, one characteristic found in our series is the use of a higher number of shots and smaller-sized collimators compared with those required with previous versions of the GK.

The data varied, however, based on the treatment-related indications, reflecting different parameters related to

TABLE 3
Limitation of APS requiring use of trunnions

Lesion Type	No. of Lesions (%)		
	Patient's Shoulders	Collision in Helmet	Outside APS Range
meningiomas	2 (11.8)	4 (23.5)	11 (64.7)
VS	2 (40)	2 (40)	1 (20)

the location, volume, and the shape of the target volume. This is exemplified by the comparison between the treatment parameters required for meningioma and VS. In contrast to VS, meningioma usually presents with larger volumes, more complex shapes, or more difficult and variable anatomical locations, requiring more complex treatment planning. Additionally, it is assumed that a higher number of shots of smaller collimator size should lead to better conformity and specificity of targeting. Although various indices may be used to evaluate the conformity of a radiosurgical plan,⁶ we found significant differences between meningioma and VS when using different measures of conformity. This may be due to complex interactions between the quality of the treatment plan and the intrinsic characteristics of the lesion. As is the case in open surgery, one cannot evaluate the human strategies and decisions that may bias the radiosurgical approach to meningioma compared with VS. For example, many GKS-treated meningiomas are skull base lesions for which some area of voluntary overtreatment in nonfunctional tissue (the bone of the skull base, for example) may be harmless, although the conformity of treatment of those lesions looks poorer. In specific indications, such as VS, it may be easier to simulate accurately and compare different treatment strategies performed with the GK-C.¹⁶ Whether this new technology will translate into better clinical outcome is unknown, and our series is too small and the follow-up period too short to allow for an evaluation of this issue.

The assumption in using the GK-C is that the treatment could be performed with APS and a minimum number of runs, limiting human interventions. This implies that the APS is technically functional and that there are no limitations to its use. Even when the APS cannot be used, however, the treatment can be completed manually by using trunnions, as in the previous GK models. Even a mixed-mode treatment, combining shots performed with APS and those performed with trunnions, may be planned if all isocenters are not treatable using the APS. Altogether, we found limitations with APS in 21% of the cases, due to technical failure (that is, the APS was not working properly and could not be used at all) in more than one third of these cases. The robustness of the system, however, greatly improved over time. Indeed, most of the technical failures occurred with the old APS, and since the installation of the new one, its technical failure has been infrequent. The other occasions when we could not use the APS (although it was technically functional) represent the limitations intrinsic to the system (collisions in the helmet, insufficient space between the patient's shoulders and APS, and coordinates too extreme to be reached with APS). These limitations are indication dependent, and they vary according to the characteristics of the treated lesions. This is illustrated by the greater degree of difficulty when using the APS only to treat meningioma (trunnions were required in 24% of the treatments) compared with VS (trunnions used only in 10% of treatments). The possibility of successfully using the APS only increased over time, especially after installation of the new APS. This is certainly due to both the learning curve (mostly optimization of frame placement, and better handling of the APS) and the increased robustness/design refinement of the system. This latter issue is exemplified by the fact

that the distance between patient's shoulders is no longer limited by the new APS.

Motorized positioning of the target at the isocenter saves time compared with earlier models of the GK in which the stereotactic coordinates had to be set manually on both sides of the frame.¹⁶ This is even more significant when multiple shots of the same collimators are applied because, for each treatment run, the APS changes the coordinates in a defocus position. During that change of coordinates, the couch and the helmet are only partially withdrawn from the GKS unit, the doors of which remain open, and thereafter the couch moves back into the radiation unit. The time saved by the motorized manipulations is counterbalanced, however, by the tendency to require more shots of smaller size, which increases the total time of irradiation. It has been claimed that the GK-C may be safer in terms of protection from radiation because the shuttle dose is lower.^{4,5,9} Our ongoing evaluation of the radiocarcinogenic risk, based on phantom and in vivo measurements with GK-C shows, however, that although not apparently a major health problem, it should be kept in mind that increasing the numbers of shots to achieve better conformity also leads to a higher effective dose delivered to the patient.¹⁹ Similarly, Bradford, et al.,¹ have reported epilation at the top of the head in two patients with VS after undergoing fractionated GK-C-based radiosurgery. They found that the use of the APS increased the transit dose approximately 5 and 15% for a distance greater than 12 and 20.4 cm, respectively, and concluded that for treatments involving a large number of shots (> 50), off-target doses greater than 8 Gy were possible.

CONCLUSIONS

The APS-equipped GK-C represents a progressive step in radiosurgery. The majority of patients can be treated with the APS, whose design and robustness have improved over time. The system requires adjustments by the treating team to accommodate its specific limitations, which are compensated for by its increased quality and safety. Its limitations are dependent on the lesion to be treated. This was evidenced by the differences in treatment parameters between meningioma and VS, which represent the two benign tumors most frequently treated with radiosurgery. Automatic positioning system-equipped GKS allows treatment plans involving a higher number of isocenters and better conformity, especially in difficult target volumes. Further clinical experience is needed to determine the effect of the GK-C on improving clinical results.

Disclosure

The Centre Gamma Knife of the Université Libre de Bruxelles is an official reference and training center of Elekta A.B., for the GK-C. None of the authors has financial interests in this device or other Elekta products.

References

1. Bradford CD, Morabito B, Shearer DR, et al: Radiation-induced epilation due to couch transit dose for the Leksell gamma knife model C. *Int J Radiat Oncol Biol Phys* 54:1134–1139, 2002

Leksell gamma knife for meningioma and schwannoma

2. Flickinger JC, Kondziolka D, Niranjan A, et al: Results of acoustic neuroma radiosurgery: an analysis of 5 years' experience using current methods. **J Neurosurg** **94**:1–6, 2001
3. Gardner G, Robertson JH: Hearing preservation in unilateral acoustic neuroma surgery. **Ann Otol Rhinol Laryngol** **97**: 55–66, 1988
4. Goetsch SJ: Risk analysis of Leksell Gamma Knife Model C with automatic positioning system. **Int J Radiat Oncol Biol Phys** **52**:869–877, 2002
5. Horstmann GA, Schöpgens H, van Eck AT, et al: First clinical experience with the automatic positioning system and Leksell gamma knife Model C. Technical note. **J Neurosurg (Suppl 3)** **93**:193–197, 2000
6. Horstmann GA, Van Eck AT: Gamma knife model C with the automatic positioning system and its impact on the treatment of vestibular schwannomas. **J Neurosurg (Suppl 5)** **97**:450–455, 2002
7. House JW, Brackmann DE: Facial nerve grading system. **Otolaryngol Head Neck Surg** **93**:146–147, 1985
8. Kondziolka D, Levy EI, Niranjan A, et al: Long-term outcomes after meningioma radiosurgery: physician and patient perspectives. **J Neurosurg** **91**:44–50, 1999
9. Kondziolka D, Maitz AH, Niranjan A, et al: An evaluation of the Model C gamma knife with automatic patient positioning. **Neurosurgery** **50**:429–431, 2002
10. Koos WT, Spetzler RF, Lang J: **Color Atlas of Microneurosurgery: Microanatomy, Approaches and Techniques**, ed 2. New York: Thieme, 1993
11. Levivier M, Wikier D, Goldman S, et al: Integration of the metabolic data of positron emission tomography in the dosimetry planning of radiosurgery with the gamma knife: early experience with brain tumors. Technical note. **J Neurosurg (Suppl 3)** **93**:233–238, 2000
12. Levivier M, Wikler D Jr, Massager N, et al: The integration of metabolic imaging in stereotactic procedures including radiosurgery: a review. **J Neurosurg (Suppl 5)** **97**:542–550, 2002
13. Maitz A, Flickinger JC, Lunsford LD: Gamma knife technology and physics: past, present, and future, in Lunsford LD, Kondziolka D, Flickinger JC (eds): **Gamma Knife Brain Surgery. Progress in Neurological Surgery**. Basel: Karger, 1998, Vol 14, pp 5–20
14. Paddick I: A simple scoring ratio to index the conformity of radiosurgical treatment plans. Technical note. **J Neurosurg (Suppl 3)** **93**:219–222, 2000
15. Prasad D, Steiner M, Steiner L: Gamma surgery for vestibular schwannoma. **J Neurosurg** **92**:745–759, 2000
16. Régis J, Hayashi M, Porcheron D, et al: Impact of the model C and Automatic Positioning System on gamma knife radiosurgery: an evaluation in vestibular schwannomas. **J Neurosurg (Suppl 5)** **97**:588–591, 2002
17. Régis J, Pellet W, Delsanti C, et al: Functional outcome after gamma knife surgery or microsurgery for vestibular schwannomas. **J Neurosurg** **97**:1091–1100, 2002
18. Shaw E, Kline R, Gillin M, et al: Radiation Therapy Oncology Group: radiosurgery quality assurance guidelines. **Int J Radiat Oncol Biol Phys** **27**:1231–1239, 1993
19. Simon S, De Smedt F, Vanderlinden B, et al: Radioprotection of patients treated with Leksell Gamma Knife C: evaluation of the radiocarcinogenic risk based on phantom and in-vivo measurements. **Proc 11th Int Meeting Leksell Gamma Knife Soc**:55, 2002 (Abstract)
20. Stafford SL, Pollock BE, Foote RL, et al: Meningioma radiosurgery: tumor control, outcomes, and complications among 190 consecutive patients. **Neurosurgery** **49**:1029–1038, 2001

Manuscript received March 17, 2003.

Accepted in final form April 14, 2003.

Funding for this work was provided by Fonds National de la Recherche Scientifique, Loterie Nationale, and Ministère de la Politique Scientifique (Belgium).

Address reprint requests to: Marc Levivier, M.D., Ph.D., Department of Neurosurgery and Gamma Knife Center, Université Libre de Bruxelles–Hospital Erasme, 808, route de Lennik, B-1070 Brussels, Belgium. email: Marc.Lvivier@ulb.ac.be.