OBJECTIVE: The results of radiosurgical treatment of acoustic neuromas have improved by reducing the tumor marginal doses. We report relatively long-term follow-up results (>5 yr) for patients who underwent low-dose radiosurgery.

METHODS: We treated and followed 51 consecutive patients with unilateral acoustic neuromas who were treated from January 1994 to December 1996 by gamma knife radiosurgery at low doses (≤12 Gy to the tumor margin). The average age of the patients was 55 years (range, 32–76 yr). The treatment volume was 0.7 to 24.9 cm³ (median, 3.6 cm³). The marginal radiation dose was 8 to 12 Gy (median, 12 Gy), and the follow-up period ranged from 18 to 96 months (median, 60 mo).

RESULTS: Clinical tumor growth control (without tumor resection) was achieved in 96% of patients, and the 5-year tumor growth control rate was 92%. Hearing was preserved in 59% of those with preradiosurgical hearing preservation (Gardner-Robertson Classes 1–4), and improvements (>20 dB of improvement) were noted in 9% of the patients with any hearing. Hearing was preserved at a useful level (Gardner-Robertson Classes 1 and 2) in 56% of patients. Although preexisting trigeminal neuropathy worsened in 4% of the patients, our patients did not experience new facial palsies or trigeminal neuropathies after radiosurgery. Facial spasm occurred in 6% of the patients, and intratumoral bleeding occurred in 4% of patients.

CONCLUSION: Low-dose radiosurgery (≤12 Gy at the tumor margin) can achieve a high tumor growth control rate and maintain low postradiosurgical morbidity (including hearing preservation) for acoustic neuromas.

KEY WORDS: Acoustic neuroma, Low dose, Radiosurgery, Vestibular schwannoma

Radiosurgery is rapidly becoming a useful treatment for acoustic neuromas. Recently, the tumor marginal dose has been shown to cause neurological complications after radiosurgery. In patients treated with an average marginal dose of 16 Gy, facial palsy occurred in 21%, facial numbness occurred in 27%, and decreased hearing was noted in 49% (1). With reductions in the marginal dose, the frequencies of facial and trigeminal neuropathies have been declining (1, 9). We report the treatment results of low-dose radiosurgery (≤12 Gy) for acoustic neuroma patients. Our results, which are based on relatively long follow-up periods (>5 yr), evaluated the use of lower radiation doses than reported previously.

PATIENTS AND METHODS

We evaluated 56 consecutive patients with unilateral acoustic neuromas treated between January 1994 and December 1996 by gamma knife radiosurgery (GKS). Four patients were treated with 13 to 14 Gy at the tumor margins and were excluded from this study. Fifty-two patients were treated with low-dose radiosurgery (≤12 Gy). Among these 52 patients, one patient was lost to follow-up, and 51 patients were successfully followed. Two patients had a short follow-up period because of tumor resection at 18 and 26 months after GKS. The other patients could be followed for more than 60 months, and the follow-up period ranged from 18 to 96 months (median, 60 mo). The mean age of the patients was 55 years (range, 32–76 yr); 19 patients were men, and 32 patients were women. Nine patients had undergone previous operations for their tumors (17.6%; with diagnoses based on pathological findings), whereas the other 42 patients were diagnosed by magnetic resonance imaging. Radiosurgery was performed using a gamma knife unit (Elekta Instruments, Norcross, GA). Stereotactic magnetic resonance imaging was obtained for the dose...
The dose plan was performed according to the KULA system (Elekta Instruments) from January 1994 to July 1994; thereafter, the GammaPlan (Elekta Instruments) was used for dose planning. The intracanalicular tumor was measured using the diameter at the internal auditory canal, and the tumor extending into the cerebellopontine angle was measured at the diameter of the extracanalicular portion. The mean tumor diameter varied from 5.2 to 32.7 mm (median, 18.8 mm). The tumor volume varied from 0.7 to 24.9 cm³ (median, 3.6 cm³). The marginal dose varied from 8 to 12 Gy (median, 12 Gy). The dose for the tumor was selected according to the tumor diameter; in small tumors, we used 12 Gy for the tumor margins, and in large tumors (mean diameter >25 mm), we decreased the dose to between 8 and 11 Gy, depending on the specific tumor size (Fig. 1). In two patients with mean tumor diameters of 32.7 and 36.3 mm, we used 8 Gy for the tumor margins.

Hearing evaluations were possible in all patients before radiosurgery, and the Gardner-Robertson classification system was used for evaluation (4). Before GKS, 9 patients were in Class 1 (18%), 11 were in Class 2 (22%), 14 were in Class 3 (27%), 4 were in Class 4 (8%), and 13 were in Class 5 (25%). Facial palsy was evaluated according to the House-Brackmann grading system (6); seven patients (14%) sustained facial palsy before GKS and, among them, six patients had such palsies because of previous surgeries, and one patient had palsy attributed to the acoustic neuroma. The House-Brackmann grades were as follows: one patient was Grade 2, one was Grade 3, four were Grade 4, and one was Grade 5. The patients with postoperative facial palsy had severe facial palsy, with Grades 3 to 5 in all patients.

Flickinger et al. (1) described tumor growth as 1 mm of tumor growth in two directions or 2 mm of tumor growth in one direction. They also determined clinical tumor growth control by whether surgery was necessary or not, because transient swelling of acoustic neuromas sometimes occurred. We evaluated tumor growth control using the same criteria as Flickinger et al. (1), and we also determined tumor growth control as the stabilization of the tumor size at the final follow-up.

**RESULTS**

**Tumor Size**

The tumor sizes decreased in 34 patients (66.7%), remained stable in 10 patients (19.6%), and increased in 7 patients (13.7%) (Fig. 2). In the patients who had operations before GKS, tumor growth occurred in 21%, whereas such growth only occurred in 11% of patients of patients who had not had previous operations. Among the patients with tumor growth, four patients were followed without further treatment, and two patients (4%) underwent resections. At the time of final follow-up for patients with tumor growth, in two patients the tumor was still growing compared with previous images obtained 60 months after GKS, and in two patients the tumor was still growing 72 months after GKS. One patient was retreated with radiosurgery. Among the patients undergoing reoperation, one patient had an operation 18 months after GKS because of tumor enlargement, and another patient underwent an operation 60 months after GKS because of intratumoral bleeding. Our tumor growth control rate was 86.3%, and the actuarial 5-year tumor growth control rate was 92% in all follow-up patients (Fig. 3). Our clinical tumor growth control (without surgery) was 96%. Progression of facial numbness in one patient prompted resection of the tumor 26 months after GKS, although the tumor had decreased in size. This patient was operated on at another institution without our approval. One patient with tumor growth was treated again by GKS 24 months after the initial GKS. In this patient, the first treatment was performed using a marginal dose of 12 Gy, and the second treatment was performed using a tumor marginal dose of 14 Gy. This patient was followed for 66

**FIGURE 2.** Serial contrast-enhanced magnetic resonance images obtained in a 67-year-old woman with a left acoustic neuroma. She had a tumor volume of 0.85 cm³ and underwent radiosurgery with 12 Gy at the tumor margins. Images were obtained at the time of treatment (A), 2 years after treatment (B), and 6 years after treatment (C). Her hearing level was 48 dB before radiosurgery and 51 dB 6 years after radiosurgery.
months; the tumor did not increase in size, and the preexisting seventh and eighth cranial nerve palsies caused by previous operations did not worsen. In addition, no new neurological deficits developed after GKS.

**Hearing**

We evaluated 47 patients for hearing function. Among the hearing preservation noted (Gardner-Robertson Classes 1–4) in 34 patients before GKS, improvements (>20 dB improvement) were achieved in 3 patients (9%), whereas hearing was unchanged in 17 patients (50%) and deteriorated (>20 dB deterioration) in 14 patients (41%). Among the 18 patients with useful hearing before GKS (Gardner-Robertson Classes 1 and 2), 10 patients (56%) were able to maintain useful hearing. The hearing deterioration occurred 6 to 36 months (mean, 19.8 mo) after GKS.

**Facial and Trigeminal Nerve Function**

No patients developed facial palsy after radiosurgery. Trigeminal neuropathy was present in six patients (11%) before radiosurgery and, among them, two patients (4%) experienced a worsening of their neuropathies (in one patient, the deterioration of trigeminal neuropathy was caused by tumor growth, whereas in the other, it was caused by radiation injury after GKS). The other patients had the same trigeminal neuropathy without improvement. However, no new trigeminal neuropathies developed after radiosurgery.

Facial spasms occurred in three patients (6%) after radiosurgery. This phenomenon occurred a mean of 21 months (range, 9–36 mo) after radiosurgery. Among the three patients, two experienced the disappearance of facial spasms a mean of 39 months (range, 30–48 mo) after radiosurgery. Another patient had facial spasms that continued for 72 months after radiosurgery.

**Complications**

Intratumoral bleeding occurred in two patients (4%) 60 and 80 mo after radiosurgery. One patient underwent an operation because of the progression of an intratumoral hematoma and deterioration of cerebellar ataxia (Fig. 4). In this patient, the bleeding from the hematoma wall was difficult to control intraoperatively, and the intratumoral hematoma could not be removed. Two months after the first surgery, a reoperation was performed, and the intracapsular hematoma was evacuated. However, regrowth of the intratumoral hematoma occurred with worsening cerebellar ataxia at the time of follow-up. The intratumoral hematoma was removed partially 2.6 years after the first operation. Another patient experienced a sudden onset of facial pain and revealed a small amount of intratumoral bleeding on magnetic resonance images. This patient was followed without clinical deterioration.

Hydrocephalus occurred in four patients (8%). One patient (2%) underwent a shunt operation before GKS, and three patients (6%) underwent shunt operations after GKS. Symptomatic radiation edema surrounding the brain did not occur in any patients.

**DISCUSSION**

Radiosurgery has a long history of use in treating acoustic neuromas. The first acoustic neuroma patient was treated in 1969 at Karolinska Hospital using a gamma knife unit (10). Norén et al. (15) reported performing 227 procedures at the Karolinska Hospital, with a minimum follow-up period of 12 months. They used 25 to 35 Gy for the periphery and gradually decreased this level to 10 to 15 Gy. Tumor growth control was achieved in 85% of the patients, and hearing preservation or slightly impaired hearing was noted in 77% of the patients. Facial palsy occurred in 16% of patients, and 4% of them experienced permanent deficits. Facial numbness occurred in 12% of the patients. This report represents the first...
known use of radiosurgery by a health institution to treat acoustic neuroma (15).

Linskey et al. (11) reported the early clinical experience in the United States; they achieved a tumor growth control rate of 97%, a hearing preservation rate of 62%, and a 1-year rate of developing new facial palsy of 30%. Trigeminal neuropathy was noted in 33% of the patients, whereas eight patients had perifocal edema. These authors used 16 Gy for the tumor margins. Konziolka et al. (9) reported 5-year follow-up results from the same institute as Linskey et al. (11) in 165 patients; 98% clinical tumor growth control was achieved. Flickinger et al. (1) concluded that the relationship between treatment dose and neuropathy was almost the same as that found by Konziolka et al. (9) and that a 13-Gy tumor marginal dose achieved the same tumor growth control as 15 Gy, but with lower postradiosurgical morbidity. Their tumor growth control was 91.0 ± 2.5%. Few patients experienced facial weakness (1.1 ± 0.8%), and 0% of those who received less than 13 Gy experienced facial palsy. Serviceable hearing was preserved in 73.5 ± 4.7% of the patients after 5 years. However, they also speculated that if the marginal dose was further reduced to 12 Gy or 11 Gy, hearing preservation would improve to 15 to 10%, respectively, and that the incidence of new facial numbness would decrease to 2.6% or 1.8%. They postulated that increasing the radiation dose correlated with an increased development of facial weakness and a decreased preservation of testable speech discrimination, although they mentioned that reducing the treatment dose resulted in a lower tumor growth control rate (1). However, their experience revealed 90.9% tumor growth control using less than 13 Gy for the tumor margin and 91.4% when using more than 14 Gy for the tumor margin; there was no statistical difference in the tumor marginal dose. Prasad et al. (17) treated patients using 13.2 ± 2.2 Gy for the tumor margins; 89% tumor growth control was achieved in patients who had previous operations and 94% tumor growth control in patients who did not have previous operations, along with 40% hearing preservation. Facial weakness occurred in 2% of patients, and new trigeminal neuropathy occurred in 3% of patients (17).

We performed tumor resections in three patients (6%): two patients required resections because of tumor progression, and one patient underwent an operation without our approval at another institution despite decreasing tumor size. We achieved clinical tumor growth control (without tumor resection) in 96% of patients, and the 5-year tumor growth control rate was 92%. These results are the same as those of Flickinger et al. (1) and Prasad et al. (17); decreasing the treatment dose to 12 Gy did not lessen tumor growth control (Table 1).

Several authors have discussed the tumor marginal dose and the postradiosurgical morbidity associated with GKS. Some authors reported a relationship between the treatment dose and the preservation of cranial nerve function (7, 13). However, others reported that no correlation was found between hearing preservation and tumor volume, nor between

| Series (ref. no.) | No. of patients | Method of radiosurgery | Median marginal radiation dose (Gy) | Median follow-up period (mo) | Tumor growth control (%) | Facial neuropathy (%) | Trigeminal neuropathy (%) | Hearing preservation (%) |
|------------------|-----------------|------------------------|----------------------------------|-----------------------------|------------------------|----------------------|-------------------------|-------------------------|
| Prasad et al., 2000 (17) | 153 GKS | 13 (9–20) | 51 | 92 | 2 | 3 | 65 |
| Ito et al., 2000 (7) | 125 GKS | 15.4 (12–25) | 37 | — | 16 | 25 | 58 |
| Suh et al., 2000 (21) | 29 Linac | 16 (8–24) | 49 | 94 | 32 | 15 | 26 |
| Flickinger et al., 2001 (1) | 190 GKS | 13 (11–18) | 30 | 91<sup>b</sup> | 1.1 | 2.6 | 74 |
| Foote et al., 2001 (2) | 149 Linac | 14 (10–22.5) | 36 | 93 | 29/5<sup>c</sup> | 29/2<sup>c</sup> | — |
| Petit et al., 2001 (16) | 47 GKS | 12 (10–15)/12 (7.5–14)<sup>d</sup> | 43.2 | 96 | 4 | 0 | 88 (G-R Classes 1–3) |
| Spiegelmann et al., 2001 (20) | 44 Linac | 14.6 (11–20) | 32 | 98 | 24 | 18 | 71 |
| Present study | 51 GKS | 11.7 (8–12) | 64 | 92<sup>b</sup> | 0 | 0 | 59 |

<sup>a</sup> GKS, gamma knife radiosurgery; Linac, linear accelerator; G-R, Gardner-Robertson.

<sup>b</sup> 5-year actuarial results.

<sup>c</sup> Before/after 1994.

<sup>d</sup> Previous operation/no previous operation.
central and marginal dose and the number of shots (22). Low-dose radiosurgery results for acoustic neuromas using a mean dose of 12.1 Gy for the tumor margins were reported by Hirato et al. (5) and Petit et al. (16) with good tumor growth control and a high rate of preserving cranial nerve function. In our experience, with marginal doses of 12 Gy, we were able to reduce the incidence of facial palsy to 0% and the incidence of facial neuropathy to 0% as well. Also, the seven patients treated with less than 12 Gy (one with 11 Gy, four with 10 Gy, and two with 8 Gy) also experienced tumor growth control (five patients had decreases in tumor size, and two patients had tumor sizes that were unchanged). We think that 8 to 12 Gy for the tumor margins, depending on the tumor size, may be an effective dose for acoustic neuromas.

Linear accelerator radiosurgery has also been developed recently. Suh et al. (21) treated 29 patients with acoustic neuroma with marginal doses of 16 Gy (median). A 5-year tumor growth control rate of 94% was achieved, and new trigeminal and facial palsy occurred in 15% and 32% of patients, respectively. Hearing disturbances occurred in 74%. Spiegelmann et al. (20) reported on 44 patients treated by linear accelerator radiosurgery, with a 98% tumor growth control rate and 71% hearing preservation. In their series, new facial neuropathy occurred in 24% of patients, and permanent facial palsy occurred in 8%. They used 15 to 20 Gy in 24 patients and 11 to 14 Gy in 20 patients for the tumor margins. They concluded that radiation neuropathy correlated significantly with radiation dose. Foote et al. (2) reported that tumor marginal doses above and below 10 Gy resulted in relative differences in tumor growth. In addition, they recommended 12.5 Gy for the tumor margins for maximum tumor control and minimal complications.

Fractionated stereotactic radiotherapy has been introduced to reduce hearing deterioration after radiosurgery. Song et al. (19) reported on the use of fractionated stereotactic radiotherapy in 31 patients with acoustic neuromas. These patients did not have tumor growth or facial palsy; two patients (6.5%) experienced trigeminal neuropathy, and 48% of the patients with hearing had preservation using these methods. Shirato et al. (18) also reported good hearing preservation and good tumor growth control by fractionated stereotactic radiotherapy. They compared 27 patients who had no treatment with 50 patients who received stereotactic radiotherapy. Clinical tumor growth control was achieved in 98%, and hearing preservation was the same as with the natural course of the disease. Meijer et al. (12) reported 91% tumor growth control and 66% hearing preservation after 5 years, 3% trigeminal neuropathy, and no facial neuropathy using both fractionated stereotactic radiotherapy and radiosurgery with low-dose treatment. Fuss et al. (3) reported excellent results for stereotactic fractionated radiotherapy for acoustic neuromas, with 97.7% tumor growth control after 5 years, 85% hearing preservation, no facial palsy, and only 1.9% new trigeminal neuropathy. Fractionated stereotactic radiotherapy is one option for preserving cranial nerve function. However, hearing dysfunction, facial sensory loss, or facial weakness still can occur after fractionated stereotactic radiotherapy. Furthermore, radiation therapy is not performed in the same way as radiosurgery. The results seem no different from those obtained with radiosurgery, although patients must be treated for a longer interval of time involving many hospital visits.

We noted facial spasms in three patients (6%) after radiosurgery. Two of the patients’ symptoms spontaneously disappeared, but one patient continued to have symptoms. The occurrence of facial spasm after GKS was previously reported to be between 2 and 10% (8, 14). We recognize that facial spasm is one complication after radiosurgery.

Intratumoral bleeding has not been reported as a radiosurgical complication of acoustic neuromas. However, two of our patients experienced intratumoral bleeding. In one patient, the operation was performed because of the growth of the mass and deterioration of cerebellar ataxia. The intraoperative findings revealed an intratumoral hematoma with neovascularization of the hematoma wall, and the histological findings revealed no malignancy. In these patients, the intratumoral bleeding was noted 60 and 80 months after radiosurgery. This finding demonstrates the need for long follow-up periods in evaluating complications in these patients. Hearing deterioration in our patients occurred within 3 years of treatment; this finding suggests that longer follow-up periods will not demonstrate increased deterioration rates in terms of hearing function.

CONCLUSION

Tumor growth control and hearing preservation are the treatment goals for small- to medium-sized acoustic neuromas. In addition, low-dose radiosurgery is an effective modality with low morbidity and a high degree of hearing preservation. In the future, we will need to examine treatment outcomes in terms of the patients’ quality of life after the use of different treatment modalities.

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Radiosurgery for Acoustic Neuromas

The authors have analyzed well the results of gamma knife surgical treatment of patients with small or medium-sized acoustic neuromas with a considerably long follow-up period (median follow-up, 64 mo). They used the tumor marginal radiation dose of 8 to 12 Gy (mean dose, 11.7 Gy). The dose that they used was less than the average marginal dose generally used in other centers. Neither facial nor trigeminal neuropathy was noted after the treatment, and hearing preservation was noted in 59% of the patients. This work suggests that the relatively low radiation dose is enough to control the growth of acoustic neuromas with minimal morbidity, but further follow-up of the patients might be required.

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During the past decade, significant changes have been implemented that have improved patient outcomes after vestibular schwannoma radiosurgery (4). Two technical advancements include the conversion from computed tomography to magnetic resonance imaging as the imaging database for dose planning and better dose-planning software, which allows exceptional conformity for these irregularly shaped targets. The most important change, however, is likely the reduction in tumor margin doses from 16 to 18 Gy to the currently used 12- to 13-Gy range. This article provides additional evidence that low-dose radiosurgery of vestibular schwannomas provides a high rate of tumor control with follow-up of up to 96 months (median, 5 yr). A comparison of recent reports of hearing preservation between patients who underwent radiosurgery (3, 6) with those who underwent stereotactic radiotherapy (1, 2, 5, 7, 8) shows comparable results, despite greater maturity in the radiosurgical data. Moreover, the risk of new tumor induction after radiotherapy is at least 10 times higher than the risk of radiation-induced neoplasms after radiosurgery (estimated risk, 1:1000 to 1:10,000). On the basis of these facts and in recognition that tumor growth control after vestibular schwannoma radiosurgery has been confirmed over many years, I see little rationale for the use of

This fear seems to be unsubstantiated by the present study and others like it. In general, growth indicating treatment failure tends to occur within the first couple of years after surgery. The risk of recurrence after more than 5 years seems to be minimal.

A new and important observation described in this article is that of intratumoral hemorrhage in two patients 5 and almost 7 years after treatment. Spontaneous hemorrhages in acoustic neuromas are exceedingly rare. A MEDLINE search of studies published between 1966 and 2003 produced six citations of articles describing a total of eight patients. Whether spontaneous hemorrhages in acoustic neuromas occur more frequently after radiosurgery cannot be determined on the basis of these two observations, which are the only ones reported after radiosurgery to date.

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When the first acoustic neuromas were treated with gamma knife radiosurgery in the late 1960s and early 1970s, it was assumed that these benign tumors would be insensitive to radiation, as would the adjacent cranial nerves. Consequently, a dose to the tumor periphery of 25 Gy or even higher was used. We now know that half of this dose will control the tumor growth in the vast majority of patients. The present study provides further support for the findings of other authors that a minimum dose of 12 Gy is enough to achieve a satisfactory (i.e., 96–97%) level of growth control together with low or even no incidence of facial and trigeminal neuropathy. The focus is increasingly on improving the preservation of hearing.

Some fear that this lower dose level, although beneficial in the short term, may carry greater risk of recurrence in the long term.
either hypofractionation or conventional fraction schedules for the treatment of patients with these benign tumors.

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These investigators report the results of radiosurgical treatment in 51 patients, the vast majority of whom were administered a tumor margin dose of 12 Gy for the management of acoustic neuromas. The patients were managed between 1994 and 1996 with median follow-up of 5 years. The authors found a high rate of tumor growth control and an approximately 60% chance of hearing preservation at the patient’s preexisting level. The authors contrast these data to that presented in earlier reports published in the late 1980s and early 1990s regarding the use of higher tumor margin doses. In that era, the rate of facial neuropathy was higher, and the rate of hearing preservation was lower. Many physicians have argued that morbidity has decreased as a result of the use of lower radiation doses. This contention is only partially true. Perhaps more important have been significant improvements in stereotactic imaging and dose planning. Simply put, for the past 10 years, radiation has been delivered more accurately to the tumor margin than it was previously. At a time when higher doses were used, most radiosurgical planning was facilitated by computed tomographic imaging. The use of this modality led to problems with identifying tumors in the auditory canal, evaluating the extracanalicular tumor on images that had marked petrous bone artifact, and lack of direct imaging in the coronal or sagittal planes. A trend toward the use of lower radiosurgical doses occurred when magnetic resonance imaging replaced computed tomography as the imaging modality of choice, and many began to use workstations that incorporated the use of imaging in dose planning. In my opinion, image quality has had as much to do with the success of radiosurgery as radiation dosage. At present, most centers use tumor margin doses of 12 to 13 Gy for patients with vestibular schwannomas. By doing so, rates of tumor growth control and cranial nerve function preservation have been high.

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