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Gamma Knife Radiosurgery for the Vestibular Schwannomas, Technical Considerations and Hydrocephalus as a Complication

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1. Introduction

Vestibular schwannomas are slow-growing, benign tumours. Microsurgery has been the standard treatment for vestibular schwannoma over the past 30 years. Following the introduction of stereotactic radiosurgery for the treatment of vestibular schwannoma in 1969, its increasing use worldwide had led to its acceptance by many as a safe and efficient alternative to microsurgery. The primary advantages of stereotactic radiosurgery are its safety in terms of morbidity and its high tumour control rate.

Because the cerebello-pontine angle is composed of many important cranial nerves and vessels, planning quality is expressed as various indices such as conformity or homogeneity that are regarded as being related to the development of complications. Improved technology and the development of the new gamma knife radiosurgery units—such as the automatic positioning system and the fusion technique in the gamma plan—increase the planning accuracy of the irradiated target area. However, the relationship with the course of the response of the tumour and the complication rate remains poorly understood. In this chapter, we will review how the high conformity indices contribute to the post-radiosurgery course of the disease by analysing the literature.

With regard to the complications of stereotactic radiosurgery (despite the many benefits that allow it replace microsurgery as a primary treatment modality), additional research is needed to reduce the complications that are associated with stereotactic radiosurgery in order to improve patient quality of life. Complications that are associated with stereotactic radiosurgery for vestibular schwannoma include hearing deficits, facial palsy, hydrocephalus, and brain stem damage, although the incidence of some of these conditions is much lower than with microscopic open surgery. We reviewed complications and their risk factors (with a particular emphasis on hydrocephalus) from our experience of gamma knife radiosurgery for the treatment of vestibular schwannoma.

Regarding hydrocephalus, this complication can occur at various stages during the natural course of a vestibular schwannoma. The reported incidence ranges from 3.7% to 15% of cases (Atlas et al., 1996; Litvack et al., 2003). Large vestibular schwannomas sometimes cause obstructive hydrocephalus; however, CSF malabsorption may be the cause of communicating-

type hydrocephalus. The hydrocephalus can develop as a complication of treatment using either gamma knife radiosurgery or microsurgery. However, the incidence, aetiological factors, mechanisms, and management of hydrocephalus following stereotactic radiosurgery and microsurgery are not well understood. We present a review of the incidence, characteristics and management experience of hydrocephalus in patients with vestibular schwannoma who were treated using gamma knife radiosurgery and compare these findings with those of patients who received microsurgery as the primary treatment.

2. Technical consideration of gamma knife radiosurgery for treating vestibular schwannoma

2.1 Conformity

Vestibular schwannomas are located in the cerebello-pontine angle, and in most cases, they extend into the internal acoustic foramen. Many functionally important structures such as the trigeminal, facial and acoustic nerves, arteries, and the brainstem are located around the tumour. Many of the hazards of microsurgery for vestibular schwannoma are related to the tumour's location. Damaging these structures during microsurgery is the most common cause of morbidity and mortality. Gamma knife radiosurgery should also take these structures into consideration. The principle underlying gamma knife radiosurgery is the concentration of high energy into the localised area of the lesion while sparing surrounding functional structures. Accumulated data have justified the use of gamma knife radiosurgery as the primary treatment of vestibular schwannoma without causing significant complications related to the damage of the important surrounding structures. Historically, many experts in this field have reduced the radiation dose without compromising the tumour control rate. A marginal dose of 12 or 13Gy is now accepted as the standard dose for controlling a tumour using gamma knife radiosurgery. However, although the intended marginal dose is similar, the planned radiation field can differ in its conformity and distribution of radiation. Several parameters have been proposed to describe the quality of the radiation plan. Aside from these parameters, one should consider that some specific structures are more vulnerable to even relatively low doses of radiation. Special somatic sensation fibres are regarded to be more vulnerable to external damage, including radiation, than are other cranial nerves. In this regard, hearing loss is a high concern when using gamma knife radiosurgery for treating a vestibular schwannoma.

To achieve maximum effectiveness, radiosurgery should deliver the highest permissible radiation to the target whilst reducing the surrounding radiation dose as rapidly as possible. To quantify this quality of planning, various conformity and sensitivity indices are used. Advances in the gamma knife radiosurgery unit—including the automatic positioning system, gamma plan, and (more recently) the new Perfexion system—provide higher accuracy and improved patient convenience and comfort. Hayashi et al. (Hayashi et al., 2006) introduced the concept of robotic micro-radiosurgery and demonstrated high accuracy in the planning of gamma knife radiosurgery.

A dose-volume histogram of the gamma plan that represents the three-dimensional dose distribution provides a measure of the quality of planning. The neurosurgeon or radiation oncologist who is responsible for the radiosurgery uses this dose-volume histogram to compare the conformity of the dose plan to concentrate the radiation dose at the target. However, there are no established standard parameters, and even the role for such

parameters in the control of the disease with gamma knife radiosurgery has not been clarified. The most commonly used parameter to quantify the dose distribution of the tumour and normal tissue is conformity. Various conformity indices have been proposed by many authors. The Radiation Therapy Oncology Group proposed several routine evaluation parameters for stereotactic radiotherapy plans, including the quality of coverage, the homogeneity index, and the conformity index (Feuvret et al., 2006; Nedzi et al., 1993). Paddick (Paddick, 2000) proposed an index based on the dose-volume histogram and volume analysis tools of the GammaPlan criticizing existing indices. Figure 1 shows the basic concept of the planning during radiosurgery, and Figue 2 typical dose-volume histogram with volume measurement in the GammaPlan. Here, we present several examples of parameters that are used in gamma knife radiosurgery in Table 1.

The role of these quality parameters in the complication and tumour control rates is not clear and may differ based on the disease. With regard to metastatic tumours, Woo et al. (Woo et al., 2010) reported that a high conformity dose plan was related with a poor tumour control rate. Nakamura et al. (Nakamura et al., 2001) studied 1,338 available artriovenous malformation patients who were treated with gamma knife radiosurgery and found that the conformity index was higher than in the linac surgery series, and the complication rate was not related to the conformity index. Beegle et al. (Beegle et al., 2007) studied 390 patients with regard to the issue of conformity and dose gradient in treating vestibular schwannoma and found no significant effect of these dosimetric parameters on cranial neuropathy. These authors found that tumour volume and dose were associated with an increased risk of facial weakness and facial sensory change (Beegle, et al., 2007). These disparate findings indicate that a standard index does not exist (Feuvret, et al., 2006).

It is interesting to note that the gradient index (which represents radiation dispersion outside of the target) is not related with the adverse radiation effect (Hayhurst et al., 2011). It is assumed that a marginal radiosurgery dose for treating vestibular schwannoma is sufficiently low to spare the surrounding cranial nerve and brain stem. The tumour control rate and hearing outcome are not significantly related to conformity indices of dose distribution within and surrounding the target volume (Massager et al., 2011). The outcome seems to be influenced more by the local radiation dose that is delivered to specific structures or volumes than by the global dose gradient (Massager, et al., 2011).

Although the complication rate is related to tumour size (but not to the conformity index), the relationship between the tumour control rate and the conformity index is not known. This is due to several factors. First, tumour size decreases during the prolonged times following gamma knife radiation therapy, and the response of a vestibular schwannoma following gamma knife radiosurgery in terms of genetic and pathological alterations is poorly understood. Secondly, most responsible neurosurgeons and radiation oncologists always apply the maximum effort to achieve a higher available conformity. Planning priority could differ according to various indications. Dose planning for treating vestibular schwannoma places high priority on the dose conformity whilst sparing the neighbouring facial nerves and brain stem, despite a slightly reduced coverage of the tumour. On the other hand, with regard to metastatic tumours, target coverage receives the highest priority (Lomax & Scheib, 2003). Lamax and Scheib (Lomax & Scheib, 2003) reported a median conformity index for vestibular schwannoma of 0.85 and a median target coverage of 92%, whereas for metastasis, these values were 0.67 and 100%, respectively.

Thus, it is difficult to evaluate the role of conformity in radiosurgery for treating vestibular schwannoma. Accumulated data from long-term follow-up studies are clearly needed. The effect regarding small vascular injuries due to radiosurgery remains poorly understood. There is general agreement that the size of the tumour is related to complications that are associated with the treatment. Hayhurst et al. (Hayhurst, et al., 2011) reported that adverse radiation effects were increased with target volumes that were greater than 2.1 cc; in addition, they reported a second peak at 5 cc. However, several authors reported positive treatment results even for large tumours (Iwai et al., 2003; Rowe et al., 2003a). In selecting a candidate for radiosurgery, tumour size should be a primary consideration. To prevent complications (in particular, facial nerve palsy), some authors recommend using a partial or subtotal microsurgical removal approach while applying special care to preserve the facial nerve, and this should then be followed by a secondary gamma knife radiosurgery (Fuentes et al., 2008; C. K. Park et al., 2006).

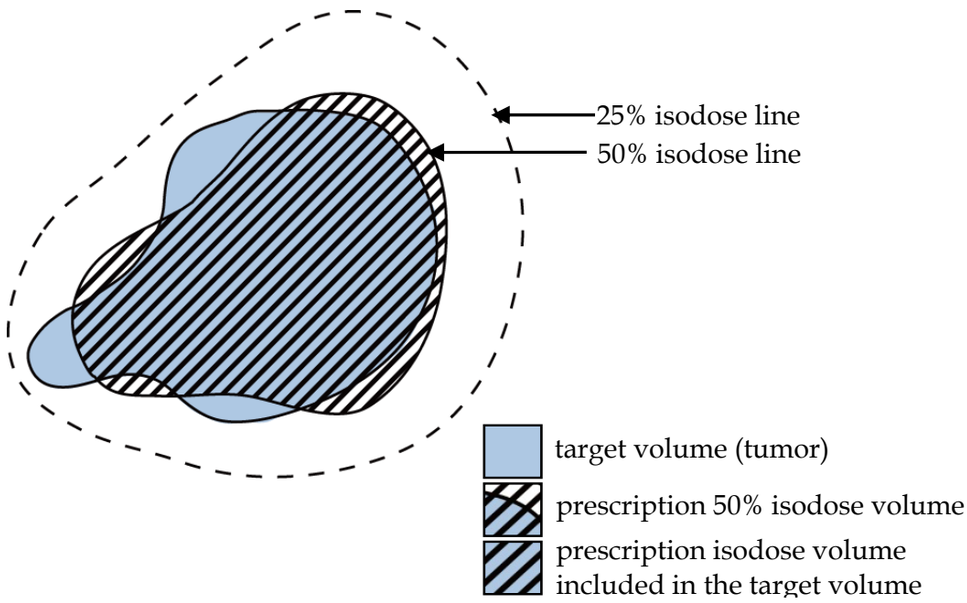


Fig. 1. Schematic drawing of planning of gamma knife radiosurgery of the tumour.

Conformity index of Paddick (Paddick, 2000): $\frac{(TV_{PIV})^2}{TV \times PIV}$
CI_{RTOG} (Shaw et al., 1993) = PIV/TV
Gradient index (Paddick & Lippitz, 2006) = $\frac{PIV_{25\%}}{PIV_{50\%}}$

CI_{RTOG}: conformity index of Radiation Treatment Oncology Group
TV: target volume
PIV: prescription isodose volume
TV_{PIV}: prescription isodose volume included in the target volume
$PIV_{25\%}$: prescription 25% isodose volume
$PIV_{50\%}$: prescription 50% isodose volume

Table 1. Examples of quality indices of radiosurgery.

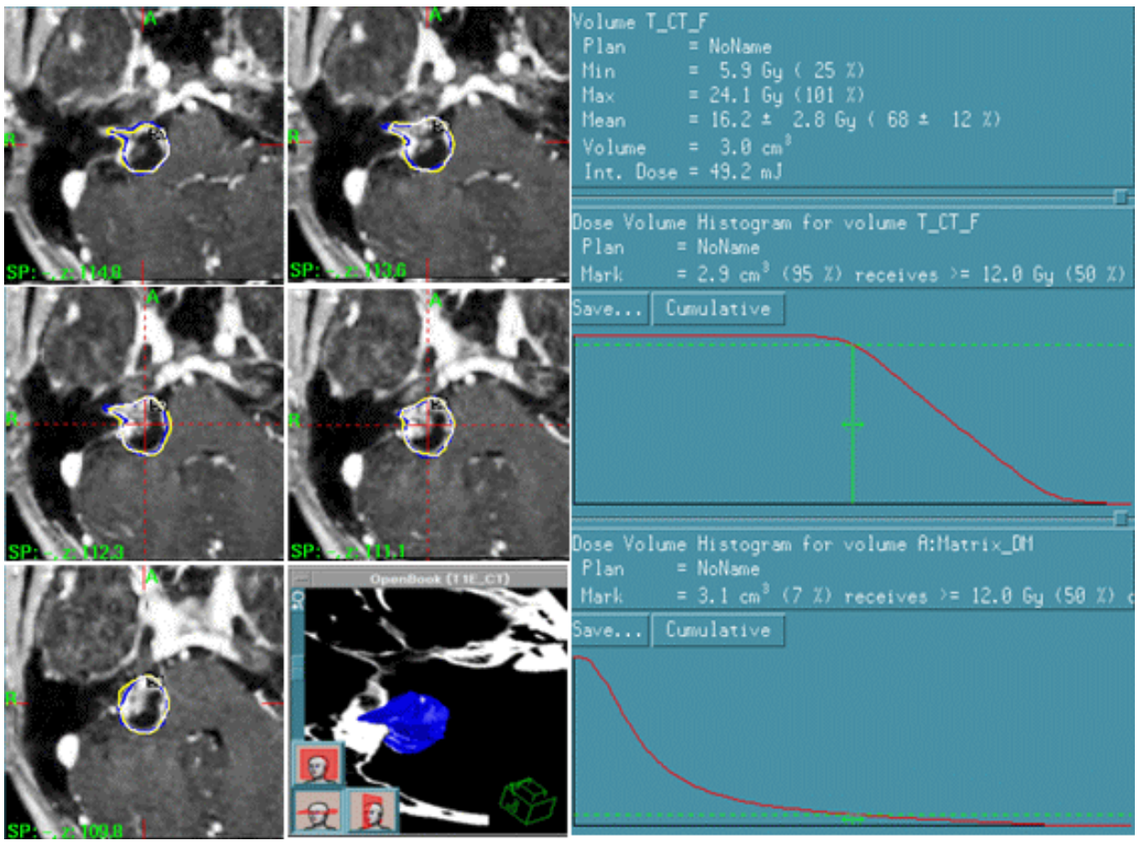


Fig. 2. Typical plan of gamma knife radiosurgery for treating vestibular schwannoma and the dose-volume curve. The prescription 50% isodose is 12 Gy. In this 53-year-old female patient, the target volume (tumour volume) was 2.9 cc, and 95% of this volume received more than 12 Gy. The total volume that received more than 12 Gy in the brain was 3.1 cc. The volume outside of the target area that received more than 12 Gy was 0.2 cc.

2.2 Hearing preservation

Hearing preservation is another important issue to consider in the treatment of vestibular schwannoma with either microsurgery or radiosurgery. The hearing preservation rate following microsurgery was reported to be 40-70% in patients with serviceable hearing (Betchen et al., 2005; Briggs et al., 2000; Samii et al., 2008; Samii & Matthies, 1997a, 1997b; Samii et al., 1997; Staecker et al., 2000). Hearing preservation is an important issue in gamma knife radiosurgery as well. As the experience with gamma knife radiosurgery has grown, the radiation dose has decreased. Currently, a marginal dose of 12 or 13 Gy is the standard dose for treating vestibular schwannoma. Regis et al. (Regis et al., 2008) reported a 60% hearing preservation rate in patients in a large study with a mean follow-up of 7 (minimum 3) years. These authors also mentioned that patients who were not treated using gamma knife radiosurgery lost an average of 9-39 dB compared with an average loss of 2 dB at 3 years following radiosurgery, which corresponds with a preservation of hearing functionality of 60-75%. Tamura et al. (Tamura et al., 2009) reported a 78.4% hearing preservation rate in Gardner-Robertson Class 1 patients. The probability of preserving functional hearing was higher in patients who had initial symptoms that were other than a

decrease in hearing, in patients who were younger than 50 years, and in those patients whose cochlea received a dose of less than 4 Gy during treatment. (Tamura, et al., 2009).

The mechanism that underlies hearing deterioration following gamma knife radiosurgery is not fully understood. Some of the mechanisms that have been proposed include a temporary expansion of the tumour in the canal, vascular insufficiency of the auditory system, the toxic dispersion of free radicals, among others (Chang et al., 1998; Regis, et al., 2008; Timmer et al., 2009; Wackym et al., 2010).

A tolerable dose for the cochlea has not been clearly established. However, several studies have proposed a threshold of 4 Gy for radiosurgery (Anker & Shrieve, 2009; Regis, et al., 2008; Timmer, et al., 2009; Wackym, et al., 2010). Keeping the cochlear dose below this threshold is therefore recommended. Combined imaging using a CT scan and MRI is helpful for identifying the intracanalicular boundary between the tumour and the cochlear structure. Plugging or sector occlusion strategies provide the steep drop out of the radiation dose that is applied to these structures. The potential for improved hearing following radiosurgery has also been reported. Narajan et al. (Niranjan et al., 1999) reported improved hearing in 21 of 487 consecutive radiosurgery patients. Although this may not represent the actual potential for hearing improvement, it provides evidence that hearing improvement is at least possible following radiosurgery (Niranjan, et al., 1999).

2.3 Non-auditory complications

Hayhurst et al. (Hayhurst, et al., 2011) reviewed the non-auditory complications that were associated with gamma knife radiosurgery in 80 patients who were followed for more than 2 years. Twenty-seven (33.8%) of their patients developed non-auditory adverse radiation effects, and patients with a target volume that exceeded a threshold of 5 cc were more likely to develop complications. Treatment plan dosimetric characteristics are not associated with adverse radiation effects. Applying the maximum dose to the 5th cranial nerve is a reliable predictor of trigeminal dysfunction with a threshold of 9 Gy. However, the dose that is tolerated by the cranial nerves is not clear, and reports vary among authors. Anker and Shrieve (Anker & Shrieve, 2009) reviewed the literature and reported the recommended normal structure dose constraints in which one could avoid complications when using a single fraction. According to their study, the maximum doses for sparing trigeminal and facial function are below than 12.5-13 and 12.5-15 Gy, respectively.

3. Hydrocephalus as a complication of gamma knife radiosurgery and risk factors

3.1 Hydrocephalus and gamma knife radiosurgery

Hydrocephalus can occur at various stages during the natural course of a vestibular schwannoma (K. Park et al., 2009), and the reported incidence ranges from 3.7 to 15% of cases (Atlas, et al., 1996; Pirouzmand et al., 2001; Rogg et al., 2005). Occasionally, a large vestibular schwannoma can cause obstructive hydrocephalus, and CSF mal-absorption may be the cause of the communicating hydrocephalus (Gardner et al., 1954; Prasad, 2001; Rogg, et al., 2005). It has been proposed that protein molecules clog the pores of the semi-permeable membrane that forms the barrier in the arachnoid granulations, thereby leading to impaired absorption of CSF. Among 157 patients who were reported by Rogg et al. (Rogg, et al., 2005), 28 (18%) had a pre-existing hydrocephalus before receiving treatment; 39% of

these patients had a non-communicating hydrocephalus, and 61% had a communicating type, and no significant association with tumour size was observed.

We reviewed experiences of hydrocephalus in patients with vestibular schwannomas who were treated in our institute using gamma knife radiosurgery and compared these findings with those patients who received microsurgery as the primary treatment.

3.2 Materials and methods

We conducted a retrospective review of 51 patients who were treated with gamma knife radiosurgery for a vestibular schwannoma (group 1) from January 2005 through December 2010 and 19 consecutive patients who were treated with microsurgery as the primary treatment (group 2) from January 2003 through May 2008. The diagnoses of vestibular schwannoma and hydrocephalus and the measurement of the tumour size were based on the results of the CT scan and MRI results. Hydrocephalus was diagnosed using the age-adjusted bicaudate index (van der Jagt et al., 2009). The size of tumour was calculated on the basis of the largest diameter of the tumour on the MRI scan.

Radiosurgery was performed using a Leksell Gamma Knife Model C (Elekta Instrument AB, Stockholm, Sweden) with Gamma Plan ver. 5.34 (Elekta Instrument). The marginal doses were 12 and 13 Gy in 39 and 12, respectively; the maximum doses were 24 and 26 Gy. Microsurgeries were performed with the retrosigmoid or translabyrinthine approach according to the preference of the surgeon preferences and the hearing status of the patient. The CSF diversion procedure that was used for the hydrocephalus was either an endoscopic third ventriculostomy or a ventriculo-peritoneal shunt.

Before and after the radiosurgery or microsurgery, the development of hydrocephalus with regard to the patient's age, tumour size, and radiation dose were evaluated, and the management of hydrocephalus was discussed. The statistical analysis was performed using the chi-square or Fisher's exact test. Differences with a p-value of less than 0.05 were considered to be statistically significant.

3.3 Results

In group 1, all of the patients were followed for more than 6 months, and the mean follow-up duration was 37.9 months (range, 7-76 months). The mean age of the patients was 54.7 years (range, 13-74 years). The mean maximum tumour diameter was 1.6 cm (range, 0.4 - 3.7 cm). In group 2, nineteen patients were followed for more than 6 months, and the mean follow-up was 21.2 months (range, 6 - 54 months). The mean age of the patients was 50 years (range, 23 - 67 years). The mean maximum tumour diameter was 3.1 cm (range, 1 - 5.5 cm) (Table 2).

In group 1, five patients had hydrocephalus before undergoing gamma knife radiosurgery. None of the patients with a tumour diameter of less than 1 cm had hydrocephalus. Three patients had a tumour that was between 1- 3 cm, and two had a tumour that was larger than 3 cm. The hydrocephalus in the one out of three patients with a tumour diameter of less than 3 cm was improved progressively following gamma knife radiosurgery. After gamma knife radiosurgery, a newly developed (*de novo*) hydrocephalus was noted in six of the patients. In two of the patients with pre-gamma knife radiosurgery hydrocephalus and with a tumour that was larger than 3 cm, the hydrocephalus was worse following treatment. Among the 46 patients with a tumour diameter less than 3 cm, three developed *de novo*

hydrocephalus after gamma knife radiosurgery. Three of the five patients with the tumour size larger than 3 cm developed hydrocephalus after gamma knife radiosurgery. The size of the tumour was significantly related with the *de novo* development of hydrocephalus ($p<0.05$). The patient characteristics are presented in Table 3 and 4. A marginal dose of radiosurgery and patient age were not significantly associated with hydrocephalus.

	Group 1(n=51) (GKRS)	Group 2 (n=19) (Microsurgery)
Mean age, years (range)	54.7 (13-74)	50 (23-67)
Sex (M:F)	15:36	3:16
Mean follow-up, months (range)	37.9 (7-76)	21.2 (6-54)
Mean tumour diameter, cm (range)	1.6(0.4-3.7)	3.2 (1-5.5)
MaximumTumour diameter, cm		
<1	5	0
1-3	41	7
≥3	5	12

Table 2. Demographic and clinical parameters of the patients who underwent gamma knife radiosurgery (GKRS) or microsurgery.

	Total Patients (n=51)	Hydrocephalus before GKRS (n=5)	Hydrocephalus after GKRS (n=11)	*p*-value
Age				
<50 years	14	2	1	NS
≥50 years	37	3	10	
Maximum tumour diameter, cm (see Table 4 for detailed data)			total (*de novo*)	See Table 3
<1	5	0	0 (0)	
1-3	41	3	6 (3)	
≥3	5	2	5 (3)	
Prescription dose (50%)				
12 Gy	39	5	7	NS
13 Gy	12	0	4	

NS: not significant

Table 3. Characteristics of the patients who underwent gamma knife radiosurgery (GKRS).

Among the 11 patients who were diagnosed with hydrocephalus, three underwent a CSF diversion procedure due to clinical deterioration or increasing ventricle size. Two of these patients initially underwent an endoscopic third ventriculostomy because their hydrocephalus was radiologically considered to be an obstructive type (such as a poorly visualised aqueduct of Sylvius and a small fourth ventricle). However, these two patients ultimately needed to receive a ventriculo-peritoneal shunt due to endoscopic third ventriculostomy failure. One patient underwent a ventriculo-peritoneal shunt as the primary treatment for hydrocephalus. The protein levels in the CSF of the patients with hydrocephalus were not routinely evaluated. However, two of the three patients who

Size of tumour	Number of patients	Pre-GKRS hydrocephalus		Post-GKRS hydrocephalus	
		No	Yes	total number	*de novo*
<1	5	5	0	0	0
1-3	41	38*	3	6	3*
≥3	5	3§	2	5	3§

1. GKRS: gamma knife radiosurgery
2. * and §: The *p*-value was less than 0.05, representing *de novo* development of post-gamma knife radiosurgery and was significantly related to the tumour size.

Table 4. Development of hydrocephalus according to tumour size.

underwent a CSF shunting procedure had elevated ventricular CSF protein levels of 147 and 150 mg/dl. Three of the five patients who developed hydrocephalus with a tumour that was larger than 3 cm underwent surgery using the translabyrinthine approach due to persistent symptoms or an enlarged tumour.

In group 2, seven of the patients had hydrocephalus before microsurgery, and all of these patients had a maximum tumour diameter that was larger than 3 cm. After microsurgery, all of the cases of hydrocephalus improved (Table 5). Tumour size, patient age, and surgical procedure were not significantly related to hydrocephalus and microsurgery.

	Total Patients (n=19)	Hydrocephalus before microsurgery (n=7)	Hydrocephalus after microsurgery (n=0)	*p*-value
Age				
<50 years	8	2	0	NS
≥50 years	11	5	0	
Maximum tumour diameter, cm				NS
1-3	7	0	0	
≥3	12	7	0	
Surgical approach				
Retrosigmoid	15	3	0	NS
Translabyrinthine	4	4	0	

NS: Not significant ($p>0.05$)

Table 5. Characteristics of the patients who underwent microsurgery.

3.4 Discussion regarding the development of hydrocephalus in patients with vestibular schwannoma and their management

It has been reported that both gamma knife radiosurgery and microsurgery can contribute to the development or aggravation of hydrocephalus (Fukuda et al., 2007; Roche et al., 2008). However, the mechanism that is associated with the development of hydrocephalus following gamma knife radiosurgery is not known. Obstructive cases are not common, particularly if care is taken to avoid treating large tumours with a significant mass effect (Roche, et al., 2008). Sawamura et al. (Sawamura et al., 2003) studied a group of patients who underwent stereotactic radiation therapy and suggested that radiation-induced

modifications of the tumour resulted in an accumulation of cellular and protein-laden material from the degradation and necrosis of the tumour. Although we did not analysed the CSF protein content in all patients, two of the patients who underwent a CSF shunting procedure had elevated ventricular CSF protein levels of 147 and 150 mg/dl. A systematic analysis of the biochemical components in the CSF in vestibular schwannoma has not been reported. In addition, the mechanism of hydrocephalus that is associated with microsurgery remains to be clarified. One likely explanation is that after microsurgery, the local inflammatory processes might impair circulation. Following the direct manipulation of the tumour capsule, the delivery of intracisternal haemoglobin and protein-laden material have been observed (Nassar & Correll, 1968; Samii & Matthies, 1997b). In our series, however, we found no *de novo* development or aggravation of hydrocephalus following microsurgery.

The incidence of hydrocephalus—including non-obstructive hydrocephalus—was higher in patients with larger tumours, and 3 cm is typically considered to be the maximum size for gamma knife radiosurgery. Four of the five patients with a tumour diameter that was larger than 3 cm had hydrocephalus that was believed to be the obstructive type radiologically due to a narrowing of the aqueduct of Sylvius and a normal or collapsed 4th ventricle, despite having enlarged lateral and third ventricles. Therefore, we initially performed an endoscopic third ventriculostomy in two of these patients. However, the patients' symptoms and ventricle size did not improve, and a ventriculo-peritoneal shunt was ultimately placed. In our cases, there was a weak correlation between the size of the tumour and obstructive type hydrocephalus. Hayhurst et al. (Hayhurst et al., 2006) reported a role of endoscopic third ventriculostomy in hydrocephalus after treating vestibular schwannomas. When successful, endoscopic third ventriculostomy has several benefits over placing a ventriculo-peritoneal shunt. We therefore recommend carefully selecting patients for the indication of undergoing an endoscopic third ventriculostomy.

Several authors have reported treatment strategies for hydrocephalus before microsurgery or gamma knife radiosurgery (Atlas, et al., 1996; Fukuda, et al., 2007; Roche, et al., 2008). With respect to microsurgery, several investigators preferred a wait-and-see-approach and therefore focused only on the surgery for the tumour. In most cases, the hydrocephalus resolved, and there was no need for additional shunt surgery. Atlas et al. (Atlas, et al., 1996) reported 14 patients with hydrocephalus in a series of 104 consecutive cases of vestibular schwannoma. In nine of these cases, the treatment consisted only of tumour removal, and there were no cases that required ventricular drainage or a shunting procedure following microsurgery. In a larger series of 1,000 cases of vestibular schwannoma, Samii and Matthies (Samii & Matthies, 1997b) reported that pre-existing hydrocephalus required CSF shunt insertion in nine of the cases (1%) before removal of the tumour.

The decision of whether to perform a shunt procedure for hydrocephalus before gamma knife radiosurgery remains challenging. Noren (Noren, 1998) reported that treatment-related peritumour reactions were sufficient to block CSF circulation and required shunt insertion in 1.4% of vestibular schwannoma cases that were treated using gamma knife radiosurgery. According to other reported studies of gamma knife radiosurgery, shunt surgery was needed in 0 to 3% of cases (Chopra et al., 2007; Pollock et al., 1995). In our series, 1 out of 46 (2.1%) patients with a tumour diameter that was less than 3 cm required a shunting procedure, whereas two out of five patients with a large tumour underwent a shunting procedure (and another two patients underwent microsurgery after gamma knife radiosurgery). Two of the patients with pre-gamma knife radiosurgery hydrocephalus and

a tumour diameter that was larger than 3 cm worsened during the initial follow-up after gamma knife radiosurgery. In addition, two of the patients with pre-gamma knife radiosurgery hydrocephalus and a tumour diameter that was less than 3 cm improved after gamma knife radiosurgery. These findings support a wait-and see-policy when pre-gamma knife radiosurgery hydrocephalus or newly developed hydrocephalus occurs in patients with a small or medium size vestibular schwannoma. The progression of hydrocephalus must be followed closely, and patients with a large vestibular schwannoma must be monitored more intensely.

4. Conclusions

The vestibular schwannomas are located in the cerebello-pontine angle, in which many functionally important structures are included. Radiosurgery has become a reliable alternative treatment to the microsurgery for vestibular schwannoma. High conformity and sensitivity in the planning of radiosurgery are required to prevent the complication. However, most of the reports emphasize that the tumour size is the most important factor to reduce the complication. Keeping the cochlear dose below 4Gy is recommended for hearing preservation.

The development or worsening of hydrocephalus is a major complication of both gamma knife radiosurgery and microsurgery. In our experience, it can be assumed that in some patients, gamma knife radiosurgery plays a direct role in the occurrence of hydrocephalus but has no relationship to tumour growth or treatment failure. The presence of a large tumour was a significant factor that was associated with the development of both communicating and non-communicating hydrocephalus. The course and symptoms of hydrocephalus that develops following gamma knife radiosurgery differ from those in patients who are treated with microsurgery. Most microsurgery patients can be managed conservatively; however, many of the hydrocephalus patients who were treated with gamma knife radiosurgery required shunt surgery. Patients should be closely monitored for the development of hydrocephalus following gamma knife radiosurgery. Endoscopic third ventriculostomy was not effective in the management of hydrocephalus.

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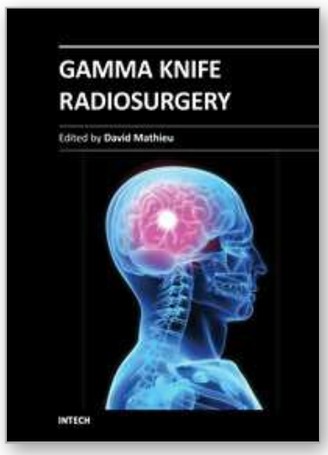
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