Vestibular schwannomas (VSs) are histologically benign tumors of the vestibular division of the eighth cranial nerve. Nowadays, radiosurgery has a well-established role in the treatment of VSs, with reported effective growth control of more than 93%. The 7-year actuarial clinical tumor control or resection-free survival rate at our institution is 95% of 195 patients treated by Gamma Knife surgery (GKS). However, treatment failure, although it affects only a small percentage of patients, still occurs. The purpose of the current study was to determine the clinical and quantitative MRI features of VS as predictors of long-term tumor control after GKS.

OBJECTIVE Gamma Knife surgery (GKS) is a promising treatment modality for patients with vestibular schwannomas (VSs), but a small percentage of patients have persistent postradiosurgical tumor growth. The aim of this study was to determine the clinical and quantitative MRI features of VS as predictors of long-term tumor control after GKS.

METHODS The authors performed a retrospective study of all patients with VS treated with GKS using the Leksell Gamma Knife Unit between 2005 and 2013 at their institution. A total of 187 patients who had a minimum of 24 months of clinical and radiological assessment after radiosurgery were included in this study. Those who underwent a craniotomy with tumor removal before and after GKS were excluded. Study patients comprised 85 (45.5%) males and 102 (54.5%) females, with a median age of 52.2 years (range 20.4–82.3 years). Tumor volumes, enhancing patterns, and apparent diffusion coefficient (ADC) values were measured by region of interest (ROI) analysis of the whole tumor by serial MRI before and after GKS.

RESULTS The median follow-up period was 60.8 months (range 24–128.9 months), and the median treated tumor volume was 3.54 cm³ (0.1–16.2 cm³). At last follow-up, imaging studies indicated that 150 tumors (80.2%) showed decreased tumor volume, 20 (10.7%) had stabilized, and 17 (9.1%) continued to grow following radiosurgery. The postradiosurgical outcome was not significantly correlated with pretreatment volumes or postradiosurgical enhancing patterns. Tumors that showed regression within the initial 12 months following radiosurgery were more likely to have a larger volume reduction ratio at last follow-up than those that did not (volume reduction ratio 55% vs 23.6%, respectively; p < 0.001). Compared with solid VSs, cystic VSs were more likely to regress or stabilize in the initial postradiosurgical 6–12-month period and during extended follow-up. Cystic VSs exhibited a greater volume reduction ratio at last follow-up (cystic vs solid: 67.6% ± 24.1% vs 31.8% ± 51.9%; p < 0.001). The mean preradiosurgical maximum ADC (ADCmax) values of all VSs were significantly higher for those with tumor regression or stabilization at last follow-up compared with those with progression (2.391 vs 1.826 × 10⁻³ mm²/sec; p = 0.010).

CONCLUSIONS Loss of central enhancement after radiosurgery was a common phenomenon, but it did not correlate with tumor volume outcome. Preradiosurgical MRI features including cystic components and ADCmax values can be helpful as predictors of treatment outcome.

KEY WORDS cystic vestibular schwannoma; Gamma Knife radiosurgery; magnetic resonance imaging; vestibular schwannoma; stereotactic radiosurgery
study was to identify imaging predictors of the treatment response of VSs to GKS.

**Methods**

**Patient Characteristics**

In this retrospective study, approved by our institutional review board, we reviewed a collected database of all patients with VS treated between January 2005 and June 2013 at our institution using the Leksell Gamma Knife Unit (Elekta Instruments). The database has been collected prospectively since 1992 by a team of neuroradiologists and neurosurgeons. Patients with non-neurofibromatosis Type 2 VS and a minimum of 24 months of clinical and radiological assessment before and after radiosurgery were included in the study. The excluded patients were those who had undergone surgery for tumor removal before GKS and those who had undergone surgery or more than 1 session of radiosurgery within 24 months after their first GKS. In all, a total of 187 patients meeting the aforementioned criteria were enrolled in the study. They comprised 85 (45.5%) males and 102 (54.5%) females, with a median age of 52.2 years (range 20.4–82.3 years). The tumor was located on the right side in 100 patients (53.5%) and on the left side in 87 (46.5%). Twenty-seven tumors (14.4%) were located in the internal acoustic meatus, 9 (4.8%) in the cerebellopontine angle, and 151 (80.7%) in both the internal acoustic meatus and cerebellopontine angle.

**Radiosurgical Technique**

Treatments were performed using the Leksell Gamma Knife B model between January 2005 and May 2006 and the Leksell Gamma Knife 4C thereafter. After stereotactic frame application, target detection was performed using high-resolution transaxial and coronal contrast-enhanced 1-mm section T1-weighted imaging and T2-weighted imaging sequences in all cases. The median prescribed dose delivered to the margin of the tumor was 12 Gy (range 11–13 Gy), and the median maximum dose was 21.05 Gy (range 15–23 Gy). The median mean dose was 16.3 Gy (range 13.2–21.8 Gy). The mean number of isocenters was 9.54 (range 1–27).

**Radiological Characteristics and Quantification**

MR images were obtained in all patients by using a 1.5-T scanner (Signa Horizon LX2, GE Medical Systems). All patients were followed up with serial contrast-enhanced MRI examinations at 6 and 12 months after radiosurgery and then yearly thereafter. MR enhancing pattern analysis, tumor volume, and diffusion coefficient measurements were performed on a picture archiving and communication system before radiosurgery and at each follow-up time point by experienced neuroradiologists (C.C.W., W.Y.G., and H.M.W.) at our institution. The enhancing pattern on MRI within the first 6 and 12 months after GKS was defined according to constant homogeneous enhancement and initial loss of central enhancement. “Cystic VS” was defined according to the definition of previous studies regarding cystic VS after radiosurgery, and referred to tumors with cysts (including both intramural and extramural cysts) making up at least one-third of the whole tumor volume.33,39

The diffusion-weighted imaging parameters were as follows: TE 60–75 msec, TR 4000–5000 msec, matrix size 128 × 128, field of view 300 mm, slice thickness 5 mm, voxel resolution 1.2 mm × 1.2 mm × 6.0 mm, and number of excitations 1. Diffusion was measured in 3 orthogonal directions by use of 3 b-values (0, 500, and 1000 s/mm²). Postprocessing of diffusion-weighted imaging data with calculation of apparent diffusion coefficient (ADC) maps was performed using OsiriX MD software version 7.5 (Pixmeo SARL) with ADC Map Calculation plugin version 1.9 (Stanford University). In each slice, a region of interest (ROI) was delineated according to the tumor geometry on ADC maps in conjunction with T2-weighted and postcontrast sequences. The pixel-by-pixel mean ADC (ADC mean), minimum ADC (ADC min), and maximum ADC (ADC max) values for the entire volume were calculated using OsiriX MD software. Considering that diffusion-weighted images are more susceptible to field inhomogeneity, we performed ADC measurements with preradiosurgical imaging before stereotactic frame placement. To reduce a partial volume effect from CSF, tumors smaller than 1 slice thickness (3 mm) were excluded from ADC measurements.

The gross tumor volume or gross target volume (GTV), was calculated as the sum of the products of the surface area and thickness of slices on all tumor slices on a picture archiving and communication system. The surface area was obtained by neuroradiologists, who manually traced the tumor on each high-resolution Gd-enhanced spin-echo T1-weighted MR image, with a 1–3-mm slice thickness without gaps. The same imaging protocol and volumetric measurement were performed at every follow-up time point. Absolute changes in volume were calculated by subtracting the GTV at treatment from volume at the last follow-up. The tumor volume reduction ratio was calculated as the absolute change divided by the GTV at diagnosis. Considering the cutoff value of a 10% change in volume as the generally accepted limit of growth/progression, the postradiosurgical volume change was defined as significant enlargement or regression if the tumor volume increased or decreased, respectively, more than 10% compared with baseline GTV at GKS. Otherwise, the case was considered stable. Transient tumor enlargement, in which a transient increase in tumor volume occurred within the first postradiosurgical 12 months followed by either stability or regression, was considered pseudoprogression. Considering treatment outcome, tumor control was defined as volume regression or stable disease, whereas treatment failure was defined as tumor enlargement at last follow-up.

**Statistical Analysis**

To determine the independent predictors of the tumor volume reduction ratio and treatment outcome, the following were assessed: sex (male vs female), age, prescribed dosage, maximum dose, mean dose, number of isocenters, tumor volume and volume reduction ratio, status of tumor volume changes (transient enlargement or not), and MRI features including enhancing patterns, enhancing pattern changes, and ADC values.

Fisher’s exact and chi-square tests were used for cate-
gorical data comparisons, and differences in mean values between 2 groups with categorical factors were tested for significance using an independent samples t-test. Linear regression was used to test the volume reduction ratio and continuous variables, with predictive performance and optimal evaluation cutoff values determined using receiver operating characteristic curves and areas under the curve. Statistical significance was set at probability values < 0.05. All analyses were performed with SPSS (version 22.0, IBM).

Results

Tumor Characteristics and Control

The median follow-up period was 60.8 months (range 24–128.9 months, mean 64.4 months), and the mean treated tumor volume was 3.54 cm$^3$ (median 2.0 cm$^3$, range 0.1–16.2 cm$^3$). At last follow-up, 150 tumors (80.2%) showed decreased tumor volume, 20 (10.7%) had stabilized, and 17 (9.1%) continued to grow following radiosurgery. The mean GTV of tumors that remained either stable or regressed (mean 3.66 ± 3.74 cm$^3$, median 2.1 cm$^3$, range 0.1–16.2 cm$^3$) was not significantly different from the mean GTV of those that progressed (mean 2.38 ± 2.66 cm$^3$, median 1.2 cm$^3$, range 0.19–8.3 cm$^3$; p = 0.171; Table 1). The mean last tumor volume was 1.78 cm$^3$ (median 0.9 cm$^3$, range 0.00–11.45 cm$^3$) with a mean tumor volume reduction ratio of 38.7% for all tumors. For tumors that shrunk at last follow-up, the mean tumor volume reduction ratio reached 55% (median 59%, range 12%–100%), and for tumors that continued to grow, the mean tumor enlargement ratio was 74% (median 29%, range 10%–249%).

Tumor Morphology Versus Treatment Outcome

Of all 187 tumors, 36 (19%) were cystic VSs containing cystic components and 151 (81%) were solid VSs. A total of 122 (65%) of 187 tumors showed homogenous enhancement, and 65 (35%) of 187 tumors had various degrees of nonenhancing areas before GKS (Table 2). The enhancing pattern at the time of GKS did not significantly correlate with the volume reduction ratio at last follow-up. After radiosurgery, 162 tumors (87%) showed initial loss of central enhancement, and 97 tumors (52%) showed pseudoprogression on follow-up MRI. Tumors with larger pretreatment volumes were more likely to have initial loss of enhancement (p < 0.001), but there was no significant correlation between loss of enhancement and pseudoprogression after radiosurgery. The postradiosurgical outcome was not significantly correlated with postradiosurgical enhancing patterns, but those tumors without pseudoprogression were more likely to regress or stabilize at last follow-up (p = 0.008). Tumors with pseudoprogression

### Table 1. Univariate analysis of variables that influence tumor control

<table>
<thead>
<tr>
<th>Variables</th>
<th>Tumor Regression or Stable</th>
<th>Tumor Progression</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patient age (yrs)*</td>
<td>52 (55, 20–82)</td>
<td>51 (51, 25–72)</td>
<td>0.596</td>
</tr>
<tr>
<td>Female/male ratio</td>
<td>93:77</td>
<td>9:8</td>
<td>0.889</td>
</tr>
<tr>
<td>GTV (cm$^3$)*</td>
<td>3.66 (2.1, 0.1–16.2)</td>
<td>2.38 (1.2, 0.19–8.3)</td>
<td>0.171</td>
</tr>
<tr>
<td>Prescribed dose (Gy)*</td>
<td>12 (12, 11–13)</td>
<td>12 (12, 12–13)</td>
<td>0.553</td>
</tr>
<tr>
<td>Maximum dose (Gy)*</td>
<td>21 (21, 17–23)</td>
<td>20 (21, 15–23)</td>
<td>0.624</td>
</tr>
<tr>
<td>No. of isocenters</td>
<td>9.6 (9, 1–27)</td>
<td>9.1 (9, 4–17)</td>
<td>0.678</td>
</tr>
<tr>
<td>Follow-up (mos)*</td>
<td>66 (60, 24–129)</td>
<td>60 (60, 24–114)</td>
<td>0.933</td>
</tr>
<tr>
<td>Cystic VS/solid VS</td>
<td>36:134</td>
<td>0:17</td>
<td>0.047†</td>
</tr>
<tr>
<td>Mean pre-GK ADC ± SD (×10$^{-3}$ mm$^2$/sec)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>2.391 ± 0.604</td>
<td>1.826 ± 0.535</td>
<td>0.010†</td>
</tr>
<tr>
<td>Mean</td>
<td>1.296 ± 0.281</td>
<td>1.135 ± 0.229</td>
<td>0.105</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.680 ± 0.224</td>
<td>0.680 ± 0.144</td>
<td>1.000</td>
</tr>
<tr>
<td>Maximum (in solid VS)</td>
<td>2.291± 0.085</td>
<td>1.825 ± 0.178</td>
<td>0.033</td>
</tr>
<tr>
<td>Mean ADC at 6 mos ± SD (×10$^{-3}$ mm$^2$/sec)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>2.109 ± 0.573</td>
<td>2.405 ±0.681</td>
<td>0.109</td>
</tr>
<tr>
<td>Mean</td>
<td>1.534 ± 0.292</td>
<td>1.383 ± 0.160</td>
<td>0.004†</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.899 ± 0.460</td>
<td>0.933 ± 0.431</td>
<td>0.782</td>
</tr>
<tr>
<td>Loss enhancement after GKS (present: absent)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 mos</td>
<td>144:26</td>
<td>15:2</td>
<td>1.000</td>
</tr>
<tr>
<td>12 mos</td>
<td>109:61</td>
<td>12:5</td>
<td>0.595</td>
</tr>
<tr>
<td>Enlarge after GKS (present: absent)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 mos</td>
<td>84:83</td>
<td>7:9</td>
<td>0.617</td>
</tr>
<tr>
<td>12 mos</td>
<td>38:126</td>
<td>9:8</td>
<td>0.008†</td>
</tr>
<tr>
<td>Mean volume reduction ratio ± SD (%)</td>
<td>50 ± 27.5</td>
<td>-74.5 ± 76.9</td>
<td>&lt;0.001†</td>
</tr>
</tbody>
</table>

* Values represent mean (median, range).
† Significant difference at p < 0.05.
following radiosurgery were more likely to have a smaller volume reduction ratio at last follow-up than those that did not (volume reduction ratio 24% vs 55%, p < 0.001; Table 2). In this analysis, the mean GTV of cystic VSs was significantly larger than that for solid VSs (6.2 ± 3.8 cm$^3$ vs 2.9 ± 3.4 cm$^3$; p < 0.001). Compared with solid VSs, cystic VSs were more likely to regress or stabilize in the initial postradiosurgical 6–12 months and at follow-up. Cystic tumors also had greater volume reduction ratios at last follow-up (cystic vs solid: 67.6% ± 24.1% vs 31.8% ± 51.9%; p < 0.001, Table 2; Figs. 1 and 2).

The mean preradiosurgical ADC$_{\text{max}}$ of all VSs was significantly higher for those with tumor regression or stabilization at the last imaging follow-up compared with those with progression (2.391 ± 0.604 vs 1.826 ± 0.535 × 10$^{-3}$ mm$^2$/sec; p = 0.010). Those that showed tumor regression or stabilization at the last imaging follow-up had significantly higher ADC$_{\text{mean}}$ at 6 months postradiosurgery than those without (1.534 ± 0.292 vs 1.383 ± 0.160 × 10$^{-3}$ mm$^2$/sec; p = 0.004). However, there was substantial overlap of mean ADC$_{\text{mean}}$ of 6-month postradiosurgery values between groups (Table 1). Considering the different tumor components, the mean preradiosurgical ADC$_{\text{max}}$ of solid VSs was also significantly higher for those with tumor regression or stabilization at the last imaging follow-up compared with those with progression (2.291 ± 0.085 vs 1.825 ± 0.178 × 10$^{-3}$ mm$^2$/second; p = 0.033).

Of those tumors showing enlargement at 12 months after GKS, tumors that regressed at last follow-up had significantly higher mean preradiosurgical ADC$_{\text{mean}}$ values than those with persistent tumor enlargement or stabilization (1.357 ± 0.25 vs 1.212 ± 0.193 × 10$^{-3}$ mm$^2$/second; p = 0.038). Using the receiver operating characteristic curve, a cutoff value of 1.274 × 10$^{-3}$ mm$^2$/sec for preradiosurgical ADC$_{\text{mean}}$ generated the optimal combination of sensitivity (69.2%) and specificity (70%), and had good discriminating power, with the AUC at 0.68 (95% confidence interval 0.518–0.836, p = 0.041). The ADC values changed heterogeneously after GKS, and the changes in the ADC did not significantly correlate with the presence of pseudoprogression or final outcome. This was true whether considering all VS cases or just the solid or cystic subtypes.

**Radiosurgical Parameters**

The maximum dose, prescribed dose, and mean dose of radiation, and the number of isocenters and mean isodose line, did not significantly influence tumor volume outcome (Table 1).

**Discussion**

VSs are heterogeneous tumors, with various different tissue compositions, growth rates, MRI appearances, and responses to treatment. GKS has proven to be a highly effective treatment for VS, but the course after GKS is not uniform, with dynamic volume changes generally observed. While most VSs may shrink after transient enlargement within the first 2 years after GKS, a small percentage of VSs continues to grow. Currently no known predictors of VS response to radiosurgery have been discovered, and a wait-and-see policy is the current strategy. In this study we provide a comprehensive analysis that sought to determine whether any imaging characteristics could serve as predictors of treatment response in the early post-GKS follow-up period before persistent tumor growth is evident.

**Cystic VS Versus Solid VS Outcomes Following GKS**

One of the main findings of our study is that cystic VSs exhibited a greater volume reduction ratio after GKS.
Cyst formation in VS is commonly observed in radiological studies, but the incidence differs among imaging modality and the definition of cystic VS, with a reported incidence of 5.7%–20.4% reported in the literature. In our series, tumors were classified as cystic according to MRI appearance on the day of GKS. In the literature, few studies on the mechanism of cyst formation and enlargement in cystic VS have been published, and these had inconclusive findings. From early histological studies, the coalescence of microcysts in the Antoni type B area in VS had been suggested to cause grossly detectable cystic areas in neuroimaging. Some investigators have reported differences in the distribution of Antoni type cells between cystic and solid VSs, showing that cyst formation is due to the degeneration of tumor tissues. On the other hand, a study by Park et al. showed no significant relationship between cyst formation and the distribution of Antoni cell types. Instead, these authors reported that abnormal vessel proliferation is significantly more prominent in cystic VSs compared with solid VSs based on histological evidence.

Other pathogeneses, including intratumoral hemorrhage, necrosis, and secretion within the type B tissue, are proposed mechanisms leading to cyst formation in VS. Moreover, the density of cells positive for Ki-67, a marker of cell proliferation, was found to be higher in cystic VSs than in solid VSs. A heterogeneous enhanced appearance of larger VSs was found more commonly in lesions with a higher ratio of Antoni type B tissue to type A tissue.

In the current study, the degree of enhancement was not a predictor of post-GKS outcome, but the presence of cysts inside VSs was correlated with greater volume reduction ratios at last follow-up. According to the few histological studies on resections of post-radiosurgical residual or growing tumors, the biological effects of radiosurgery on VS are apoptotic pathways and vasculopathy. As compared with the solid VS with an inherently low proliferative index, the high density of Ki-67–positive cells, which represent more radiosensitive dividing cells, and the abnormal vessel proliferation observed in cystic VS may be mechanisms underlying the greater tumor shrinkage exhibited by these tumors following GKS. In addition, the radiation effects on apoptotic pathways and vasculature are usually not immediate and may be attributable to the delayed regression of cystic VSs observed in this and previous studies.

**ADC Values as Useful Predictors of Early VS Response Following GKS**

Another main finding of our study is that pre-GKS ADC values of VSs were helpful in evaluating treatment results and in distinguishing transient tumor enlargement or persistent tumor growth early in the posttreatment period when other imaging results are not definitive. Diffusion imaging is a sensitive imaging biomarker, representing cellularity and extracellular free water content, and has shown promise as a robust approach for preoperative tumor typing, preoperative glioma grading, and meningioma grading and prediction of postoperative recurrence. In addition, the ADC value is reported as a practical method for evaluating the efficacy of stereotactic radiosurgery and predicting...
early intracranial metastatic response to GKS. Cellular density is considered a major factor responsible for changes in ADCs. In the current study, we used whole-tumor analysis, which is the most common technique for assessing therapeutic response. The high preradiosurgical ADC values of VSs may reflect cystic components, the increase in the tumor’s fluid component, and lower nucleus-to-cytoplasm ratios or lower cellularity in VS. They also probably reflect the higher density of Antoni Type B tissue. VSs with a higher content of radiographically identified cysts and Antoni type B tissue might represent areas with higher ADC values and a better response to radiosurgery.

There was no significant correlation between treatment outcome and the absolute ADC values or the differences of ADC values at 6 months and 12 months after GKS in the current study. These results are in agreement with the results from the study by Chuang et al., who reported that after GKS, the ADC values for solid VSs significantly increased from the first follow-up at 6 months, but ADC values did not significantly differ among tumors, regardless of whether they exhibited increased, decreased, or stable volumes. However, the placement of the ROIs was not clearly described in their study, and the ADC values may vary depending on the selected MRI slice, especially in tumors with mixed cystic and solid components. Moreover, in the current study, we found that among the tumors showing enlargement at the first 12 months after radiosurgery, tumors with higher pre-GKS ADCmean (> 1.273 × 10−3 mm²/sec) were more likely to shrink after 12 months. We suggest that preradiosurgical ADC values could be useful for predicting pseudoprogression or treatment failure early in the posttreatment period.

**Loss of Central Enhancement Is Not a Predictor of Tumor Response**

Loss of central contrast enhancement is a common morphological change in the early postradiosurgical period, with a reported incidence ranging from 54% by Prasad et al. to 84% by Nakamura et al. Loss of central contrast enhancement is generally transient. The incidence of this loss was 86.7% in our study. The postradiosurgical tumor enhancing patterns are usually classified as a transient loss of enhancement, continuous increase in enhancement, or no change in enhancement. Several possible mechanisms for the loss of central enhancement have been proposed, including tumor necrosis and obvious vascular damage based on histopathological findings, decreased vascularity in Tc-99 human serum albumin-DTPA PET/CT, hyperacute tumor ischemia and associated edema, and apoptosis. However, none of these clarifies the actual meaning of the development or absence of central enhancement. In an earlier study by Nakamura et al., changes in contrast enhancement were not found to be predictive of clinical outcome. In the current study, we also found no significant correlation between postradiosurgical outcome and the postradiosurgical MRI enhancement pattern in the initial 6–12 months following radiosurgery. We postulate that early postradiosurgical loss of central enhancement represents an early radiation effect and is not a predictor of tumor volume control.

A transient increase in size followed by stability or regression has been recognized as treatment effects rather than treatment failures in the first 24 months after GKS in many studies. However, the mechanisms of these different volumetric responses to radiosurgery have yet to be fully elucidated. A relationship between alternations in enhancing and growth patterns has also been reported, but the results are inconsistent. Nakamura et al. suggest that no significant correlation exists between changes in tumor volume and tumor enhancement on MRI. On the other hand, studies by Hasegawa et al. and Régis et al. show that initial loss of central enhancement is usually associated with the presence of transient tumor expansion. Our study showed that tumors with larger pre-GKS volumes were more likely to exhibit initial loss of enhancement on MRI after radiosurgery, but the loss of enhancement was correlated with neither early tumor enlargement nor treatment outcome. Although pseudoprogression within the initial 6–12 months after radiosurgery was commonly observed, we found that VSs with a larger tumor volume ratio within the first 12 months after GKS were more likely to show a lesser degree of volume reduction at last follow-up.

The limitations of the present study include the single-institution nature of the study and the relatively small number of patients. The patients in the failure group were limited (a total of 17), and multivariate analysis was not performed due to the small sample size. Furthermore, the application of imaging features and ADC values to modify the radiosurgical dose could not be evaluated thoroughly. Accordingly, further prospective studies on larger cohorts of patients are warranted. Nevertheless, this is still one of the larger series published on this topic, and it identifies specific MRI features, including ADC values, as predictors of the treatment response of VSs to GKS.

**Conclusions**

GKS is an effective treatment modality for both solid and cystic VS. The presence of loss of central enhancement after radiosurgery is a common phenomenon, which does not correlate with tumor volume outcomes. Transient enlargement of tumor size is also frequently observed in the initial 6–12 months following radiosurgery, and it is associated with a lesser degree of volume reduction at last follow-up. Postradiosurgical MRI features, including cystic components and ADCmax values, can be helpful when the results of early posttreatment imaging are ambiguous. Cystic VS ultimately can have a larger volume reduction ratio than that of solid VS in the long term.

**Acknowledgments**

We thank Miss Feng-Jiau Lee and Miss Shueh-Jen Huang for their assistance in the preparation of this paper. This paper was part of a research project (project for a junior researcher) of the Ministry of Science and Technology, Taiwan (no. 104-2314-B-075-033).

**References**

2. Benech F, Perez R, Fontanella MM, Morra B, Albera R,


**Disclosures**

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

**Author Contributions**

Conception and design: Guo, CC Wu, HM Wu. Acquisition of data: all authors. Analysis and interpretation of data: Guo, CC Wu, HM Wu, Lin, Lee. Drafting the article: CC Wu. Critically revising the article: Guo, CC Wu. Reviewed submitted version of manuscript: all authors. Statistical analysis: CC Wu. Administrative/technical/material support: Guo, CC Wu, Chung, Lin, Lee. Study supervision: Guo.

**Supplemental Information**

**Previous Presentations**

The abstract of this paper was presented at the 18th International Leksell Gamma Knife Society Meeting, May 15–19, 2016, Amsterdam, The Netherlands.

**Correspondence**

Wan-Yuo Guo, Department of Radiology, Taipei Veterans General Hospital, 201, Section 2, Shih-Pai Rd., Taipei 112, Taiwan, Republic of China. email: wyguo@vghtpe.gov.tw.