Central neurocytomas are neuronal tumors that most commonly arise from the wall of the lateral ventricle. Historiologically, these lesions are typically benign, although atypical tumors have also been reported. Central neurocytomas were first described in 1982, when Hassoun et al. reported 2 tumors that were histologically different from typical neurocytomas. Electron microscopy revealed a striking neuronal differentiation with numerous synapses.

Central neurocytomas are usually diagnosed when there is blockage of the CSF pathways, causing hydrocephalus and elevated intracranial pressure. Microsurgical removal is the treatment of choice. The results of microsurgical removal are dependent on the extent of the resection and the histological features of the tumor. Total resection and an MIB-1 index of < 2–3 indicate a high likelihood of local tumor control. Correspondingly, the risk for tumor recurrence is higher in patients in whom subtotal tumor resection is performed or in whom the tumor is histopathologically atypical.

Fractionated radiotherapy results in an increased likelihood of tumor control in cases of subtotal tumor removal or lesions with atypical histological characteristics. However, severe long-term complications have been reported following radiotherapy. Multiple reports suggest that GKS may result in a high rate of tumor control and a low complication rate, making it conceptually an attractive alternative to radiotherapy.

Chen et al. reported 100% tumor control and no complications in 14 patients following GKS for CN and a median follow-up lasting more than 5 years. However, those authors thought that their documentation was not strong enough to be conclusive and recommended that a multicenter study be conducted with more patients and a longer follow-up time to confirm their results. We therefore decided to add data from 4 additional centers to update information on the patient population described in the report by Chen et al.

Methods

All patients who harbored CNs that were treated with GKS before July 1, 2010, in the participating institutions were eligible for the study. Most patients (21) were treated
Gamma Knife surgery for central neurocytomas

at Veterans General Hospital, Taipei, Taiwan. In addition to these, 8 patients were treated at Jiro Suzuki Memorial Gamma House, Furukawa Seiryo Hospital, Furukawa, Japan; 7 patients at Katsuta Hospital Mito Gamma House, Ibaraki, Japan; 5 patients at the Singapore Gamma Knife Center, Singapore; and 2 patients at Gamma Knife Zentrum Krefeld, Germany. Excluded was 1 patient in whom no follow-up information was available. In total, 42 eligible patients were included in the study. Informed consent was obtained from the patients when possible, and approval of the study was granted by the ethics committees of all participating institutions.

The tumors included recurrent lesions after gross total removal in 2 patients and tumor remnants after subtotal removal in 33 patients. A biopsy was performed in 1 patient, and the diagnosis was based on imaging studies in 6 patients. All 36 tumors for which histological results were available were benign. There was evidence of tumor growth between microsurgery and GKS in the 2 patients who underwent gross total tumor removal and in 9 of the 33 patients in whom partial tumor removal was performed. One patient had received prior radiotherapy.

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The end points in the study were tumor growth or tumor removal by microsurgery. Tumor control was defined as no growth of the treated tumor as well as absence of distant recurrence. For the purposes of this report, a lack of local tumor control as well as a distant recurrence are defined as tumor recurrence. Time at risk for tumor growth is defined as the time interval between GKS and the first of the following events: local tumor growth (2 patients) or distant tumor recurrence (2 patients); tumor removal due to ventricle enlargement (2 patients); death (1 patient); and latest imaging follow-up examination (35 patients). Clinical follow-up ranged from 0.5 to 14.7 years (mean 6.1 years, median 4.9 years).

The latest follow-up information for the 35 patients still at risk for tumor recurrence is presented here. The year of the latest imaging study was 2012 in 2 patients, 2011 in 21 patients, 2010 in 9 patients, and 2009 in 3 patients. Eight patients were followed up for more than 10 years and another 10 patients for 5–10 years. The interval between GKS and the latest imaging examination ranged from 1.4 to 14.1 years (median 5.0 years, mean 6.2 years), and the latest clinical data were collected between 1.4 and 14.7 years (median 5.0 years, mean 6.4 years).

Statistical Analysis

Kaplan-Meier survival statistics were used to analyze time free from tumor recurrence, and a log rank (Mantel-Cox) test was performed to compare 2-group variables using survival statistics. The Mann-Whitney U-test was used to compare nominal and continuous data, and the Wilcoxon signed rank test was used to analyze the correlation between paired continuous data. The Fisher exact test was used for nominal data. A difference was considered statistically significant when p < 0.05.

Results

Tumor Control Rate Following GKS

Four cases of tumor recurrence occurred in the patient population: 2 recurrent tumors were local (2.4 and 9.6 years after GKS) and 2 were distant (1.6 and 4.8 years after GKS). Thus, the 5- and 10-year tumor control rates were 91% and 81%, respectively (Fig. 1). The local tumor control rate was unrelated to the prescribed dose (< 13 vs > 13 Gy, p = 0.95) and tumor volume (< 7.55 vs > 7.55 cm<sup>3</sup>, p = 0.83). Patients who underwent partial or total tumor removal had a higher chance of local tumor control than patients who did not undergo surgery (p = 0.025); however, no statistical significance was found when prior surgery or not was compared with tumor recurrence (local or distant) (p = 0.32).

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Clinical Outcome Following GKS

In 1 patient a symptomatic edema developed close to the target volume posterior to the left occipital horn. The edema developed parallel to an increase in the size of the ventricle horn (Fig. 3), and edema as well as symptoms disappeared simultaneously when the ventricle horn was reduced to normal size. No other symptoms, besides those caused by hydrocephalus as mentioned earlier, developed in the patient population. All but 1 patient, who died of injuries sustained in a traffic accident, were alive and well at the time the study was closed.

Management of Tumor Recurrences

One of the 2 patients with local tumor recurrence was treated again with GKS; the other continues to be monitored 22 months after diagnosis of recurrent tumor because there are still no symptoms. One of the 2 patients who harbored a distant recurrence was retreated with GKS; the other was scheduled to undergo fractionated radiotherapy but declined treatment. Follow-up times are still too short to assess the results of repeated treatment. Not using tumor removal in the management of tumor recurrences in our patient population is in line with earlier published data, in which 4 of 5 local recurrent tumors were retreated with GKS; management of the fifth recurrent tumor was not reported.10,16,27

Discussion

Histological Characteristics of CNs

Central neurocytomas were initially defined as benign tumors, and thus the prognosis was deemed good following total tumor removal. Today we know that this definition does not apply to all CNs. A less favorable prognosis has been reported in tumors with a high MIB-1 index or atypical histological characteristics.14,21 This must be taken into account when comparing the results in the present study to those from other studies. To extrapolate our results to what can be expected should atypical tumors be treated with GKS would be a questionable move. Genc et al.6 reported results following GKS for 18 CNs of which 3 had an MIB-1 index ≥ 4. Tumor control was reported in all but 1 case, in which there was recurrence of a tumor with an MIB-1 index of 4. Thus, it is possible that GKS will yield less favorably outcomes when atypical CNs are treated.

Including CNs Based on Imaging Only

The imaging features of a CN are quite characteristic. On MR images, this tumor usually presents as an intraventricular, circumscribed, lobular, and “bubbly” mass lesion. In most cases, it is attached to the septum pellucidum, may cause an obstruction of the cerebrospinal fluid circulation at the level of the foramen of Monro, and results in an isolated dilated ventricle containing high-protein fluid. Magnetic resonance imaging also displays moderate-to-strong heterogeneous enhancement following administration of gadolinium. On MR spectroscopic images, a glycine peak at 3.55 ppm is typically present.

We concur with the opinion that histological verification of CNs should be recommended, but we also believe that it is fair to treat patients with CNs based on imaging evidence alone in cases in which there are contraindications to open surgery. There was only imaging evidence and no histological verification in 6 of the 42 tumors included in this series. We have just stated one rationale
not to exclude treating these lesions. Another is that most vestibular schwannomas and meningiomas included in radiosurgical reports lack histological verification of the type of lesion. An additional argument is that including these 6 cases enabled us to analyze the impact of surgery on the incidence of ventricle enlargement following GKS. The most compelling argument for us, however, is that excluding these 6 cases would have changed the results of the study. With them, the 10-year tumor control rate was 81%, and the median radiological follow-up time was 4.8 years. Without these 6 patients, the respective numbers would have been 83% and 5.0 years. We therefore believe that our results were made more representative of CN cases by including these 6 patients.

Enlargement of the Ventricular System Following GKS

The relationship between ventricle enlargement and tumor and treatment parameters should be analyzed using survival statistics if we assume that the likelihood for ventricle enlargement increases with time and that an increase is irreversible. Other statistical methods should be used if this is not the case.

We found a statistically significant relationship between treatment dose and the incidence of ventricle enlargement using survival statistics. This significance disappeared when we used the Mann-Whitney U-test; instead the relationship between tumor volume and ventricle enlargement became statistically significant. Our interpretation of the findings is that larger tumor volumes result in a higher incidence of post-GKS ventricle enlargement, and the observation that tumors treated with lower radiation doses have a higher incidence of ventricle enlargement is due to the fact that lower doses were given to larger tumors.

No treatment was deemed necessary for the majority of patients in whom ventricle enlargement developed following GKS. This and the generally uncomplicated management of hydrocephalus are probably reasons why ventricle enlargement has not been addressed in earlier publications. We believe that our observations may be of value. Ventricle size should be monitored even in patients with tumor control. An impairment of the cerebrospinal fluid circulation may lead to serious consequences if left untreated. An example of this was reported by Kulkarni et al.: 1 of their 8 patients “died 5 years after treatment from shunt dysfunction.”

Comparison of the Results of This Study and Other Published Data

The results from 12 earlier published studies are listed in Table 1.1,2,4,6,7,10,11,15,16,20,25,27 Six tumor recurrences (1 local and 5 distant) and no complications were reported among 68 patients, yielding an approximate tumor control rate of 93%. These results are comparable to ours; in our study there were no permanent complications and 4 recurrent tumors (2 local and 2 distant) in 42 patients (38/42 = 90%).

Results of Radiotherapy for CN

Radiotherapy is conceptually a more appealing treatment choice if suspicion is high that tumor cells may be present outside the visible tumor volume. The literature reporting results following radiotherapy is, however, quite sparse. A Medline search performed using the search term “neurocytoma” resulted in 544 references. The titles of these references indicated that the results of radiotherapy for CN were addressed in only 5 of these publications.12,13,17,19 Two articles were from the same institution, and it is thus likely that some patients were included in both papers.15,19 Consequently, we only included the results from the latest of these 2 articles in Table 2. Tumor control was reported in 16 of 17 patients—a tumor control rate similar to that achieved by GKS. Rades et al.23 added data from 78 patients with CNs reported in the literature to 11 patients treated at their own institution, yielding 89 patients. We have been unable to trace most of the publications in which the additional cases were reported. The patient population was divided into low-dose (< 54 Gy) and high-dose (≥ 54 Gy) groups. The 10-year local tumor control rate was 65% for the low-dose group and 89% for the high-dose group, indicating that higher radiotherapy doses are needed to achieve tumor control.

The important difference between radiotherapy and GKS seems to be the risk of complications. Paek et al.19 reported results for 6 patients who were treated with radiotherapy (median dose 54 Gy) and followed up for more than 10 years. Tumor control was observed in all patients, but radiation-induced complications developed in half of...
them. In addition, 1 patient was found to harbor an atypical meningioma that may have been radiation induced. In this group of patients, 1 complication was lethal and the other 2 resulted in white-matter degeneration and slow deteriorations in patient performance. This complication rate seems to be higher than the 5% risk of severe toxicity at 5 years that was estimated by Emami et al.\(^5\) when one-third of the brain was given 60 Gy. The fact that no radiation-induced complication occurred among the 9 patients in our patient population observed for more than 10 years strongly suggests that the risk for radiation-induced complications is lower following GKS than it is following radiotherapy.

### Tumor Control After GKS

Tumor control following GKS denotes shrinkage or no growth of the irradiated tumor, as shown in Fig. 2. In contrast, failed tumor control is generally defined as an increase in the volume of the irradiated tumor or a growth of tumor contiguous with the treated tumor. Tumor growth found elsewhere is often referred to as a distant or out-of-field recurrence. The distinction between local and distant recurrences is logical when analyzing the tumor response to radiosurgery. It is, however, less logical from a clinical standpoint, because in both cases the intracerebral disease is uncontrolled.

### Conclusions

The tumor control rate following GKS is high, and the risk-benefit relationship compares favorably to that following fractionated radiotherapy of CN, even when low prescribed doses are used. As the long-term complication rate following fractionated radiotherapy seems to be significantly higher than that following GKS, it seems that GKS qualifies as the radiation treatment of choice for well-defined tumor remnants after CN surgery. The

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#### TABLE 1: Summary of cases of CN treated by radiosurgery\(^*\)

<table>
<thead>
<tr>
<th>Authors &amp; Year</th>
<th>Treatment</th>
<th>No. of Patients</th>
<th>Radiation Dose (Gy)</th>
<th>Follow-Up (yrs)</th>
<th>No. of Patients w/ Tumor Control (%)</th>
<th>No. of Complications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anderson et al., 2001</td>
<td>GKS</td>
<td>4</td>
<td>Low: 16, High: 20, Mean: 17</td>
<td>Follow-Up: 1.0, Longest: 2.3, Median: 1.4</td>
<td>No. of Patients w/ Control: 4 (100)</td>
<td>0</td>
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<tr>
<td>Bertalanffy et al., 2001</td>
<td>GKS</td>
<td>3</td>
<td>Low: 10, High: 13, Mean: 12</td>
<td>Follow-Up: 1.0, Longest: 5.0, Median: 2.7</td>
<td>No. of Patients w/ Control: 3 (100)</td>
<td>0</td>
</tr>
<tr>
<td>Cobery et al., 2001</td>
<td>GKS</td>
<td>4</td>
<td>Low: 9, High: 13, Mean: 11</td>
<td>Follow-Up: 1.0, Longest: 8.3, Median: 3.7</td>
<td>No. of Patients w/ Control: 4 (100)</td>
<td>0</td>
</tr>
<tr>
<td>Genc et al., 2011</td>
<td>GKS</td>
<td>18</td>
<td>Low: 12, High: 22, Mean: 16</td>
<td>Follow-Up: 0.5, Longest: 9.2, Median: 3.0</td>
<td>No. of Patients w/ Control: 17 (94)</td>
<td>0</td>
</tr>
<tr>
<td>Hara et al., 2003</td>
<td>GKS</td>
<td>1</td>
<td>Low: 20, High: 20, Mean: 20</td>
<td>Follow-Up: 1.0, Longest: 1.0, Median: 1.0</td>
<td>No. of Patients w/ Control: 1 (100)</td>
<td>0</td>
</tr>
<tr>
<td>Kim et al., 2003</td>
<td>LINAC</td>
<td>1</td>
<td>Low: 18, High: 18, Mean: 17</td>
<td>Follow-Up: 4.3, Longest: 4.3, Median: 4.3</td>
<td>No. of Patients w/ Control: 1 (100)</td>
<td>0</td>
</tr>
<tr>
<td>Kim et al., 2007</td>
<td>GKS</td>
<td>13</td>
<td>Low: 9, High: 20, Mean: 16</td>
<td>Follow-Up: 0.5, Longest: 8.0, Median: 5.1</td>
<td>No. of Patients w/ Control: 11 (85)</td>
<td>0</td>
</tr>
<tr>
<td>Martin et al., 2003</td>
<td>LINAC</td>
<td>4</td>
<td>Low: 16, High: 18, Mean: 17</td>
<td>Follow-Up: 0.3, Longest: 4.5, Median: 2.8</td>
<td>No. of Patients w/ Control: 4 (100)</td>
<td>0</td>
</tr>
<tr>
<td>Matsunaga et al., 2010</td>
<td>GKS</td>
<td>8</td>
<td>Low: 12, High: 18, Mean: 14</td>
<td>Follow-Up: 1.3, Longest: 11.3, Median: 5.3</td>
<td>No. of Patients w/ Control: 7 (88)</td>
<td>0</td>
</tr>
<tr>
<td>Pollock &amp; Stafford, 2001</td>
<td>GKS</td>
<td>1</td>
<td>Low: 18, High: 18, Mean: 18</td>
<td>Follow-Up: 2.8, Longest: 2.8, Median: 2.8</td>
<td>No. of Patients w/ Control: 1 (100)</td>
<td>0</td>
</tr>
<tr>
<td>Tyler-Kabara et al., 2001</td>
<td>GKS</td>
<td>4</td>
<td>Low: 14, High: 20, Mean: 16</td>
<td>Follow-Up: 1.5, Longest: 3.5, Median: 2.8</td>
<td>No. of Patients w/ Control: 4 (100)</td>
<td>0</td>
</tr>
<tr>
<td>Yen et al., 2007</td>
<td>GKS</td>
<td>7</td>
<td>Low: 13, High: 20, Mean: 17</td>
<td>Follow-Up: 0.6, Longest: 10.2, Median: 5.5</td>
<td>No. of Patients w/ Control: 5 (71)</td>
<td>0</td>
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</tbody>
</table>

\(*\) Data from the article by Chen et al.\(^3\) are excluded because their patients are included with ours in this paper. Abbreviation: LINAC = linear accelerator.

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#### TABLE 2: Summary of cases of CN treated by radiotherapy\(^*\)

<table>
<thead>
<tr>
<th>Authors &amp; Year</th>
<th>No. of Patients</th>
<th>Dose per Fraction</th>
<th>Radiation Dose (Gy)</th>
<th>Follow-Up (yrs)</th>
<th>No. of Patients w/ Tumor Control (%)</th>
<th>No. of Complications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kulkarni et al., 2002</td>
<td>8</td>
<td>1.8</td>
<td>Min: 50, Max: 50</td>
<td>Follow-Up: 1.3, Longest: 9.5, Median: 6.5</td>
<td>No. of Patients w/ Control: 7 (88)</td>
<td>0</td>
</tr>
<tr>
<td>Nakagawa et al., 1993</td>
<td>2</td>
<td>NR</td>
<td>Min: 58, Max: 60</td>
<td>Follow-Up: 2.5, Longest: 9.5, Median: 6.0</td>
<td>No. of Patients w/ Control: 2 (100)</td>
<td>0</td>
</tr>
<tr>
<td>Namiki et al., 1998</td>
<td>1</td>
<td>NR</td>
<td>Min: 70, Max: 70</td>
<td>Follow-Up: 15.0, Longest: 15.0, Median: 15.0</td>
<td>No. of Patients w/ Control: 1 (100)</td>
<td>0</td>
</tr>
<tr>
<td>Paek et al., 2008</td>
<td>6</td>
<td>(\leq1.8)</td>
<td>Min: 50, Max: 56</td>
<td>Follow-Up: 10.7, Longest: 19.1, Median: 14.3</td>
<td>No. of Patients w/ Control: 6 (100)</td>
<td>3</td>
</tr>
</tbody>
</table>

\(*\) NR = not reported.
fact that GKS is presently the best documented radiation treatment supports this conclusion. Local and distant tumor recurrences can be favorably managed using additional radiation treatment. The size of the ventricle needs to be monitored following GKS, because an enlargement of the ventricular system, or parts of it, may occur even in patients in whom the tumor is controlled. Ventricle enlargement among these patients sometimes necessitates surgical intervention.

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Disclosure

Professor Karlsson is a consultant to Elekta AB.

Author contributions to the study and manuscript preparation include the following. Conception and design: all authors. Acquisition of data: all authors. Analysis and interpretation of data: Karlsson, Guo, Yeo. Drafting the article: Karlsson, Dinesh, Yokura, Yeo, Yamamoto. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Karlsson.

Statistical analysis: Karlsson.

References