Laser interstitial thermal therapy compared with open resection for treating subependymal giant cell astrocytoma

Diane J. Aum, MD, Rebecca A. Reynolds, MD, Sean D. McEvoy, MD, Michael Wong, MD, PhD, Jarod L. Roland, MD, and Matthew D. Smyth, MD

1Division of Pediatric Neurosurgery, Johns Hopkins All Children’s Hospital, St. Petersburg, Florida; 2Department of Neurological Surgery, Washington University in St. Louis, Missouri; and 3Department of Neurology and the Hope Center for Neurological Disorders, Washington University School of Medicine, St. Louis, Missouri

OBJECTIVE Subependymal giant cell astrocytomas (SEGAs) are WHO grade 1 tumors associated with tuberous sclerosis that classically arise from the ventricular wall near the caudate groove and foramen of Monro. Laser interstitial thermal therapy (LITT) is a minimally invasive surgical technique, which works by heating a stereotactically placed laser fiber to ablative temperatures under MRI thermometry monitoring. In this paper, the authors present LITT as a surgical alternative to open resection of SEGAs.

METHODS Twelve patients with SEGAs who underwent 16 procedures between 2007 and 2022 at a single institution were retrospectively reviewed. These patients underwent either open resection or LITT. Clinical data, imaging, recurrence rate, further treatments, and related complications were analyzed.

RESULTS Among the 16 procedures, 9 were open resection and 7 were LITT. An external ventricular drain was placed in 66% (6/9) of open procedures and 57.1% (4/7) of LITT cases. A septostomy was performed in 56% (5/9) of open procedures and 29% (2/7) of LITT cases. Complication rates were higher in open cases than in LITT procedures (44% vs 0%, p < 0.05). Complications included hydrocephalus, transient venous ischemia, wound infection, and bone flap migration. The median length of hospital stay was 4 days (IQR 3.3–5.5 days) for open cases and 4 days (IQR 3.0–7.0 days) for LITT procedures. Recurrence or progression occurred after 3 open cases and 2 LITT cases (33% vs 33%, p = 0.803). For the recurrences, 2 open cases underwent stereotactic radiosurgery, 1 open case underwent LITT, and 1 LITT case underwent repeat LITT. Among the LITT cases, only the patients with no decrease in tumor size by 6 months experienced tumor progression afterward. The 2 LITT cases with progression were the only ones with calcification present on preoperative imaging. The median follow-up times for cases assessed for progression were 8.4 years (IQR 3.8–14.4 years) for open resection and 3.9 years (IQR 3.4–5.1 years) for LITT.

CONCLUSIONS The small size of this case series limits generalizability or adequate comparison of safety. However, this series adds to the literature supporting LITT as a less invasive surgical alternative to open resection of SEGAs and demonstrates that LITT has similar recurrence and/or progression rates to open resection. Additional studies with more data are necessary for comprehensive comparisons between open resection and LITT for treating SEGAs.

https://thejns.org/doi/abs/10.3171/2023.8.PEDS23370

KEYWORDS tuberous sclerosis; subependymal giant cell astrocytoma; SEGA; laser interstitial thermal therapy; LITT

Tuberous sclerosis complex (TSC) is a multisystem autosomal dominant condition typically associated with germline mutations of the TSC1 gene in chromosome 9 or TSC2 gene in chromosome 16. Mutation of these tumor suppressor genes leads to tumor growth in multiple organ systems, including the brain, spinal cord, nerves, eyes, lung, heart, kidneys, and skin. One of the hallmark tumors associated with TSC is subependymal giant cell astrocytoma (SEGA). SEGAs are low-grade tumors of mixed glioneuronal cells and giant cells representing 1%–2% of all pediatric brain tumors. They occur overwhelmingly in TSC patients, but not exclusively. SEGAs are most commonly diagnosed during childhood and adolescence, which is also the
time they pose the most risk. They are typically located in the ventricle lining near the foramen of Monro. Because of this particular location and growth potential, SEGAs can cause seizures, obstructive hydrocephalus, and death. SEGAs are typically slow growing with little evidence of spontaneous regression. Rarely, SEGAs are associated with parenchymal invasion and/or extensive peritumoral edema. Without intervention, a growing SEGA can occlude the foramen of Monro and cause obstructive hydrocephalus, leading to neurological injury and death. For this reason, serial neuroimaging every 1–3 years is recommended for pediatric patients with TSC, even in the absence of symptoms.

There are currently multiple treatment modalities for SEGAs, including recent pharmacological developments (mTOR inhibitors, rapamycin, and its derivate, everolimus), resection, and radiotherapy (e.g., Gamma Knife). Historically, surgery has been performed for one of the following indications: acute hydrocephalus, worsening seizure burden, or significant interval growth on serial neuroimaging. While gross-total resection can often be curative, partial resection carries a high rate of tumor progression and recurrence. There has also been recent discussion regarding earlier surgical intervention to avoid the neurological sequelae of hydrocephalus.

Although resection can be curative and help avoid the neurological sequelae associated with these tumors, the significant risk of complications associated with open craniotomy for SEGAs resection has to be taken into account in decision-making. These complications include hydrocephalus requiring shunt implantation, hemiparesis, intracranial hemorrhage, cognitive decline, meningitis/infection, diabetes insipidus, seizures, precocious puberty, and neuropathic headache, as well as death. Postoperative complication rates have been previously reported as 29%–57%. In particular, resection of SEGAs has been associated with significant risk in individuals with bilateral tumors, those with tumor widths larger than 2 cm, and children younger than 3 years of age.

In the present study, we discuss the implementation of a less invasive surgical alternative for the treatment of SEGAs: laser interstitial thermal therapy (LITT). LITT is an FDA-approved method to necrotize or coagulate soft tissue in the brain and other organs under real-time guidance of advanced MRI thermometry monitoring. LITT is a minimally invasive surgical technique that works by heating stereotactically placed laser fibers to ablative temperatures. LITT has been adopted in a wide range of neurosurgical procedures and has been demonstrated to be a safe and effective method for the treatment of epilepsy and intracranial tumors. Although there have been reports on the use of LITT for SEGAs, this study represents the largest published cohort of LITT patients that also directly compares LITT with open craniotomy for the treatment of SEGAs.

Methods

Study Population

This study is a retrospective IRB-approved case series of 16 surgical procedures for the treatment of SEGAs among 12 patients between 2007 and 2022 at Washington University in St. Louis, performed by three surgeons. These patients underwent either open resection or LITT. Indications for surgical intervention included the following: 1) acute hydrocephalus, 2) worsening seizure burden refractory to medication, or 3) significant interval growth on serial neuroimaging. If deemed to be appropriate, patients were offered both options of open craniotomy and LITT beginning in 2015. Candidacy for LITT included no prior implant or anatomy prohibiting fiber placement, favorable size and configuration of the tumor, and the ability to obtain MR images under general anesthesia. Since LITT was first offered at our institution in 2015, all patients have unanimously elected for LITT treatment and were subsequently treated with LITT. Clinical data, imaging, recurrence and/or progression rates, further treatments, and related complications were obtained from medical documentation and records.

Open Craniotomy for Resection of SEGAs

Open craniotomy for resection of SEGAs was performed using either a transcortical or transcallosal approach. In general, a transcortical approach was used for midline intraventricular tumors, and a transcallosal approach was used for tumors located laterally within the ventricle. In general, the transcallosal approach minimizes cortical disruption but carries a higher risk of bilateral fornical injury. In contrast, the transcallosal approach causes more disruption of frontal cortex but avoids risks associated with interhemispheric dissection, such as injury to bridging veins and the superior sagittal sinus.

The transcallosal approach was performed with the patient’s head in a neutral flexed position using a biconical incision just anterior to or over the coronal suture. After interhemispheric dissection was performed with careful preservation of cortical veins, a retractor system was placed to expose both pericallosal arteries and the underlying corpus callosum. Microsurgical dissection was then used to section the corpus callosum and dissect the tumor off the ventricular wall. The transcrational approach was also performed with the patient’s head positioned in a neutral flexed position. After making a biconical incision, we performed a paramedian craniotomy and durotomy accordingly. Microsurgical dissection was used to debulk and resect the tumor. For both approaches, an external ventricular drain (EVD) and/or endoscopic septostomy can be performed after tumor removal and irrigation.

LITT Treatment of SEGAs

As previously described, trajectories were planned on preoperative high-resolution MRI with gadolinium contrast. Figure 1A–C demonstrates intraoperative MR images for a single-fiber trajectory for a left frontal intraventricular tumor. For all cases, we used the ROSA (Zimmer Biomet) robotic navigation system for planning and placement. After the patient was intubated and sedated, either bone fiducials or a Leksell frame was placed, and an intraoperative CT scan was obtained for coregistration with the robotic navigation system. The patient’s head was then immobilized in a neutral or slightly turned posi-
tion with either a Mayfield skull clamp or Leksell frame and secured to the ROSA robotic system. After accurate registration was confirmed, the robotic arm was used to mark the entry points for each planned fiber trajectory on the scalp, which was then shaved, prepped, and draped. In sterile fashion, local anesthetic was infiltrated, and a stab incision was made at the entry point. The steriley draped robotic arm was then used to direct a handheld high-speed drill to make a small opening for the bone anchor. We then passed a dural dilator down the tract with use of monopolar electrocautery to the proximal end of the dilator for coagulation of the dura. Irrigation was used to clear debris between each step. The robotic arm was then used to measure the distance from the tip of the bone anchor to the depth of the target for the planned trajectory. The cooling catheter was then manually measured with the appropriate distance marked with a folded adhesive strip. At our institution, two laser ablation systems were used: Visualase (Medtronic) and NeuroBlate (Monteris Medical). From this point on, the steps slightly varied depending on the laser system used.

For the Visualase laser ablation system, the outer cooling catheter with a stiffening stylet was placed down the tract of the bone anchor to the target depth. The stylet was then removed, and the laser fiber was carefully inserted and secured. This procedure was repeated for each fiber trajectory, with each fiber labeled accordingly. An intraoperative CT scan was obtained and merged to the preoperative plan to confirm fiber position prior to disconnecting the surgical robot. Sterile drapes were then taken down, and the patient was transported to the MRI unit for ablation.

At our institution, the NeuroBlate laser ablation system is installed in an intraoperative MRI operating suite. After the bone anchors were placed, they were temporarily capped while the room was configured for intraoperative MRI. The ROSA robotic arm was detached from the bed, and the interface platform was attached to the head of the bed. The robotic probe driver was then sterilly attached to the bone anchor. The length of the laser delivery probe was adjusted to the calculated length and the depth stop was set. The laser delivery probe was inserted down the bone anchor and attached to the robotic probe driver. The cables from the robotic probe driver were then plugged into the interface platform. A cover was then placed over the patient and laser ablation system, and the intraoperative MRI unit was brought into the operating room.

During MRI-guided ablation, a gradient recalled echo sequence was continuously acquired, from which the proton resonance frequency shift was measured and deviations from the baseline temperature were calculated. Through these means, MRI thermometry was used to follow the thermal damage estimate (TDE) in real time. Ablation was performed sequentially throughout the trajectory of the fiber catheter in increments starting from the deepest point, with each increment overlapping with the previous treatment zone. TDE margins extend radially from the laser source, causing the treatment zone to be roughly ovoid in shape. In both laser ablation systems, temperature checkpoints were placed on surrounding structures. These temperature checkpoints were often placed near the forni, surrounding brain parenchyma, and thalamus. Continuous safety checks for temperature thresholds at these adjacent structures were made throughout the procedure. Given the intraventricular location of these tumors, it is important to expect and consider the heat sink effect of surrounding CSF during ablation.

After the ablation was finished, T1-weighted images with and without gadolinium and diffusion-weighted images were acquired to assess the treatment zone. Additional treatment can be performed if there is insufficient ablation identified on the MR images acquired. The patient was

---

**FIG. 1.** A and B: Intraoperative pre-ablation sagittal (A) and axial (B) T1-weighted MR images with gadolinium contrast showing a single fiber trajectory. C: Intraoperative post-ablation diffusion-weighted MR image. D and E: Postoperative sagittal (D) and coronal (E) MR images acquired the following day (with ventriculostomy catheter in place). F: Postoperative post-ablation diffusion-weighted MR image. In reference to Table 1, these images were obtained in patient 10.
<table>
<thead>
<tr>
<th>Op Approach</th>
<th>Pt No.</th>
<th>Medical Comorbidities</th>
<th>FU, yrs</th>
<th>Age at op, yrs</th>
<th>SEG A Location</th>
<th>LOS, days</th>
<th>EVD &amp;/or Septostomy</th>
<th>Complications</th>
<th>Tumor Vol, cm³</th>
<th>Progression &amp;/or Recurrence</th>
<th>Further Tx</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open craniotomy</td>
<td>1</td>
<td>TSC, Sz, dev delay, autism</td>
<td>1</td>
<td>15</td>
<td>Lt</td>
<td>4</td>
<td>Septostomy</td>
<td>No</td>
<td>4.4</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>TSC, Sz, dev delay, autism</td>
<td>16</td>
<td>7</td>
<td>Lt</td>
<td>4</td>
<td>Septostomy</td>
<td>Hydrocephalus, EVD</td>
<td>2.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>TSC, Sz</td>
<td>10</td>
<td>4</td>
<td>Lt</td>
<td>3</td>
<td>EVD</td>
<td>Wound washout</td>
<td>4.3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Sz</td>
<td>4</td>
<td>14</td>
<td>Rt</td>
<td>2</td>
<td>EVD</td>
<td>No</td>
<td>1.2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>None</td>
<td>4</td>
<td>14</td>
<td>Lt</td>
<td>6</td>
<td>EVD</td>
<td>No</td>
<td>20.3</td>
<td>0</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>TSC, Sz</td>
<td>16</td>
<td>1</td>
<td>Lt</td>
<td>—</td>
<td>Septostomy</td>
<td>No</td>
<td>2.0</td>
<td>0</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>TSC, Sz, dev delay, autism</td>
<td>15</td>
<td>4</td>
<td>Lt</td>
<td>4</td>
<td>EVD, septostomy</td>
<td>Return to OR, bone flap migration</td>
<td>4.7</td>
<td>0</td>
<td>2.7</td>
</tr>
<tr>
<td>LITT NeuroBlate</td>
<td>5</td>
<td>Rt</td>
<td>4</td>
<td>EVD</td>
<td>No</td>
<td>1.4</td>
<td>0</td>
<td>0</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>TSC, Sz, dev delay, autism</td>
<td>15</td>
<td>13</td>
<td>Lt</td>
<td>1</td>
<td>EVD</td>
<td>No</td>
<td>2.7</td>
<td>0.6</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>TSC, Sz, dev delay, autism</td>
<td>5</td>
<td>14</td>
<td>Lt</td>
<td>9</td>
<td>EVD</td>
<td>No</td>
<td>2.0</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>TSC, Sz, dev delay, autism</td>
<td>5</td>
<td>12</td>
<td>Rt</td>
<td>7</td>
<td>No</td>
<td>No</td>
<td>6.9</td>
<td>6.9</td>
<td>7.8</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>TSC, Sz, dev delay, autism</td>
<td>4</td>
<td>4</td>
<td>Lt</td>
<td>3</td>
<td>No</td>
<td>No</td>
<td>2.6</td>
<td>2.6</td>
<td>3.9</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>Lt</td>
<td>3</td>
<td>EVD, septostomy</td>
<td>No</td>
<td>3.9</td>
<td>3.9</td>
<td>—</td>
<td>NA</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>LITT Visualase</td>
<td>11</td>
<td>TSC, Sz</td>
<td>5</td>
<td>18</td>
<td>Lt</td>
<td>4</td>
<td>No</td>
<td>No</td>
<td>2.9</td>
<td>2.9</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>TSC, Sz, dev delay</td>
<td>&lt;1</td>
<td>3</td>
<td>Rt</td>
<td>6</td>
<td>EVD, septostomy</td>
<td>No</td>
<td>1.5</td>
<td>1</td>
<td>—</td>
</tr>
</tbody>
</table>

Dev = developmental; FU = follow-up; NA = not available; OR = operating room; pt = patient; Sz = seizures; Tx = treatment; — = unknown.
then transported back to the operating room (or removed from the MRI unit if in an MRI suite). The bone anchors and bone fiducials (if used) were then removed and closed with single absorbable suture stitches. In general, biopsies were not obtained prior to ablation given the high degree of diagnostic certainty based on MRI characteristics in a patient with genetically confirmed TSC. The patient was then extubated and taken to the intensive care unit overnight for monitoring. Figure 1A–C depicts intraoperative MR images and Fig. 1D–F demonstrates the appearance of the tumor on MR images obtained the day after LITT.

**EVD and Septostomy**

The decision to place an EVD was based on concern for possible obstruction of the foramen of Monro on review of preoperative imaging. An EVD was typically placed for patients with a higher risk of obstruction of the foramen of Monro from post-ablation edema or tumor swelling. A septostomy was used as either an alternative or supplement to the EVD to mitigate the risk of obstruction. A septostomy provides this protective benefit for a longer duration than a temporary EVD, which is eventually weaned and removed during hospitalization. With gross-total resection, the risk of obstruction was typically low and an EVD and septostomy were usually not needed. In contrast, the need for an EVD and/or septostomy is higher in LITT, since there is no tissue removal and post-ablation edema increases the risk of obstructive hydrocephalus. For transcortical or transcallosal approaches, the ventriculostomy catheter was typically placed down the tract of the resection cavity at the end of the procedure and tunneled under the skin. After LITT procedures, a ventriculostomy catheter was placed in two possible ways: 1) the laser fiber was removed and the ventriculostomy catheter was passed down the same trajectory, or 2) a new burr hole was made at Kocher’s point and the ventriculostomy catheter was passed into the ipsilateral lateral ventricle per routine technique.

**Assessment of Tumor Progression and/or Recurrence**

Preoperative and postoperative T1-weighted MR images with and without gadolinium contrast were used to assess tumor progression and/or recurrence. Coronal, transverse, and longitudinal measurements of the tumor were made at the maximal width in each imaging study. Tumor volume in cubic centimeters was calculated as the product of the three measurements divided by 2. Tumor progression or recurrence was determined when the tumor volume was increased compared with measurements from the prior imaging study. Patients generally underwent MRI the day after surgery, 3–6 months after surgery, and 1 year after surgery.

**Statistical Analysis**

Statistical analysis was performed using IBM SPSS Statistics software (version 28.0, IBM Corp.). Correlations were considered significant at p < 0.05. The independent-samples t-test was used to analyze the comparisons of means, and Fisher’s exact test was used to analyze the comparisons of categorical variables.

**Results**

**Patient Characteristics**

A summary of clinical, demographic, and surgical characteristics is provided in Table 1. There were 16 surgical procedures among 12 patients from 2007 to 2022 at a single institution. The majority of patients were White (83%, n = 10/12) and male (75%, n = 9/12). The median age at surgery was 8.7 years (IQR 4.4–14.4 years). The median follow-up was 5.3 years (IQR 3.6–12.4 years). Of the 16 surgical procedures, 56% (9/16) were through open craniotomy and 44% (7/16) were with LITT. A comparison of surgical factors between open resection and the LITT approach is provided in Table 2. Of the 16 surgical procedures, all intraventricular tumors were located in the frontal horn; 69% (11/16) were left-sided and 31% (5/16) were right-sided. Of the 16 surgical procedures, 8 were due to enlargement of ventricle size indicative of hydrocephalus and 8 were due to enlargement of tumor on serial imaging. In all cases, a ventriculostomy catheter was placed in 63% (10/16) of patients and a septostomy was performed in 44% (7/16). The median length of hospital stay (LOS) was 4 days (IQR 3–6 days). The mean tumor volume was 4.1 cm³ (median 2.7 cm³, IQR 2.0–4.4 cm³). Tumor progression or recurrence occurred in 36% (5/14) of patients (Table 3).

**Surgical Complications**

There were 4 patients who experienced complications, all of which occurred with open craniotomy (Table 3). Pa-
tient 2 experienced postoperative ventriculomegaly, which resolved after a period of temporary external ventricular drainage. After this patient’s planned second procedure on the contralateral side, he experienced left-sided hemiparesis postoperatively. On postoperative MRI, there was a signal change thought to be consistent with basal ganglia venous congestion. The weakness improved over time with therapy and rehabilitation. Patient 3 experienced wound dehiscence requiring reoperation for washout. Patient 7 experienced bone flap migration on serial imaging, which required reoperation. There were no perioperative deaths or permanent neurological deficits in any of the patients.

Hydrocephalus and CSF Diversion

Indications for surgery were ventriculomegaly and/or hydrocephalus in 50% (8/16) of procedures and enlargement of tumor on serial imaging in the other 50% (8/16). Only 1 patient (patient 2) experienced hydrocephalus postoperatively requiring ventriculostomy catheter placement. Interestingly, this patient’s indication for surgery was not ventriculomegaly or hydrocephalus, but rather enlargement of tumor on serial imaging with stable ventricle size. Twelve days after uneventful gross-total resection, this patient returned to the clinic with a persistent severe headache and was found to have increased ventricle size on imaging. An EVD was placed, and the patient was monitored in the intensive care unit. The patient’s ventriculostomy catheter was eventually weaned and removed. None of the patients in the case series required shunt placement.

Comparison of Open Craniotomy and LITT

The open craniotomy group had a median follow-up duration of 8.4 years (IQR 3.4–14.4 years) compared with the LITT group, which had a median follow-up duration of 3.9 years (IQR 3.4–5.1 years). Both groups had a median LOS of 4 days. The median preoperative tumor volume in the open group was 2.3 cm$^3$ (IQR 1.7–4.6 cm$^3$) compared with the LITT group, at 2.7 cm$^3$ (IQR 2.0–3.9 cm$^3$). Among the open procedures, 66% (6/9) had EVD placement and 55.6% (5/9) had septostomy performed during surgery. Among the LITT procedures, 57.1% (4/7) had EVD placement and 28.6% (2/7) had septostomy performed during surgery. There was a significantly higher rate of complications in the open group than in the LITT group (44% [4/9] vs 0% [0/7], $p = 0.042$) (Table 3). The complication rate of 44% in the open group is higher than expected for similar open craniotomy procedures for resection of a lesion, and therefore comparison with LITT in this cohort should be interpreted with caution as the generalizability of these results may be limited. Figure 2 shows preoperative, 1-day postoperative, and follow-up MR images of open and LITT cases with and without progression and/or recurrence. There was no significant difference in rates of tumor progression and/or recurrence between the open and LITT groups (33% [3/9] vs 33% [2/6], $p = 0.803$) (Table 3). Interestingly, the 2 patients in the LITT group who had tumor progression were the only LITT patients who had intratumoral calcification present on preoperative CT imaging (Fig. 3).

Discussion

This single-institution experience suggests the safety and effectiveness of LITT as a treatment for SEGAs. Given the known curative nature and low recurrence rate after gross-total resection, it is notable that similar results to those of open resection were achieved with less invasive laser ablation. In the LITT cohort, all the patients with no recurrence demonstrated shrinkage of the tumor size by follow-up imaging within 6 months of surgery (Fig. 4). In contrast, those with eventual tumor progression showed no shrinkage of tumor size within 6 months of surgery (Fig. 4). Figure 4 demonstrates a trend in tumor size toward no progression or progression that can be observed by 6 months postoperatively. Interestingly, we also observed that the 2 LITT cases with progression were the only cases that had intratumoral calcification on preoperative CT imaging (Fig. 3). While these small numbers prohibit assuming causation, this observation of decreased effectiveness of laser ablation on calcified tumors does represent a plausible mechanism to be considered in future studies. This raises the question of whether intratumoral calcifications possibly hinder the process of thermal ablation and in turn tissue coagulation and necrosis. Given the known heat sink effects of materials with lower thermal conduc-

tion (such as flowing CSF), intratumoral calcification could represent a possible negative prognostic factor for the LITT approach if replicated on future studies.

LITT does have its own set of limitations, however, with longer intraoperative times than the open craniotomy standard and increased need for hospital resources. LITT surgeries require extensive hospital resources, which include intraoperative CT imaging, intraoperative advanced MRI, anesthesia considerations for MRI and patient transport, operating room accommodations for MRI and patient transport, stereotactic guidance (e.g., robotic ROSA arm), and a laser ablation system with emitters that are both costly and nonreusable. In addition, a misstep or error in any of these moving parts can prevent the entire case from running smoothly, which makes this procedure more vulnerable to equipment failures. In addition, many of these factors are outside the direct control of the surgical, anesthesia, and operating room personnel. This is an

<table>
<thead>
<tr>
<th>Complication</th>
<th>%</th>
<th>Total</th>
<th>Total</th>
<th>%</th>
<th>Total</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complication</td>
<td>25%</td>
<td>4/16</td>
<td>44%</td>
<td>4/9</td>
<td>0%</td>
<td>0/7</td>
</tr>
<tr>
<td>Progression &amp;/or recurrence</td>
<td>36%</td>
<td>5/14</td>
<td>33%</td>
<td>3/9</td>
<td>33%</td>
<td>2/6</td>
</tr>
</tbody>
</table>

This single-institution experience suggests the safety and effectiveness of LITT as a treatment for SEGAs. Given the known curative nature and low recurrence rate after gross-total resection, it is notable that similar results to those of open resection were achieved with less invasive laser ablation. In the LITT cohort, all the patients with no recurrence demonstrated shrinkage of the tumor size by follow-up imaging within 6 months of surgery (Fig. 4). In contrast, those with eventual tumor progression showed no shrinkage of tumor size within 6 months of surgery (Fig. 4). Figure 4 demonstrates a trend in tumor size toward no progression or progression that can be observed by 6 months postoperatively. Interestingly, we also observed that the 2 LITT cases with progression were the only cases that had intratumoral calcification on preoperative CT imaging (Fig. 3). While these small numbers prohibit assuming causation, this observation of decreased effectiveness of laser ablation on calcified tumors does represent a plausible mechanism to be considered in future studies. This raises the question of whether intratumoral calcifications possibly hinder the process of thermal ablation and in turn tissue coagulation and necrosis. Given the known heat sink effects of materials with lower thermal conduc-

Discussion

This single-institution experience suggests the safety and effectiveness of LITT as a treatment for SEGAs. Given the known curative nature and low recurrence rate after gross-total resection, it is notable that similar results to those of open resection were achieved with less invasive laser ablation. In the LITT cohort, all the patients with no recurrence demonstrated shrinkage of the tumor size by follow-up imaging within 6 months of surgery (Fig. 4). In contrast, those with eventual tumor progression showed no shrinkage of tumor size within 6 months of surgery (Fig. 4). Figure 4 demonstrates a trend in tumor size toward no progression or progression that can be observed by 6 months postoperatively. Interestingly, we also observed that the 2 LITT cases with progression were the only cases that had intratumoral calcification on preoperative CT imaging (Fig. 3). While these small numbers prohibit assuming causation, this observation of decreased effectiveness of laser ablation on calcified tumors does represent a plausible mechanism to be considered in future studies. This raises the question of whether intratumoral calcifications possibly hinder the process of thermal ablation and in turn tissue coagulation and necrosis. Given the known heat sink effects of materials with lower thermal conduc-

TABLE 3. Statistical comparison of complication and progression and/or recurrence rates between open resection and LITT

<table>
<thead>
<tr>
<th>Complication</th>
<th>%</th>
<th>Total</th>
<th>%</th>
<th>Total</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complication</td>
<td>25%</td>
<td>4/16</td>
<td>44%</td>
<td>4/9</td>
<td>0%</td>
</tr>
<tr>
<td>Progression &amp;/or recurrence</td>
<td>36%</td>
<td>5/14</td>
<td>33%</td>
<td>3/9</td>
<td>33%</td>
</tr>
</tbody>
</table>
important trade-off when using this new surgical tool that relies so heavily on stereotactic navigation, laser ablation technology, and advanced MRI techniques. Since its initial implementation at our institution, however, LITT has become more frequently used and its use better orchestrated over time to allow smooth and efficient operation.

At our institution, we observed differences between the NeuroBlate and Visualase laser ablation systems. For the NeuroBlate system, the ablation tends to span a wider distance from the probe than the Visualase system. In contrast, the Visualase system ablation area is finer than that of the NeuroBlate system, which is useful when trying to avoid surrounding structures. When trying to avoid surrounding structures, the NeuroBlate system does provide the option of using SideFire directional probes, which focus ablation in one direction rather than circumferentially. The NeuroBlate system also uses a self-driving robotic probe to advance or withdraw the laser catheter over a specified length. While the Visualase system does not use a robotic probe and requires manual advancement/withdrawal of the probe, it allows for ablation throughout the entire length of the probe rather than only a specified length. The Visualase system uses bolts and catheters that are less bulky than the robotic probe driver of the NeuroBlate system, which allows for easier placement of multiple trajectories in close proximity. In our institutional experience, a large part of the selection between the NeuroBlate and Visualase systems was based on practicality and accessibility, since NeuroBlate was first available in the adjacent adult hospital system, with Visualase later becoming available within our own pediatric hospital system.

The management of SEGA recurrence and/or progression has become increasingly varied as new treatment options have emerged. Once tumor recurrence or progression is identified on follow-up imaging, a multidisciplinary approach is often needed to counsel the patients on a variety of treatment options, including pharmacological (e.g., mTOR inhibitors), surgical, and stereotactic radiotherapy options. Of the 5 patients who had tumor recurrence or progression in this case series, 2 underwent stereotactic radiosurgery (Gamma Knife), 2 underwent LITT, and 1 underwent observation of the recurrence with short-interval serial imaging and consideration of everolimus treatment. Only 1 patient in the case series underwent everolimus treatment, although this was 5 years after gross-total resection of SEGA and for treatment of renal angiomyolipoma. This demonstrates both the expansion of treatment options and the challenges in decision-making for patients and families.

Postoperative pain and discomfort is a metric that is often difficult to objectively measure in the pediatric patient population. We have generally observed a vast difference in the postoperative pain control required between patients who undergo open craniotomy versus LITT. As previously

FIG. 2. Examples of open craniotomy and LITT cases with and without tumor progression and/or recurrence. The postoperative images were obtained within 1 day of the surgical procedure. In reference to Table 1, these images were obtained in patients 2, 5, 11, and 10 (left to right columns). f/u = follow-up. Figure is available in color online only.
reported, there appears to be far less pain and discomfort experienced among patients in the LITT group, who only have small entry sites compared with a larger craniotomy incision. In addition, we observed no complications in the LITT group and 4 (44%) in the open group (p < 0.05). Other studies have reported postoperative complication rates of 29%, 35%, 12, 31, 48%, 32 and 57%. Although limited by the small and heterogeneous patient cohort in this case series, our observations support LITT as a safe and effective procedure.

The experience with both open resection and LITT for SEGAs at our institution has helped us understand the benefits of both procedures. In deciding between LITT and open resection in the future, it will be important to consider each patient’s individual factors, including clinical, physiological, anatomical, and social factors. For example, LITT may be a better surgical option for patients who have a higher risk of surgery (one study reported a higher risk for patients younger than 3 years of age, with bilateral tumors, or with tumor widths larger than 2 cm). In contrast, open resection may be a better surgical option for SEGAs that demonstrate an irregular shape, parenchymal infiltration, or need for numerous laser trajectories for total ablation. Transcallosal resection with concurrent anterior cor-

**FIG. 3.** Among the LITT cases, the tumors that developed progression and/or recurrence had calcifications noted on preoperative CT and MR images. Postoperative MR images were obtained within 2 weeks of the surgical procedure. In reference to Table 1, these images were obtained in patients 7, 8, 11, 9, and 10 (left to right columns). Figure is available in color online only.
pus callosotomy may also be a good open surgical option for SEGAs patients with medically refractory atonic seizures. In addition, given our observations of the possible decreased efficacy of LITT in tumors with intratumoral calcifications, open resection may be a better option for heavily calcified SEGAs. Lastly, MRI thermometry monitoring during LITT allows for real-time visualization of the fornices during ablation. In addition, thermal thresholds can be placed on the fornix that facilitate automatic laser shutoff for added safety. Our limited number of cases prevents objective quantification of risk, but the subjective experience suggests better control of risk to fornices with LITT via thermometry monitoring. Given the encouraging results in this small-sample case series, we look forward to future studies with larger cohorts and long-term follow-up to better understand the advantages and limitations of LITT for the treatment of SEGAs.

The major limitation of the present study is that the data were collected from a small and heterogeneous retrospective cohort at a single center. The results reflect local patterns relating to the surgical experience of our institution, and therefore may not be generalizable to all pediatric neurosurgery centers. The small number of cases prohibits any definite determination of outcome or causality associated with either surgical approach. In addition, the complication rate in the open group is higher than expected for such a procedure, which may limit the validity of comparing the safety of open resection with that of LITT in this cohort. Our observations need validation by a multicenter study with a larger sample size. Despite these limitations, this study is valuable because it demonstrates our institutional experience with LITT as a safe and less invasive alternative to open resection of SEGAs with comparable surgical outcomes.

Conclusions

This case series supports LITT as a less invasive surgical alternative to open resection of SEGAs and demonstrated that LITT has similar progression and/or recurrence rates to open resection. In the setting of extant literature, we interpret these data as insufficient to suggest the superiority of either procedure, but rather as evidence supporting LITT and open resection as viable surgical options with unique advantages and disadvantages to be considered within the context of patient-specific factors and tumor characteristics on a case-by-case basis. Further studies are warranted to better compare the efficacy and long-term outcomes of LITT and open resection for SEGAs.

References

19. Lam C, Bouffet E, Tabori U, Mabbott D, Taylor M, Bartels U. Rapamycin (sirolimus) in tuberous sclerosis associated pedi-