olfactory groove meningiomas arise from the midline anterior cranial fossa, extend from the crista galli to the planum sphenoidale, and account for 8% to 13% of meningiomas.2,41 Frequently, these massive tumors can extend posteriorly and envelop the anterior clinoid processes and the parasellar region. Moreover, these aggressive meningiomas can infiltrate and erode the cribriform plate, invading the ethmoid and sphenoid sinus. Microsurgical approaches include bicornal, pterional, and lateral supraorbital “keyhole” craniotomies.2,42 In the
absence of atypical or malignant pathology, the reported recurrence rates vary in the literature from 0% to 35% at 5 years, mostly from tumor infiltration of the bone at the base of the skull.10,25–29,44–49.53 Open surgical techniques may require obliteration of the anterior portion of the superior sagittal sinus, significant frontal lobe retraction, and exenteration of the frontal sinuses, leading to a mortality rate as high as 5% and a complication rate as high as 30% from frontal lobe trauma, venous infarcts, hemorrhages, CSF leakage, and infection.41 Vascular control of the ethmoidal arteries, which are the major feeding arteries for this tumor, is difficult to obtain from either endovascular or transcranial routes, leading to significant bleeding during tumor debulking prior to devascularization.41,58

Advances in endoscopic endonasal surgery have provided a novel minimally invasive approach to lesions of the anterior cranial fossa.1,48 Initially used for pituitary tumors and other lesions of the sella, these approaches have recently been extended to address lesions in regions as rostral as the crista galli and as caudal as the clivus and odontoid, including olfactory groove meningiomas.4,6,7,13,14,20,26–29,30,35,36,43,45,55 The advantages of the endonasal endoscopic approach are early devascularization of the tumor, preservation of the sagittal sinus, and the lack of frontal lobe retraction. Furthermore, this technique allows rapid access to intranasal regions that have been potentially invaded by the tumor, such as the ethmoid sinus. However, one major downside is the fact that manipulation of the olfactory apparatus is required, with inevitable damage and universal loss of olfaction. Access to the lateral extent of the dural tail is also limited. Moreover, a recent review of the literature showed that the extent of resection (EOR) of olfactory groove meningiomas using the endonasal approach was lower than through cranial approaches and the complication rates were higher.33 To improve the potential complications of the transcranial approach, our center has explored using the endonasal endoscopic approach and supraorbital keyhole mini-craniotomy. This latter approach allows the surgeon to slip under the frontal lobe, thereby minimizing retraction injury, and allows the preservation of olfaction with removal of the tumor that extends laterally and thereby extends over the orbits. However, the exposure is limited and visualization of the cribriform plate is often impeded by the orbital roof. For this reason, we have routinely employed endoscopic assistance to increase the exposure provided by the supraorbital approach. In this report, we present the results of performing the endonasal approach with the supraorbital approach for olfactory groove meningiomas. In addition, a group of patients in which an “above-and-below” approach was used is also described for comparison, which is used mainly in cases where the supraorbital approach may not be adequate to reach the tumor extending into the ethmoid sinuses. Discussion of the outcomes and principles of case selection are discussed. We find that the supraorbital eyebrow approach provides a higher rate of gross-total resection (GTR) and lower rate of complications than the endonasal endoscopic approach. However, if tumors extend through the cribriform plate, a combination of the 2 minimally invasive approaches is an excellent alternative to traditional transcranial approaches. The endoscopic endonasal approach by itself may be suitable for a small percentage of cases.

Methods

We reviewed a prospectively acquired database of minimal access surgeries performed by a single surgeon (T.H.S.) at New-York-Presbyterian/Weill Cornell Medical Center between 2004 and 2014 for olfactory groove meningiomas. The included patients underwent purely endoscopic endonasal surgery (Group 1), supraorbital keyhole approaches using the microscope with endoscopic assistance (Group 2), or a combined approach (Group 3), in which the endoscopic endonasal approach was combined with either a supraorbital keyhole or a standard bifrontal craniotomy approach. The details of the operative approaches are described elsewhere.9,20,50 However, the following is a brief summary of the key points of the surgeries, as well as our philosophy regarding approach selection.

Surgical Technique

Endoscopic Endonasal Approach

After administering triple antibiotics, we place a lumbar drain and administer intrathecal fluorescein (0.25 ml of 10% fluorescein; Akon Laboratories) mixed with 10 ml of CSF.45–55 Intrathecal fluorescein is useful to ensure that a watertight closure is obtained at the completion of the procedure. The head is placed in rigid fixation and registered with frameless neuronavigation, with the neck slightly extended to facilitate visualization of the cribriform plate and forvea ethmoidalis. The thigh is prepared for harvesting autologous fat and fascia lata for multilayered skull base reconstruction.37,54 A long nasoseptal flap is harvested.20,31 A bilateral transethmoidal, transcribriform approach is performed, exposing the skull base from the back of the frontal sinus to the planum sphenoidale between the forvea ethmoidalis bilaterally.39 Using a 30° endoscope on a scope holder, the anterior and posterior ethmoidal arteries are identified, cauterized, and transected at the junction between the forvea ethmoidalis and lamina papyracea. The tumor within the ethmoid sinuses is debulked using either a Nico Myriad (NICO Corporation) or Elliquence tissue shaver (Elliquience Innovations). The bone of the skull base is drilled down to the dura circumferentially around the base of the tumor and the cribriform plate is removed en bloc, exposing the attachment of the tumor. The dura is cauterized with the Elliquence tissue shaver, and aggressive internal decompression is performed aided by surgical navigation.

Once radical decompression is completed, the margins of the tumor can be mobilized into the cavity created in the center of the tumor. Likewise, the olfactory nerves can be found laterally and often preserved. However, anosmia is universally elicited as a result of the approach, due to damage to the olfactory mucosa and removal of the cribiform plate.

The closure is multilayer and has evolved at our institution. In the early years, we filled the cavity with autologous fat followed by an onlay of dural substitute, additional fat, and tissue sealant. Currently, we place an inlay of Duraform (Codman-DePuy Orthopedics Inc.) followed by an onlay of fascia lata held in place by a countersunk piece of Medpor (Porex Surgical Products Group), which we have called the “gasket seal.”43,57 This is then covered
Minimally invasive approaches for olfactory groove meningiomas

with a nasoseptal flap and tissue sealant. Foley balloons are sometimes placed in the cavity if the inlay buttress is not secure, which depends on the amount of bone remaining after surgical removal of the tumor.

The sinuses are filled with FloSeal (Baxter) for hemostasis. The lumbar drain is left open for 1 to 2 days to drain at a rate of 2.55 ml/hour. In some cases, early in our series, a lumbar drain was not used, but we now place them routinely in all cases. All patients are placed on subcutaneous heparin and mechanical compression stockings until ambulation.

Supraorbital Keyhole Approach With Both Microscope and Endoscope Assistance

After administering cefazolin (Ancef), the patient is placed in rigid head fixation and navigation is employed. Slight rotation and extension of the head is performed to facilitate the frontal lobe falling away from the skull base. An incision is made in the eyebrow in the direction of the follicles, and dissection is carried out through the orbicularis oculi muscle. A small pericranial flap is raised. A 1-piece craniotomy is performed, including the orbital rim, from the keyhole to just medial to the supraorbital nerve. We prefer to take the orbital rim to facilitate exposure of the cribriform plate. Bony prominences on the roof of the orbit are flattened. The dura is opened in a C shape and reflected toward the orbit. CSF is drained until the brain is relaxed. The tumor is internally decompressed and sharply dissected off surrounding structures in a standard microsurgical fashion. Every effort is made to preserve the olfactory nerves if possible. Given the small opening, the most difficult aspect of the operation is the removal of the tumor deep in the cribriform plate and anterior along the crista galli. To obtain adequate visualization of these areas, we use endoscope assistance with a 45° endoscope (Karl Storz). In addition, the Elliquence tip is bent almost 45° to reach around the corner, and the base of the tumor is removed down to bone. The base of the tumor is fulgurated down to the bone. If a defect is anticipated, or if the tumor extends into the ethmoids, we prefer to combine the supraorbital keyhole approach with the endoscopic endonasal approach so the defect can be patched from below and a nasoseptal flap can be used. This “combined” approach was performed in a series of patients also described in this paper.

Combined Approaches

In certain cases, we elected to use a combined “above-and-below” approach, i.e., supraorbital eyebrow keyhole craniotomy combined with an endoscopic endonasal approach. One might argue that using a single bifrontal transcranial approach might be more economical since there is no olfactory groove meningioma that cannot be removed using an extended transbasal approach. However, the principles of minimal access surgery emphasize that using natural corridors and minimizing retraction or movement of the normal neural structures will lead to improved outcomes, and we prefer to perform 2 minimal access procedures over 1 procedure if that 1 procedure involves more brain retraction, crossing the boundaries of the cranial nerves, or significant manipulation of the critical vascular structures that might be minimized through a minimal access approach. The technical aspects of combining 2 approaches are no different than performing each approach by itself, and they can be performed either sequentially or simultaneously. In some cases, however, we favor bifrontal craniotomy over the eyebrow approach based on the potential need for a pericranial flap. These flaps, based anteriorly, are superior to nasoseptal flaps for closing defects near the back wall of the frontal sinus. Hence, for tumors that extend up behind the back wall of the frontal sinus and also extend into the nasal cavity, we combine the endoscopic endonasal approach with a standard bifrontal craniotomy.

Principles of Patient Selection

Our selection criteria for each approach—either alone or in combination—has evolved over time. In presenting how our selection criteria evolved, we refer to some of the results of this paper, but a detailed discussion of the selection criteria, benefits, and limitations of each approach is critical to determining which approach is most suitable for which type of patient. In the beginning of our series, we attempted to remove all olfactory groove meningiomas that did not extend more than 1 cm beyond the lamina papyracea through an endoscopic endonasal approach. Our results were suboptimal with respect to the EOR and closure of the anterior aspects of the skull base adjacent to the frontal sinus and, of course, all patients were anosmic. We then adopted the supraorbital keyhole approach, which allowed us to remove even meningiomas that extended more laterally along the skull base and also permitted the preservation of olfaction in selected cases. However, those cases that extended through the cribiform plate required skull base repair that could not be performed through the supraorbital keyhole, and for these cases we combined the supraorbital keyhole with the endoscopic endonasal approach. Only if the tumor extended far anterior along the back wall of the frontal sinus or into the frontal sinus would we use a standard bifrontal craniotomy in order to use a pericranial flap. Since the most direct and shortest route to the tumor is always preferred, those that extend up the back wall of the frontal sinus and elevate the frontal lobe off the anterior fossa can be easily reached through craniotomy without brain retraction, and the defect in the skull base is difficult to close with only a posteriorly based nasoseptal flap. Over time, we rarely performed the endoscopic endonasal approach by itself since the most appropriate cases—namely, small olfactory groove meningiomas that do not reach forward to the frontal sinus—were the very cases where olfaction might be preserved. These are the very cases that are best removed through a supraorbital keyhole since the olfactory nerves and nasal mucosa can be maintained.

Radiological Assessment of the EOR, Mohr Class, and the Lion’s Mane Sign

The largest dimensions of the tumors were measured in the anterior-posterior, transverse, and craniocaudal dimensions on the postcontrast T1-weighted sequences obtained in the preoperative MR examination. Volumetric...
analysis was also performed utilizing the General Electric Advantage Workstation (version 2.0). The postcontrast axial 3D T1-weighted spoiled gradient echo sequence was used for preoperative tumor measurement. This sequence was reformatted in the General Electric Advantage Workstation software and, using the 3D paintbrush tool, the tumors were shaded and subsequently analyzed for volume. Postoperative volumes were assessed for those tumors with residuals by performing the same volumetric analysis on the axial T1-weighted postcontrast sequences obtained in the immediate postoperative MR exam. The volumes were assessed by a neuroradiologist in fellowship training (A.M.) in conjunction with a neuroradiologist with 10 years of experience (A.J.T.). We defined gross-total resection (GTR) as 100% resection, near-total resection (NTR) as > 95% resection, and subtotal resection (STR) as ≤ 95% resection. We did not use the Simpson grade since this scale was developed in the years before MRI scans, widespread use of the microscope, and modern neurosurgical instrumentation and, as recently reported, may have little bearing on outcome.5,21,53

The lion’s mane sign (LMS) is defined as peritumoral hyperintensity/edema extending into the bilateral frontal white matter and at least three-eighths of the total length of the external capsule, similar to the methods used by Maria Li et al.38 The presence and degree of the LMS was evaluated on the T2/FLAIR sequence. The length of each external capsule was divided into 4 quarters from the caudal nuclei toward the trigone of the lateral ventricles. This provided a total of 8 quarters. The edema from each tumor was classified based on its posterior extent and adding the number of quarters affected on both sides. Edema extending into at least three-eighths of the external capsules was considered to have a positive LMS. The Mohr classification of each anterior fossa meningioma was determined as per the classification provided by Maria Li et al. based on sagittal T1-weighted postcontrast images.38 Mohr type was determined based on tumor size and extension into different segments of the anterior fossa from the crista galli and planum sphenoidale to the tuberculum sellae and diaphragma sellae: Type I, 1 segment and < 2 cm in size; Type II, 2 segments and 2–3.9 cm; Type III, 3 segments and 4–5.9 cm; and Type IV, 4 segments and > 6 cm.

Results

General Cohort Characteristics

Overall, 19 patients met our inclusion criteria (Table 1). Mean age at surgery for the entire cohort was 61.4 years (range 41–77 years), and the study population consisted of 5 male patients (26.3%) and 14 female patients (73.7%). Of these 19 patients, there were 6 patients in Group 1 (31.6%; endonasal only), 7 patients in Group 2 (36.8%; supraorbital keyhole), and 6 patients in Group 3 (31.6%; combined endonasal approach and either supraorbital keyhole or bifrontal craniotomy). There were no statistically significant differences between the surgical groups based on age or sex (p = 0.288 and p = 0.194, respectively). Two patients (10.5%) had undergone prior surgical procedures. Of these, 1 patient had undergone transcranial resection with GTR 20 years prior with tumor recurrence after starting hormone-replacement therapy. Another patient had undergone a bicornal approach at another institution for the intracranial portion of the tumor 1 month prior and was referred to us for endoscopic endonasal management of the residual intranasal tumor. This patient was considered a staged procedure and was included in the combined group. No patients had received prior radiation therapy. Most patients presented with cognitive dysfunction and behavioral changes (7 patients; 36.8%), anosmia or dysosmia (6 patients; 31.6%), headaches (4 patients; 21.1%), and visual field deficits (4 patients; 21.1%).

Preoperative MRI studies were performed on all patients and evaluated by 2 neuroradiologists (A.M. and A.J.T.) (Table 2). The mean tumor volumes according to operative group were as follows: Group 1 (endonasal), 19.6 cm³ (range 7–49.6 cm³); Group 2 (eyebrow), 33.5 cm³ (range 7.3–61.4 cm³); and Group 3 (combined), 37.8 cm³ (range 3.2–80.7 cm³) (p = 0.401). Cortical cuff—a dissection plane between the tumor and normal brain parenchyma—was identified in 2 cases (10.5%). The majority of tumors (10 of 19; 52.6%) extended posteriorly into the planum sphenoidale and tuberculum sellae region, reaching as far as the diaphragm sella. Frontal lobe edema was identified in 10 cases (52.6%) with subsequent effacement or abutting of the lateral ventricle frontal horns, optic nerve compression or encroachment in 5 cases (26.3%), and anterior cerebral artery encasement in 5 cases (26.3%). Three of the cases with anterior cerebral artery encasement were approached using the eyebrow procedure, while 2 cases underwent a combined approach; similarly, 2 patients with optic nerve compression underwent supraorbital procedures, while the other 3 tumors were approached using a combined procedure. Six tumors (31.6%) eroded the cribiform plate and extended into the intranasal cavity, ethmoid, and/or sphenoid sinus, reaching as far as the middle turbinate; most of these cases (4 of 6; 66.7%) were approached using a combined procedure (Table 2). We then analyzed the presence of the recently described LMS and characterized each tumor using the Mohr classification system.41 Interestingly, the Mohr type significantly correlated with sex, and all 5 male patients presented with a Type III tumor (p = 0.023). The majority of tumors were either Type II (moderate) (8 of 19; 42.1%) or Type III (large) (9 of 19; 47.4%) (Fig. 1). Type IV (giant tumors) were approached using a combined procedure, while 5 of 9 Type III tumors were approached using the eyebrow approach. Most patients (14 of 19; 73.7%) did not have a clinically relevant LMS and involved less than three-eighths of the length of the external capsules (Fig. 2). The majority of patients with clinically relevant LMS (3 of 5; 60%) underwent combined surgical approaches. The other 2 patients with a clinical relevant LMS underwent the endoscopic endonasal or supraorbital keyhole approach, respectively. Due to the low number of patients in each surgical group, the associations between the Mohr type or LMS and the surgical approach were not statistically significant (p = 0.138 and p = 0.280, respectively). Similarly, preoperative tumor volumes did not correlate significantly with surgery type (p = 0.401).

Extent of Resection

The radiological and clinical outcomes are summarized in Table 3. For the entire group, GTR, NTR, and STR were
achieved in 68.4%, 21.1%, and 10.5% of patients, respectively. The overall EOR was 95.8%. However, the rates of GTR and EOR varied based on the approach. For Group 1 (the endonasal approach), GTR, NTR, and STR were 50%, 16.7%, and 33.3%, respectively. For Group 2 (the eyebrow approach), GTR, NTR, and STR were 100%, 0%, 0%, respectively. For Group 3 (the combined group), GTR, NTR, and STR were 66.7%, 33.3%, and 0%, respectively.

The EOR was 87.8% for Group 1, 100% for Group 2, and 98.9% for Group 3. Given the limited numbers of patients in each group, these results did not reach statistical significance. However, the Fisher exact test, which was used to compare the rates of GTR between the endonasal-only vs eyebrow-only approaches, did approach significance (p = 0.069). Mohr type (p = 0.451) and LMS (p = 0.397) did not correlate with EOR. The average radiographic follow-

### TABLE 1. Clinical characteristics of 19 patients undergoing olfactory groove meningioma resection

<table>
<thead>
<tr>
<th>Clinical Characteristics</th>
<th>Total No.</th>
<th>Endonasal</th>
<th>Eyebrow</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patients, no.</td>
<td>19</td>
<td>6</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>Sex</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>5</td>
<td>0</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Female</td>
<td>14</td>
<td>6</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Age, yrs (range)</td>
<td>61.4 (41–77)</td>
<td>67.3 (48–77)</td>
<td>59.3.3 (41–73)</td>
<td>57.8 (47–70)</td>
</tr>
<tr>
<td>Symptoms, no.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asymptomatic/incidental</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td>2</td>
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<tr>
<td>Seizures</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Syncope</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Headache</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Anosmia/dysosmia</td>
<td>6</td>
<td>1</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Visual field defect</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Cognitive dysfunction</td>
<td>7</td>
<td>3</td>
<td>0</td>
<td>4</td>
</tr>
</tbody>
</table>

### TABLE 2. MRI findings in 19 patients undergoing olfactory groove meningioma resection

<table>
<thead>
<tr>
<th>MRI Findings</th>
<th>Total No.</th>
<th>Endonasal</th>
<th>Eyebrow</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tumor volume, cm³ (range)</td>
<td>30.5 (3.2–80.7)</td>
<td>19.6 (7–49.6)</td>
<td>33.5 (7.3–61.4)</td>
<td>37.8 (3.2–80.7)</td>
</tr>
<tr>
<td>Planum/tuberculum/sellar extension</td>
<td>10</td>
<td>3</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Frontal lobe edema</td>
<td>10</td>
<td>3</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Optic nerve compression/encroachment</td>
<td>5</td>
<td>0</td>
<td>2</td>
<td>3</td>
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<tr>
<td>ACA impingement/encroachment</td>
<td>5</td>
<td>0</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Cortical cuff</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
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<tr>
<td>Cribriform plate extension/hyperostosis</td>
<td>4</td>
<td>0</td>
<td>2</td>
<td>2</td>
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<tr>
<td>Intranasal extension</td>
<td>6</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Effacement ventricular frontal horns</td>
<td>9</td>
<td>4</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Mohr classification</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Type II</td>
<td>8</td>
<td>4</td>
<td>2</td>
<td>2</td>
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<tr>
<td>Type III</td>
<td>9</td>
<td>2</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Type IV</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>LMS†</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>3</td>
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<td>0/8</td>
<td>10</td>
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<td>1/8</td>
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<td>2</td>
<td>1</td>
</tr>
<tr>
<td>3/8</td>
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<td>1</td>
<td>0</td>
<td>2</td>
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<tr>
<td>4/8</td>
<td>1</td>
<td>0</td>
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<td>0</td>
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<td>5/8</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
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</table>

ACA = anterior cerebral artery.

* Values represent the number of patients unless otherwise indicated.

† At least three-eighths (3/8) of the external capsules must be involved for the LMS to be considered clinically relevant.
up was 18.5 months (range 1–84 months). Residual tumor volumes ranged from 0.7 cm$^3$ to 4.3 cm$^3$. Overall, the sites of the residual tumor were around the optic nerve, at the crista galli, midline cribriform plate, ethmoid sinus, anterio-rior clinoid processes, and lamina papyracea, adherent to the anterior falx, and wrapped around the vessels at the planum sphenoidale. Two patients required postoperative radiation therapy, and 1 patient underwent Gamma Knife radiosurgery for the residual tumor.

One patient had a recurrent tumor at 4 years following endonasal endoscopic NTR (95.5%) and required bicoronal craniotomy for an enhancing mass along the tuberculum sellae. This patient was included in the endonasal endoscopic approach group for the purposes of this article. The combined above-and-below approaches were used for multicompartamental tumors with intracranial and intranasal components. In 3 cases, the 2 approaches were performed concomitantly. In 1 case, endoscopic endonasal approach decompression was performed initially and craniotomy was performed at 4 months to repair the skull base defect and resect the residual tumor. In 2 other cases, the craniotomy was performed initially and endoscopic endonasal approach followed at 2 days and 1 month, respectively.

**Visual and Olfactory Outcome**

The median follow-up time was 17.2 months (range 1–80 months). None of the 6 patients who presented with symptoms of decreased smell demonstrated improvement after resection (Table 3). Anosmia is inevitable with the endonasal approach and occurred in 100% of patients. Postoperative anosmia occurred in 57.1% of the supraorbital patients and 100% of patients who underwent a combined approach, which is again inevitable if an endonasal approach is used (Table 4). On the other hand, all 4 pa-
tients with visual field deficits, double or blurred vision, or central scotomas reported significant improvement after surgery. Visual field deterioration occurred in 0% of patients in Group 1, 0% in Group 2, and 16.7% in Group 3. Headaches subsided in 3 of 4 patients (75%), while cognitive and behavioral symptoms improved in 6 of 7 patients (85.7%). There were no recurrent seizures following resec-
tion.

Clinical outcomes after the eyebrow, endoscopic endonasal, and combined approaches were comparable. Overall, symptoms were stable in 6 of 6 patients in Group 1, improved in 3 of 7 patients in Group 2 (and remained stable in the other 4 patients), and improved in 4 of 6 patients in Group 3 (and the remaining 2 patients presented with stable symptoms). There were 0 cases of worsening symptoms following surgery. In assessing symptom improvement, we did not account for anosmia due to its subjective nature and the inevitable ensuing of anosmia following endoscopic endonasal procedures. Patients undergoing the eyebrow approaches or combined procedures were statistically more likely to have improved symptoms, as opposed to stable symptomatology following endonasal procedures ($p = 0.055$). Furthermore, the Mohr type almost reached statistical significance in predicting improved vs stable outcome ($p = 0.058$). A lower Mohr type correlates with improved outcome. LMS did not predict outcome ($p = 0.305$).

Adjuvant therapy was necessary for 5 patients: 3 patients received radiation therapy for recurrent/residual tumor, 1 patient underwent stereotactic/Gamma Knife radio-

### Table 3. Clinical and radiological outcomes following resection of olfactory groove meningioma through the endoscopic endonasal, supraorbital keyhole, or combined “above and below” approach

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Total No.</th>
<th>Approach</th>
<th>Endonasal</th>
<th>Eyebrow</th>
<th>Combined</th>
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<tr>
<td>Radiological outcome, no.</td>
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<td></td>
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</tr>
<tr>
<td>GTR</td>
<td>13</td>
<td></td>
<td>3</td>
<td>7</td>
<td>4</td>
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<tr>
<td>NTR</td>
<td>4</td>
<td></td>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>STR</td>
<td>2</td>
<td></td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Residual tumor site, no.</td>
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<td></td>
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<tr>
<td>Midline cribiform plate</td>
<td>2</td>
<td></td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ethmoid sinus</td>
<td>1</td>
<td></td>
<td>1</td>
<td>0</td>
<td>0</td>
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</table>

NA = not applicable.

* The ratio of the number of patients who improved/patients who initially presented with the respective symptom is shown.

### Table 4. Complications in patients undergoing olfactory groove meningioma resection through the endoscopic endonasal, supraorbital keyhole, or combined “above and below” approach

<table>
<thead>
<tr>
<th>Complications</th>
<th>Total No.</th>
<th>Approach</th>
<th>Endonasal</th>
<th>Eyebrow</th>
<th>Combined</th>
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<tr>
<td>Visual field deficit</td>
<td>1</td>
<td></td>
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<tr>
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<td>6</td>
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<td></td>
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<td>0</td>
</tr>
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<td>Infection</td>
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<td></td>
<td>2</td>
<td>0</td>
<td>1</td>
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<td>Opercular infarction</td>
<td>1</td>
<td></td>
<td>1</td>
<td>0</td>
<td>0</td>
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<td></td>
<td>1</td>
<td>0</td>
<td>0</td>
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<td>0</td>
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<td>Tension pneumocephalus/CSF leak</td>
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<td></td>
<td>1</td>
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<td>0</td>
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</table>

DVT = deep vein thrombosis.

* New-onset symptoms after surgery.
surgery, and 1 patient received preoperative embolization. Three patients underwent adjuvant radiotherapy.

Complications

All complications and their distributions based on the operative groups are depicted in Table 4. Overall, excluding anosmia, 5 of 6 (83.3%) cases in the endoscopic group developed postoperative complications, 0 of 7 (0%) cases in the supraorbital group developed complications, and 1 of 6 (16.7%) patients in the combined group developed complications. The endonasal approach was associated with significantly more complications (p = 0.017). Mohr type (p = 0.405) or the presence of the LMS (p = 0.603) did not significantly correlate with the development of postoperative complications. The following complications occurred in the endonasal group: anosmia, behavioral changes, infection, opercular infarction, deep venous thrombosis (DVT)/pulmonary edema, intracranial hematoma with mass effect, and tension pneumocephalus. Complications in the combined group included the following: visual field changes, anosmia, and infection. Below, we describe each complication in more detail.

There was 1 case of postoperative CSF leakage that was complicated with tension pneumocephalus. This case was part of the endonasal surgical group and required craniotomy to repair the skull base defect and evacuate accumulating air. One case developed bifrontal epidural collection that was managed conservatively. Another patient developed an intracranial hematoma with significant mass effect following endonasal endoscopic resection of the tumor. Certain complications required a second surgical intervention. A patient in the endonasal group developed a frontal sinus abscess that required a bifrontal craniotomy for evacuation. A second patient in the combined group developed fever and vomiting after surgery and underwent wound washout at 1 month. The clinical characteristics of all patients analyzed in this study are summarized in Table 5.

Follow-Up and Recurrence

After an average radiographic follow-up of 18.5 months and clinical follow-up of 17.2 months (range 1–80 months), there were 3 recurrences: 2 in the endonasal group and 1 in the combined group. Recurrence rates were not significantly different between surgical groups (p = 0.370). Furthermore, Mohr type and presence of LMS did not predict the risk of recurrence (p = 0.596 and p = 1.000). One of the residual tumors received radiotherapy following endonasal endoscopic resection. One case, described above, had a recurrence at 4 years after radiological NTR. Another tumor that recurred was a radiological GTR following a combined approach. This patient received radiotherapy to control the recurrence.

Illustrative Cases

Case 1: Endoscopic Endonasal Transethmoidal Transcribriform Approach

A 69-year-old woman with headaches, decreased smell, and the sudden loss of consciousness was found to have an olfactory groove meningioma with mild bifrontal edema that elevated the frontal lobes bilaterally. Radiologically, the tumor was classified as Mohr Type II with zero-eighths LMS. The tumor was managed expectantly and followed closely with serial MRI scans; increasing size and edema were noted on subsequent MRI scans. The tumor was removed using the endoscopic, endonasal, transethmoidal, and transcribriform approach. A lumbar drain was placed for 36 hours for prophylactic drainage. The tumor was 9.6 cm³ preoperatively, and postoperative imaging revealed that the tumor was 100% removed, thus achieving GTR (Fig. 3). She was anosmic after surgery. Soon after discharge, she collapsed and was brought back into the emergency room with a large pulmonary embolus and a small increase in her pneumocephalus. Transcranial repair of her skull base defect was performed, an inferior vena cava filter was placed, and she was eventually anticoagulated. She also had a patent foramen ovale and developed 2 small embolic strokes as the clots in her legs resolved, leaving her with mild weakness in the left hand and a visual field deficit. She ultimately recovered full strength but with persistent visual blurriness.

Case 2: Supraorbital Keyhole Approach

A 46-year-old male patient presented with headache, complaints of smelling burned plastic, blurred vision with diplopia, and dizziness. On MRI, a mass was found extending deep into the cribriform plate and ethmoids, with calcification of the cribriform plate and bilateral edema of the frontal lobes. The mass also extended posteriorly to compress the anterior cerebral arteries bilaterally. It was described as a Mohr Type III olfactory groove meningioma with a clinically relevant (four-eighths) LMS. The tumor was removed using the supraorbital keyhole approach. The tumor in the cribriform plate was removed using a 45° endoscope and the Elliguece tissue shaver. The endoscope was also used to inspect the resection cavity, and there was no evidence of residual tumor. There was also no clear breach into the ethmoid sinuses. Postoperatively, the patient was anosmic. This 47.6 cm³ tumor was considered to be 100% resected on postoperative MRI scans (Fig. 4).

Case 3: Combined Above-and-Below Bicoronal and Endoscopic Endonasal Approach

A 66-year-old female patient presented with mental status changes and was found to have a massive Mohr Type IV olfactory groove meningioma. On MRI, there was significant and associated mass effect on the parasagittal anterior frontal lobes bilaterally, as well as on the anterior and medial temporal lobes bilaterally, with thinning and posterior displacement of the corpus callosum. Both anterior cerebral arteries and the anterior communicating artery were also displaced posteriorly by this mass. There was significant and associated vasogenic edema within the anterior frontal lobes bilaterally and anterior medial temporal lobes. There was a clinically relevant LMS involving three-eighths of the length of the external capsules. The mass extended posteriorly to the planum sphenoidale and diaphragm sella with obliteration of the suprasellar cistern, circumferentially enveloping the anterior clinoid processes bilaterally. A staged procedure was attempted for this patient. A bicoronal craniotomy was initially per-
<table>
<thead>
<tr>
<th>Case No.</th>
<th>Sex</th>
<th>Age (yrs)</th>
<th>Type of Surgery</th>
<th>Previous Surgery</th>
<th>Tumor Size</th>
<th>Preop Vol (cm³)</th>
<th>Postop Vol (cm³)</th>
<th>EOR (%)</th>
<th>Location of Residual LMS</th>
<th>Mohr Type</th>
<th>Recurrence</th>
<th>Complications*</th>
<th>Postoperative Anosmia</th>
<th>Adjuvant Treatment</th>
<th>Outcome</th>
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<td>4.218</td>
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<td>II</td>
<td>No</td>
<td>Yes</td>
<td>Yes—RT</td>
<td>Stable</td>
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<td>III</td>
<td>No</td>
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<td>Yes</td>
<td>Stable</td>
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<td>III</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Improved</td>
</tr>
</tbody>
</table>

* embo = embolization; RT = radiotherapy; SRS = stereotactic surgery.

** Not including postoperative anosmia.
Fig. 3. **Upper:** Preoperative postcontrast T1-weighted image demonstrates a large enhancing mass within an anterior cranial fossa compatible with an olfactory groove meningioma. This tumor was approached using the endonasal endoscopic procedure. **Lower:** Postoperative postcontrast T1-weighted image demonstrates no residual enhancing tumor. Hyperintensity within the surgical bed is secondary to postoperative hemorrhage when compared with precontrast T1-weighted images.

Fig. 4. **Upper:** Preoperative postcontrast T1-weighted image demonstrates a large enhancing mass within the anterior cranial fossa compatible with an olfactory groove meningioma. This tumor was resected using the supraorbital eyebrow approach. **Lower:** Postoperative postcontrast T1-weighted image demonstrates no residual enhancing tumor. Hyperintensity within the surgical bed is secondary to postoperative hemorrhage when compared with the precontrast T1-weighted images.
formed. The endonasal endoscopic approach was used 2 days later to resect the portion of the tumor stuck to the cribriform plate and invading the ethmoid sinuses. Closure was achieved with a gasket seal. The patient did well postoperatively and returned to her baseline mental status. On postoperative MRI scans, this 73.4 cm³ tumor was found to be 100% resected (Fig. 5).

Discussion

Surgical treatment of olfactory groove meningiomas has traditionally required bicoronal craniotomy with excision of the frontal sinuses, sacrifice of the anterior superior sagittal sinus overlying the tumor, and closure with a vascularized pericranial flap to prevent CSF leaks. Additionally, partial frontal lobe resection has been reported as an adjunct to a limited unilateral subfrontal approach. Nevertheless, recurrence rates reportedly vary between 0% and 30% depending on the length of follow-up. Nakamura et al. recently published their experience with olfactory groove meningiomas, declaring a paradigm shift: in studying patients who died perioperatively, they theorized that routine sagittal sinus sacrifice may entail significant risks that have, until now, been underappreciated. In their study, 4 of 46 patients died in the perioperative period. Of these, 3 patients (75%) had extensive postoperative bifrontal brain edema, despite relatively small tumor sizes. The authors link their perioperative fatality rate to the type of operative approach, specifically to the routine practice of sectioning the superior sagittal sinus and draining the midline veins when performing the bifrontal approach. The principle of preserving the sinus has been supported by other studies evaluating meningioma resection techniques. Less invasive craniotomy approaches, such as the pterional approach, can spare the superior sagittal sinus in appropriately selected patients. Postoperative frontal lobe edema and injury from frontal lobe retraction has been a concern of several groups. In an effort to minimize brain retraction, Chi et al. advocated a more extended bifrontal craniotomy. Furthermore, orbital osteotomies have been used to obtain the shortest working distance while also eliminating the need for brain retraction. However, extensive craniofacial approaches increase the risk of CSF fistula due to the wide opening of the frontal sinus.

Thus, concern over brain retraction and potential sequelae has prompted efforts to modify the transcranial approaches. As a result, surgeons have attempted more limited craniotomies, including unilateral subfrontal, supraorbital, and minipterional approaches. Likewise, the endonasal endoscopic approach has been advocated. However, the endonasal approach has inherent anatomical limitations and cannot reach laterally extending tumors (Fig. 6). Furthermore, as we show in this article, the limitations of the endonasal endoscopic approach may outweigh the benefits. Indeed, if a minimally invasive technique is to be offered, the supraorbital eyebrow mini-craniotomy with endoscopic assistance results in a higher EOR with fewer complications in our hands.

![FIG. 5. Upper: Preoperative postcontrast T1-weighted image demonstrates a large enhancing mass within the anterior cranial fossa compatible with an olfactory groove meningioma. Bicoronal craniotomy was initially performed. An endonasal endoscopic approach was used 2 days later to resect the portion of the tumor stuck to the cribriform plate and invading into the ethmoid sinuses. Lower: Postoperative axial postcontrast T1-weighted image demonstrates no residual enhancing tumor. Hyperintensity within the surgical bed is secondary to postoperative hemorrhage when compared with the precontrast T1-weighted images.](image-url)
The endonasal endoscopic approach has several theoretical advantages. Since tumor-involved bone is a frequent site of recurrence, the endonasal approach facilitates resection of the invaded bone of the cribriform plate as an integral and necessary part of the approach. Likewise, the blood supply to the tumor is removed early in the operation. However, the endonasal endoscopic approach uniformly results in anosmia, and, in some midline tumors, the transcranial approach may allow the preservation of olfaction. Finally, the limitations in exposure risk by leaving the tumor extended laterally over the orbits and the high rate of postoperative CSF leakage render the approach currently less appealing than the results that can be obtained through craniotomy, as demonstrated in a recent systematic review of the literature. In this review, GTR was achieved in 92.8% of craniotomy patients compared with 63.2% of endonasal patients. Likewise, CSF leakage occurred in 6% of craniotomy patients and 31.6% of endonasal patients. Gardner et al. reported their experience using endoscopic endonasal approaches for anterior cranial base meningiomas. Within their series of 35 patients, the authors presented 14 olfactory groove meningiomas and achieved GTR or NTR (i.e., > 95%) in 10 of 12 attempts, representing 83% of patients in whom GTR was attempted and 67% overall. Their CSF leakage rate was 27%. Moreover, 2 of their 14 patients were treated for recurrent or residual disease after previous craniotomies.

In this paper we demonstrate that the principles of minimally invasive surgery can be preserved and higher rates of resection with fewer complications can be achieved using supraorbital eyebrow mini-craniotomy. With removal of the orbital rim, the surgeon can slip under the frontal lobe to minimize retraction and there is no resection of the sagittal sinus. Larger tumors extending over the orbits can be removed, and with smaller tumors there is the possibility of preservation of the olfactory nerves. One of the limitations of the eyebrow approach has been the inability to visualize the cribriform plate since the orbital roof blocks the view. We have overcome this problem using a 45° endoscope and the Elliquence tissue shaver, a thermal ablation device that can be bent at a 45° angle to permit fulguration of the dura and the invaded bone of the cribriform plate. However, removing the invaded bone is not advised using this approach since the ability to repair a defect in the ethmoid sinus is limited. For this reason, when the tumor extends through the cribriform plate, we combine the supraorbital eyebrow approach with the endonasal endoscopic approach, which leverages the strengths of each technique. Whether extensive fulguration of the skull base with the Elliquence tissue shaver is inadequate to prevent tumor recurrence will be borne out with longer follow-up studies.

The supraorbital eyebrow approach has been used for decades to approach vascular pathology as well as anterior skull base neoplasms. Supraorbital craniotomy can provide a more direct approach to certain pathologies of the anterior skull base and reduce the time from skin incision to durotomy to approximately 15 minutes. Moreover, the smaller skin incision along with limited soft-tissue dissection can reduce associated postoperative complications. Recent authors have highlighted the versatility of this approach and the use of the orbital osteotomy or endoscopic assistance to increase its utility. Another important advantage provided by the supraorbital eyebrow approach hinges on the keyhole concept. This concept relies on the following phenomenon: a small opening creates a surgical field that widens with increasing distance from the craniotomy site. Thus, paradoxically, the smaller opening of this minimally invasive approach may actually provide superior surgical fields compared with classic transcranial approaches. In their study, Figueiredo et al. were the first to show that less invasive approaches can be equally effective and valid alternatives to standard craniotomies, including periorbital approaches. Furthermore, such minimally invasive approaches can overcome the complications of periorbital craniotomies, including temporalis muscle atrophy, mandibular pain, and chewing problems. A recent literature review has demonstrated that a total of 81 cases of olfactory groove meningiomas removed using the supraorbital eyebrow approach have been reported. Of these, GTR was achieved in 91.4%. However, there were 8 (10%) CSF leaks and 5 (6.2%) wound infections. These results highlight that care must be taken not to remove too much bone in order to prevent penetration into the nasal cavity. Furthermore, large frontal sinuses are an important limitation to the supraorbital approach. A large sinus increases the risk of postoperative CSF leakage and alters the surgical trajectory. Combining the supraorbital approach with the endonasal approach when necessary reduced the number of CSF leaks to 0 in our series. The basic concept here is to recognize the limits and limitations of each approach. By combining above-and-below approaches in massive multicompartmental Mohr Type IV meningiomas, we were able to effectively resect the tumor—achieving NTR in all 6 cases—while also achieving adequate skull base reconstruction. This led to a 16.7% (1 of 6 patients) recurrence rate and a 0% CSF leakage rate.

Extracranial extension of olfactory groove meningiomas is more frequent than previously thought. It also cor-
Minimally invasive approaches for olfactory groove meningiomas

relates with a higher recurrence rate. In our series, 31.6% of patients had intranasal extension. This is similar, if not slightly higher, to what has been recently reported in the literature. DeMonte described a 15% rate of extension into the ethmoid sinuses, while Spektor et al. demonstrated a 26.3% extension rate to the paranasal sinuses, including 6 patients with both paranasal sinus and optic nerve involvement. Nakamura et al. described paranasal tumor extension of 14 tumors (30.4%) that were operated on through the bifrontal approach, whereas in their frontolateral group the rate of extracranial extension was 5.8%. Such tumors have been traditionally accessed using the subcranial approach. For massive tumors eroding the cribriform plate and invading into the nasal cavity and paranasal sinuses, we have opted for a combined, minimally invasive approach. Combined “above-and-below” approaches have been previously described for other tumors of the anterior skull base, specifically esthesioneuroblastomas. Liu et al. described an approach algorithm based on the anatomical location of anterior cranial base tumors and the extent of paranasal sinus invasion. The scope of the algorithm was to minimize craniofacial resections while enhancing surgical access. Tumors with a preponderant intracranial location or tumors involving the superior orbital region were accessed best through a transbasal approach. Tumors with a paranasal sinus component, as well as significant intracranial invasion with lateral extension across the orbits, were adequately approached using a transbasal procedure from above in conjunction with endoscopic exploration from below. The authors propose that the endoscope can function as an adjunct to the standard bifrontal craniotomy by allowing visualization of nasal and paranasal extension. The authors conclude that use of the endoscope as a supplement to classic surgical approaches can mitigate the need for any additional facial incisions by allowing access to areas hidden from the microscope’s field of view. In 7 of 13 esthesioneuroblastoma patients (53.8%), de Divitis et al. achieved complete endoscopic endonasal removal of the nasal component of the tumor; this was followed by an anterior craniotomy to remove the cribriform plate and any anterior cranial fossa extension. In their series, 3 of 13 patients had postoperative complications and 2 patients had decreased mental status. Furthermore, 1 of the patients with mental status changes also developed neurogenic adult respiratory distress syndrome. The oncological goals of esthesioneuroblastoma surgery preclude a direct comparison with our outcomes. Nevertheless, in our combined group, we achieved GTR in 4 of 6 cases and NTR in 2 of 6 cases. Furthermore, our compication rate was similar to that reported in the literature using combined approaches, irrespective of tumor type: 1 patient had a visual field deficit and 1 patient had an infection that required wound washout.

Several transcranial approaches have been described for olfactory groove meningioma resection. Tailored open approaches, according to tumor location and extension, allow complete removal with reduced morbidity. Bifrontal craniotomies and unilateral subfrontal approaches, as well as pterional approaches, have been successfully employed and become standard approaches for olfactory groove meningiomas. Meningiomas extending into the paranasal sinuses have been accessed using more aggressive techniques, such as the transbasal, subcranial, and fronto-orbital approaches. Furthermore, combined approaches have been attempted as well, such as frontal or bifrontal craniotomies in conjunction with orbital or nasal osteotomies, and craniofacial resection. Scope and surgical goals vary significantly on a case-by-case basis. Therefore, comparing EOR between minimally invasive approaches and traditional open procedures would not provide valid information. We therefore believe that complication rates are a superior parameter of comparison. With advancements in microsurgical techniques, complication rates for transcranial approaches have been steadily decreasing in the past years from the rates of 17.3%–22.7% described in older studies to nearly 0%. However, the inherent complications of open approaches include CSF leakage and infections, subdural hygromas, postoperative seizures, hematomas, hemiparesis, mental and behavioral changes, and visual deterioration. Most of these complications stem from the surgical corridors employed to access the tumor, which require prolonged retraction and manipulation of the neurovascular structures. By employing minimally invasive approaches, in various combinations and in conjunction with occasional judicious bifrontal craniotomies, we have kept our complication rate to a minimum. We had no complications in our supraorbital group, and only 1 of 6 patients in the combined group developed complications. On the other hand, the complication rate in our endonasal group was much higher at 66.6%. These findings point to the importance of optimal technique selection and to the superior role of the eyebrow minimally invasive approach, both in terms of outcome and morbidity. In their extensive series of open approaches for olfactory groove meningiomas, Spektor et al. had a 12.5% CSF leakage rate, resulting in meningitis in 5% of patients. We had a 5.3% overall CSF leakage rate, irrespective of the approach, and a 15.8% overall infection rate. Furthermore, Spektor et al. show that 5% of patients developed intracranial hematomas, and surgical evacuation was necessary in 2 cases. Nakamura et al. describe subdural hygromas in 6 patients (17.6%), with postoperative hydrocephalus in 2 patients (5.8%) and postoperative hemorrhage and brain edema in 2 patients (5.8%). In the Nakamura et al. series, 3 patients died because of extensive postoperative brain edema, their mortality rate was 8.7% in the bifrontal group and 0% in the frontolateral group, and the total perioperative mortality was 4.9%. Both of our patients who developed hematomas were in the endonasal group. We had 0 fatalities in our series.

The inherent complications of open approaches are significant brain retraction in the subfrontal or bifrontal approach, superior sagittal sinus ligation in the bifrontal approach, and a high or moderate risk of CSF leakage in the bifrontal, unilateral subfrontal, fronto-orbital, and subcranial approaches. Minimally invasive approaches are capable of overcoming several of these limitations. Furthermore, we believe that minimally invasive approaches can provide enhanced tumor visualization and accessibility. One of the main disadvantages of the subfrontal approaches stems from the late visualization of, and impeded access to, the posterior neurovascular complex. Bifrontal
cranial endonasal approaches will improve their results, the inevitable drawback of anosmia will never be overcome, rendering this approach potentially more morbid for patients with small tumors and intact preoperative olfaction. For tumors that extend through the cribiform plate, the addition of the endonasal endoscopic approach for an “above-and-below” approach is important to prevent postoperative CSF leakage and obtain complete tumor resection. Whether these minimally invasive approaches will ultimately lead to better outcomes compared with more standard craniotomies is currently only theoretical and will require long-term follow-up studies, but the early results appear favorable.

Conclusions
We have shown the advantages of the supraorbital eyebrow mini-craniotomy with orbital osteotomy and endoscopic assistance over the endoscopic endonasal approach for the majority of olfactory groove meningiomas. Although it is possible that with further development the endonasal approaches will improve their results, the inevitability of anosmia will never be overcome, rendering this approach potentially more morbid for patients with small tumors and intact preoperative olfaction. For tumors that extend through the cribiform plate, the addition of the endonasal endoscopic approach for an “above-and-below” approach is important to prevent postoperative CSF leakage and obtain complete tumor resection. Whether these minimally invasive approaches will ultimately lead to better outcomes compared with more standard craniotomies is currently only theoretical and will require long-term follow-up studies, but the early results appear favorable.

References


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Dr. Schwartz has worked as a consultant for Karl Storz, owns stock in Vision Sense, and receives clinical or research support from the National Institutes of Health.

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