Cavernous sinus compartments from the endoscopic endonasal approach: anatomical considerations and surgical relevance to adenoma surgery

Juan C. Fernandez-Miranda, MD; Nathan T. Zwagerman, MD; Kumar Abhinav, MD; Stefan Lieber, MD; Eric W. Wang, MD; Carl H. Snyderman, MD, MBA; and Paul A. Gardner, MD

Department of Neurological Surgery, University of Pittsburgh Medical Center; and Department of Otolaryngology, University of Pittsburgh, Pennsylvania

OBJECTIVE Tumors with cavernous sinus (CS) invasion represent a neurosurgical challenge. Increasing application of the endoscopic endonasal approach (EEA) requires a thorough understanding of the CS anatomy from an endonasal perspective. In this study, the authors aimed to develop a surgical anatomy–based classification of the CS and establish its utility for preoperative surgical planning and intraoperative guidance in adenoma surgery.

METHODS Twenty-five colored silicon–injected human head specimens were used for endonasal and transcranial dissections of the CS. Pre- and postoperative MRI studies of 98 patients with pituitary adenoma with intraoperatively confirmed CS invasion were analyzed.

RESULTS Four CS compartments are described based on their spatial relationship with the cavernous ICA: superior, posterior, inferior, and lateral. Each compartment has distinct boundaries and dural and neurovascular relationships: the superior compartment relates to the interclinoidal ligament and oculomotor nerve, the posterior compartment bears the gulfar segment of the abducens nerve and inferior hypophyseal artery, the inferior compartment contains the sympathetic nerve and distal cavernous abducens nerve, and the lateral compartment includes all cavernous cranial nerves and the inferolateral arterial trunk. Twenty-nine patients had a single compartment invaded, and 69 had multiple compartments involved. The most commonly invaded compartment was the superior (79 patients), followed by the posterior (n = 64), inferior (n = 45), and lateral (n = 23) compartments. Residual tumor rates by compartment were 79% in lateral, 17% in posterior, 14% in superior, and 11% in inferior.

CONCLUSIONS The anatomy-based classification presented here complements current imaging-based classifications and may help to identify involved compartments both preoperatively and intraoperatively.

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KEY WORDS cavernous sinus; endonasal endoscopic approach; pituitary adenomas; cranial nerves; internal carotid artery; pituitary surgery; anatomy

Pituitary and skull base tumors with cavernous sinus (CS) invasion represent a neurosurgical challenge. The surgical anatomy, safe-entry zones, and corresponding surgical routes to the CS have been studied by several authors. Transcranial skull base approaches have accessed the CS through its superior and lateral walls, where 4 different triangles (clinoidal and oculomotor for the superior wall, supratrochlear and infratrochlear for the lateral wall) were described to facilitate understanding of the intracavernous anatomy and neurovascular structures at risk. In contrast, the transsphenoidal microscopic technique was, until recently, standard for pituitary surgery and included drawbacks such as a limited lateral view toward the medial wall of the CS and difficulty remov-
The endoscopic endonasal approach (EEA) has opened new routes to the ventral skull base, including the CS. The wider view provided by the endoscope enables the surgeon to inspect the medial wall and the inside of the CS directly using a medial-to-lateral trajectory. In addition, significant advances in endonasal surgical anatomy and technique also allow direct access into the CS using an anterior-to-posterior trajectory. In contrast to the transcranial and transphenoideal microscopic approaches, the endonasal route provides access through the medial (sellar) and/or anterior (sphenoidal) walls of the CS. Similarly, the previously described CS triangles have limited utility when approaching CS lesions endonasally, and previous radiological classifications of CS invasion, while useful from the prognostic point of view, are not helpful for understanding the surgical anatomy of the different compartments within the CS.

In this study we propose a practical and surgically relevant endonasal classification scheme for different compartments of the CS in relation to the intracavernous internal carotid artery (ICA). The classification proposed here is partially modified from the venous spaces (“compartments”) described by Harris and Rhoton in 1976, where they differentiated posterosuperior, anteroinferior, and medial venous spaces in relation to the ICA.

Furthermore, we describe the distinct boundaries and dural and neurovascular relationships of each compartment. Based upon these findings and our extensive surgical experience, we then highlight the surgically relevant technical nuances for approaching these CS compartments. This classification scheme was retrospectively applied for radiological evaluation of patients with pituitary adenomas and surgically confirmed CS invasion to ascertain patterns of involvement of single or multiple compartments. We thereby aim to establish the potential utility of this anatomical classification for preoperative surgical planning and intraoperative guidance.

**Methods**

**Anatomical Study**

Twenty-five lightly embalmed, colored silicon–injected human postmortem head specimens were prepared for dissection. The research was approved by the Committee for Oversight of Research Involving the Dead at the University of Pittsburgh. Endoscopic endonasal dissections were performed using rod lens endoscopes (Hopkins II, 4-mm diameter × 18-cm length, 0° and 45°, Karl Storz) attached to a high-definition camera. Heads were positioned supine on the dissection table and a Mayfield head holder attached to a high-definition camera. Heads were positioned ×4-mm diameter 18-cm length, 0° and 45°, Karl Storz) attached to a high-definition camera. Heads were positioned supine on the dissection table and a Mayfield head holder attached to a high-definition camera. Heads were positioned supine on the dissection table and a Mayfield head holder was used to maintain an almost neutral position.

An EEA was performed in all specimens. Wide bilateral sphenoidotomies were performed to expose the posterior wall of the sphenoid sinus. The bone overlying the sellar and parasellar region was removed to allow access to the medial and anterior walls of the CS. We described 4 compartments in the CS based on their spatial relationship with the cavernous ICA: superior, posterior, inferior, and lateral compartments. The following were inspected thoroughly within each compartment: dural structures and layers, cranial nerves (CNs), and branches of the ICA. In selected specimens, the pituitary gland and the intracavernous ICA were removed to better expose and study the lateral wall of the CS. Three additional heads were bisected in a sagittal plane using a high-speed electric saw, which allowed for stepwise dissection and inspection of the CS sequentially from medial to lateral. A comparative transcranial approach to the CS was performed in all heads after the endonasal dissection with the aid of 4–24 magnification (Olympus OME 8000 surgical microscope). This comparative approach was performed for correlation of the endonasal findings.

**Clinicoradiological Study**

From January 2010 to July 2015, 384 patients underwent an EEA for pituitary adenoma by 2 neurosurgeons (J.C.F.M. and P.A.G.). Of these patients, 144 demonstrated CS invasion based on intraoperative findings. When the medial wall was not detectable (or was not intact) and/or intracavernous structures were visible (venous compartments, intracavernous ligaments, cavernous ICA adventitia, CNs), invasion was deemed to be present. The medial wall alone was invaded in 46 patients (32%), with 5 patients having bilateral medial wall invasion. These invasion determinations were based on careful intraoperative endoscopic observation and not on histological confirmation or MRI findings. This subgroup of patients with only medial wall invasion was excluded from this study, as tumor did not extend into any CS compartment. For the remaining 98 patients, preoperative MR1 studies were used to identify the involved compartments, because a significant number of operative notes were not sufficiently detailed to accurately discern patterns of invasion. Adequate pre- and postoperative MR1 studies were available in all cases. Postcontrast T1-weighted axial, sagittal, and coronal sequences (1.25-, 3-, and 3-mm thicknesses, respectively) through the parasellar region were carefully studied. The surgical anatomy–based classification described in this study was applied to interpret the patterns of CS invasion, namely the CS compartments potentially invaded by tumor.

**Results**

**Parasellar ICA**

Understanding the parasellar ICA anatomy is essential for understanding the anatomy of the CS from an endonasal perspective. The parasellar ICA is divided into 2 segments: cavernous and paraclinoidal. The subsegments of the cavernous ICA from proximal to distal are the short vertical (continuation of paracarotid ICA), horizontal, and anterior genu. The posterior genu is located between the short vertical and horizontal subsegments. The paraclinoidal ICA is a continuation of the anterior genu of the cavernous ICA as it emerges from the CS. It is located within the clinoideal space at the roof of the CS and is limited by the proximal and distal dural rings. It is bounded superolaterally by the lateral optic-carotid recess (or optic strut; Fig. 1). The middle clinoideal, when present, marks the transition between the cavernous and paraclinoidal ICA, while the medial optico-carotid recess at the lateral aspect
of the tuberculum sella is located just medial to the paraclinoidal-supraclinoidal ICA transition. ²,¹¹

Superior Compartment of the CS

Boundaries

The superior compartment of the CS lies superior to the horizontal cavernous ICA and posterior to the anterior genu. It is limited by the roof of the CS superiorly and laterally: the ventral surface of the paraclinoidal ICA anterolaterally (which corresponds to the clinoidal triangle), and the dura of the oculomotor triangle posterolaterally (Figs. 2, 3A, 3B, and 4).

Key Structures

The oculomotor nerve runs in the lateral wall of this compartment, which correlates with the oculomotor triangle or posterior roof of the CS. This oculomotor nerve segment travels between 2 layers of dura in the oculomotor triangle and is thus defined as the interdural segment, but it is also defined as the oculomotor cistern because CSF accompanies the nerve along this interdural segment.¹³ As the nerve travels anteriorly, it is incorporated into the most superior aspect of the lateral wall of the CS. The entry point of the oculomotor nerve into the lateral wall of the CS is just lateral to the anterior genu of the ICA. The interclinoidal ligament is a key landmark to be identified within the roof of the superior compartment of the CS. This ligament is a very well-defined dural band—which can be mistaken for the oculomotor nerve—that extends from the posterior to the anterior clinoid process and separates the clinoidal triangle from the oculomotor triangle. The paraclinoidal ICA runs medial and anterior to the interclinoidal ligament, and the oculomotor nerve runs just lateral and posterior.

Surgical Nuances

To explore the superior compartment, the bone covering the paraclinoidal ICA and anterior wall of the CS is removed. This allows lateral displacement of the ICA for direct surgical dissection within this region. The superior compartment is accessed through the medial wall of the CS and tumors invading this compartment typically destroy the medial wall, making the access easier. As recently pointed out by Micko et al., the superior compartment is often compressed and not invaded, in which case the medial wall of the CS is displaced laterally but still covers the cavernous ICA and interclinoidal ligament.¹⁴ For cases with true invasion, gentle medial-to-lateral ICA mobilization is performed with the suction shaft while a second surgical instrument is used to remove tumor. The majority of this dissection can be performed with 0° endoscopes, but the use of angled scopes is required to maximize vi-
sualization, especially of the dorsal aspect of the anterior genu of the ICA. The interdural segment of the oculomotor nerve is protected as long as the lesion does not invade and extend beyond the roof and lateral wall of the CS. The most vulnerable portion of the oculomotor nerve is located just lateral to the anterior genu of the ICA, an area that is not easily accessible from a medial to lateral trajectory. Our electrophysiological studies have typically shown a positive response for CNs III and IV at high amperage (2 mA) only when stimulating posteriorly but a positive response at low amperage (0.5–1 mA) when stimulating more anteriorly just behind the genu of the ICA. This finding is explained by the inner dural layer of the oculomotor triangle becoming thinner as CN III travels anteriorly. The interclinoidal ligament is identified repeatedly during surgery and acts as a landmark for the oculomotor nerve (located lateral to the ligament; Video 1).

VIDEO 1. Clip showing the removal of nonfunctioning pituitary adenoma that selectively invaded the superior (and inferior) compartments. Copyright Juan C. Fernandez-Miranda. Published with permission. Click here to view.

**Posterior Compartment of the CS**

**Boundaries**

The posterior compartment of the CS is located posterior to the short vertical cavernous ICA and anterior to the lateral petroclival dura, forming the posterior wall of the CS. The transition between the short vertical and horizontal subsegments of the cavernous ICA (posterior cavernous ICA genu) marks the transition between the superior and posterior compartments (Figs. 2, 3C, 3D, and 5).

**Key Structures**

The meningohypophyseal trunk arises from the posterior genu of the ICA at this transitional level. The inferior hypophyseal artery has a lateromedial trajectory toward the dura of the sellar floor, while the dorsal meningeal artery has a posterior and inferomedial trajectory toward the dura of the dorsum sella. These 2 arteries, along with the tentorial artery, may arise together from the meningohypophyseal trunk or as independent branches directly from the ICA. The gulfar segment of the abducens nerve is located at the most inferior portion of this compartment as it passes through Dorello’s canal to enter the CS, just behind the ICA. This nerve segment is above the most medial aspect of the petrous apex and is bounded posteriorly by the petro-sphenoidal or Gruber’s ligament. It is critical to note that the abducens nerve sits at the confluence (or gulf) of the inferior and superior petrosal sinuses with the basilar plexus as they enter the CS. Once it enters the CS, the nerve does not have any dural layer protecting it.

**FIG. 2.** Location of the CS compartments in relation to the segments of the ICA as visualized in a left sagittal section (medial-to-lateral view). The superior compartment (Sup. Comp.) is located superior and posterior to the horizontal and anterior (Ant.) genu segments of the cavernous ICA. The oculomotor nerve (CN III) is in the lateral wall of this compartment in the oculomotor triangle (Tr). The interclinoidal ligament (Interclin. Lig.) is an important landmark, with CN III lateral to it. The posterior compartment (Post. Comp.) is located posterior to the short vertical cavernous ICA and anterior to the lateral petroclival dura forming the posterior wall of the CS. The interdural segment of the abducens nerve (CN VI) can be seen in this compartment above the petrous (Petr.) apex. The meningohypophyseal trunk (Men-Hyp.) can be seen coming off the posterior ICA genu. The inferior compartment (Inf. Comp.) is located inferior to the horizontal and anterior genu subsegments of the ICA and anterior to the short vertical subsegment. Key structures including the sympathetic nerve (Symp. N.), and the distal segment of CN VI medial to CN V1 (ophthalmic nerve) can be seen in this compartment. Max. St. = maxillary strut; Opt. St. = optic strut; V2 = maxillary nerve.
Surgical access behind the short vertical subsegment of the cavernous ICA requires extensive bone removal to uncover the anterior wall of the CS and to expose the entrance of the ICA into the CS. This entrance point corresponds with the end of the paraclival ICA. The floor of the sella (typically an expanded sella) is followed and drilled from medial to lateral until the carotid entrance is identified. To gain access posterior to the cavernous ICA, gentle lateral mobilization of the short vertical subsegment and posterior ICA genu is needed. This may necessitate coagulation and transection of the inferior hypophyseal artery to safely advance toward the posterior compartment. The short vertical ICA is the best landmark to locate the abducens nerve, which will be more or less evident depending on the degree of tumor expansion of this compartment. Electrostimulation will confirm the presence of the abducens nerve at the floor of this compartment just behind the ICA. Venous bleeding from the inferior and superior petrosal sinuses is commonly encountered behind and above the abducens nerve, respectively, and its management requires careful hemostatic technique to prevent nerve damage from excessive packing or unnecessary coagulation (Video 2).

VIDEO 2. Clip showing the removal of a recurrent nonfunctioning pituitary adenoma that selectively invaded the posterior (and inferior) compartments. Copyright Juan C. Fernandez-Miranda. Published with permission. Click here to view.

Inferior Compartment of the CS

The inferior compartment of the CS is located inferior to the horizontal and anterior genu subsegments of the ICA and anterior to the short vertical subsegment. The anterior wall of this compartment is the anterior wall of the CS. It continues laterally with the lateral compartment (Figs. 2, 3D, 3F, and 6).

Key Structures

The sympathetic nerve or plexus is in this compartment around the ICA as it travels from the short vertical ICA to the horizontal ICA. The distal cavernous segment of the abducens nerve is just inferior and lateral to the horizontal ICA subsegment, at the transition between the inferior and lateral compartments. The sympathetic nerve is located medially in relation to the abducens nerve and has an oblique trajectory, running from the surface of the ICA to join the abducens nerve, which has a more horizontal trajectory at this segment.

Surgical Nuances

Using a transpterygoid supravidian approach with vidian nerve preservation, the lateral recess of the sphenoid sinus is widely opened to provide full access to the lateral wall of the sphenoid sinus. Surgery in the inferior compartment requires removal of the bone that covers the anterior wall of the CS. This is extended laterally to the cavernous ICA up to the lateral dural fold, marking the transition between the middle cranial fossa dura and the parasellar region dura, and may be facilitated by identification of the maxillary nerve entering the foramen rotundum. This identification enables extending the opening of the dura laterally and inferior to the anterior genu and horizontal ICA, and in front of the short vertical ICA subsegment. Tumor occupies the space between the short vertical ICA and the dura of the anterior wall of the CS, making this dural opening feasible. The intraoperative use of a Doppler ultrasonography device is very valuable toward confirming the ICA trajectory before opening this dura. A right-angled knife with a blunt tip is used to perform this dural cut. The first nerve to be encountered in this compartment is the sympathetic nerve, which runs medial to the abducens nerve. Electrostimulation in this compartment will facilitate identification of the abducens nerve lateral, inferior, and parallel to the horizontal ICA and will enable its distinction from the sympathetic nerve (Video 3).

VIDEO 3. Clip showing the removal of a large nonfunctioning pituitary adenoma that invaded the inferior (and lateral) compartments. Copyright Juan C. Fernandez-Miranda. Published with permission. Click here to view.

Lateral Compartment of the CS

The lateral compartment of the CS lies lateral to the
anterior genu and horizontal ICA subsegments. The upper limit of this compartment is formed by the proximal dural ring that covers the inferior surface of the optic strut. The maxillary strut separates the superior orbital fissure from the foramen rotundum and marks the inferior limit of the lateral compartment along with the V2 prominence. At the anterior limit of the optic and maxillary struts, the CNs have entered the superior orbital fissure and exited the CS (Figs. 2 and 7).

Key Structures

This compartment contains the third and fourth CNs, and the first division of the trigeminal nerve, which are located at the lateral wall of the CS. As mentioned above,
the distal cavernous segment of the abducens nerve is located at the transition between inferior and lateral compartments. The arterial branches of the inferolateral trunk (arising from the inferior surface of the horizontal cavernous ICA) can be identified in this region running from medial to lateral where they distribute along the lateral wall of the CS.

Surgical Nuances

Direct surgery into this compartment is performed only in select cases to avoid the risk of CN injury. Surgical access requires full exposure of the anterior genu and paracarotid ICA and anterior wall of the CS laterally up to the superior orbital fissure. The optic and maxillary struts are ideal landmarks for the superior and inferior extent of the exposure, respectively. The dura is opened in front of the anterior genu of the ICA starting from the inferior compartment and advancing superiorly and anteriorly with a blunt tip, right-angled knife. Superiorly, the dura becomes adherent to the ICA as the dural rings meet the anterior clinoid process to form the clinoidal space. The use of a Doppler device and precise neuronavigation enables accurate mapping of the carotid artery. A surgical corridor needs to be developed between the anterior genu/horizontal ICA and the CNs in the lateral wall of the CS. This is typically facilitated by tumor invasion that separates the ICA from the CNs in the lateral wall of the CS. The abducens nerve is an exception because it does not run in the wall of the sinus and may be embedded within the tumor, although it can be displaced laterally against the lateral wall, which facilitates tumor resection. To mobilize (from lateral to medial) the cavernous ICA and paracarotid ICA, the lateral aspect of the proximal ring (extending between the paracarotid ICA and lower aspect of the optic strut) requires partial sectioning. The arterial branches of the inferolateral trunk are encountered while developing this lateral corridor, and therefore careful coagulation and division are required. Tumor can be carefully removed

FIG. 5. Neurovascular relationships in the posterior compartment (Post. Comp.). A: The posterior compartment is located posterior to the short vertical cavernous ICA and anterior to the lateral petroclival dura forming the posterior wall of the CS. The posterior (Post.) ICA genu marks the transition between the superior and posterior compartments. The meningohypophyseal trunk (Men-Hyp.) is seen arising from the posterior wall of the posterior genu of the ICA at this transitional level. Note the intimate relationship of this compartment to the abducens nerve (CN VI). The interdural (Interd.) or inferior petrosal segment can be seen. Prox. Cav. = proximal cavernous. B: The gulfar or superior petrosal segment (below the dissector and above the petrous apex) of CN VI is located at the most inferior portion of this compartment as it passes under the petro-sphenoidal (Petro-Sph.) ligament to enter the CS. C: Note the location of the gulfar segment of CN VI above the petrous (Petr.) apex. The proximal cavernous segment of CN VI, usually not visible from this angle due to its paracarotid location, can be seen due to forward mobilization of the short vertical ICA. The nerve sits at the confluence of the inferior (Inf.) and superior (Sup.) petrosal sinuses (Petr. Sin.). D: A case example (sagittal MR image) shows evidence of a pituitary adenoma with extension into the posterior and inferior compartments. Note the presence of the tumor in relation to the short vertical segment of the ICA.
between the cavernous ICA and CNs with the assistance of electrostimulation to identify the oculomotor, trochlear, and especially abducens nerves. Unfortunately, tumors in the lateral compartment commonly involve the lateral wall of the CS, in which case complete resection is not feasible without CN injury (Video 4).

**VIDEO 4.** Clip showing the continuation of the removal of a large nonfunctioning pituitary adenoma that invaded the lateral and (inferior) compartments. Copyright Juan C. Fernandez-Miranda. Published with permission. Click here to view.

### Clinicoradiological Results

#### Patterns of CS Invasion

Twenty-nine patients had only a single compartment invaded, with the superior compartment invaded 14 times, and the inferior and posterior compartments invaded 11 and 4 times, respectively. There was no invasion of the lateral compartment in isolation. The remaining 69 patients had multiple compartments involved, 18 of whom had bilateral inversion. The most commonly invaded compartment was again the superior (65 patients, 4 with bilateral invasion), followed by the posterior (60 patients, 6 with bilateral involvement), inferior (34 patients, 7 exhibiting bilateral involvement), and lateral compartments (23 patients, 1 with bilateral invasion; Table 1). With tumors that invaded multiple compartments, the most common pattern was the superior/posterior (n = 32) followed by the inferior/superior/posterior/lateral (n = 17), inferior/superior/posterior (n = 14), superior/lateral (n = 11), inferior/posterior (n = 9), posterior/superior/lateral (n = 7), inferior/superior/lateral (n = 7), and finally, inferior/superior (n = 6). There were no patients who had growth into the inferior/posterior/lateral compartments without superior compartment invasion.

#### Rejection Rates by Compartments

Thirty-seven (38%) of 98 patients had residual tumor after the initial operation. The most common location for residual tumor was in the lateral compartment (n = 19, 79%), followed by posterior (n = 12, 17%), superior (n = 12, 14%), and inferior (n = 6, 11%; Table 2) compartments. These values were determined by subsequent postoperative imaging rather than intraoperative assessment. Two patients underwent further resection with subsequent complete tumor resection: 1 had residual adrenocorticotropic hormone–secreting tumor in the posterior compartment.
that grew on imaging, and the other patient had residual nonsecreting tumor in the inferior compartment that was re-explored with complete resection. Twenty-seven (74%) of those with residual tumor were treated with radiosurgery.

Complications by Compartments

No patient developed oculomotor or trochlear nerve palsies. Two patients had immediate complete abducens nerve palsies: 1 of these patients was believed to have excessive Surgifoam placed in the CS, and improved spontaneously in 2 weeks, whereas the other patient had bilateral invasion of multiple compartments and the abducens nerve was believed to be injured while working in the lateral compartment. Diplopia resolved completely at 3 months after surgery. Three patients suffered from postoperative hematomas that caused worsening of vision acuity (secondary to optic chiasm compression) immediately during the postoperative period and had to be taken back to the operative theater for evacuation; the locations of tumor invasion in these patients were inferior/superior, superior/posterior, and in all 4 compartments. In 2 of these patients, vision improved significantly immediately after the clot evacuation, and both of these patients returned to their preoperative visual baseline by the first postoperative visit.

### TABLE 1. MRI-based classification of patterns of CS invasion

<table>
<thead>
<tr>
<th>Compartment Inversion</th>
<th>Superior</th>
<th>Posterior</th>
<th>Inferior</th>
<th>Lat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single (n = 29)</td>
<td>14</td>
<td>4</td>
<td>11</td>
<td>0</td>
</tr>
<tr>
<td>Multiple (n = 69)</td>
<td>65 (4 bilat)</td>
<td>60 (6 bilat)</td>
<td>34 (7 bilat)</td>
<td>23 (1 bilat)</td>
</tr>
</tbody>
</table>

### TABLE 2. Resection rates per compartment

<table>
<thead>
<tr>
<th>Variable</th>
<th>Superior</th>
<th>Posterior</th>
<th>Inferior</th>
<th>Lat</th>
</tr>
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<tbody>
<tr>
<td>Total no. (compartments)</td>
<td>83</td>
<td>70</td>
<td>52</td>
<td>24</td>
</tr>
<tr>
<td>Resection rates (per compartment)</td>
<td>86%</td>
<td>83%</td>
<td>89%</td>
<td>21%*</td>
</tr>
</tbody>
</table>

* Near-total resection rate.
The third patient suffered from bitemporal hemianopsia up to 6 months after her surgery that was still worse than it was preoperatively. One patient (1/144) suffered from ICA injury during growth hormone tumor dissection from the cavernous ICA wall; bleeding was controlled with local packing, but intraoperative somatosensory evoked potential recording showed a significant drop in potentials, suggesting ischemia and high risk of stroke if the vessel were to be sacrificed. Successful vessel preservation was accomplished using covered stents and the patient did not develop any neurological sequelae postoperatively.

**Discussion**

In this study, we propose a classification of the CS in anatomical compartments from an endonasal perspective that has proven useful both for surgical purposes and for imaging-based presurgical planning. The adoption of endoscopic endonasal surgery requires shifting the concept of accessing the CS through anatomical triangles bounded by CNs to accessing the CS through anatomical compartments defined by the course of the intracavernous ICA. In fact, incorporating the EEA into the skull base armamentarium allows for 360° access to the CS; while transcranial approaches enter the sinus through the lateral and superior walls, the endonasal route accesses the sinus through the medial and anterior walls.

Every attempt to classify a complex anatomical region, such as the CS, has the risk of introducing arbitrary divisions and boundaries. With that in mind, however, we believe that the classification proposed here helps the surgeon to better understand the endoscopic surgical anatomy of the CS by dividing it into separate venous compartments that are selectively invaded by tumor and contain different neurovascular structures at risk. As a consequence, the surgeon will be able to predict structures to be exposed and readily identify them once exposed within each different compartment. Importantly, this classification is entirely based on the course of the intracavernous ICA, and similarly, surgery within the CS has to be based on a thorough understanding of the course of the ICA to prevent inadvertent vascular injury when performing tumor removal.

When comparing this classification with Harris and Rhoton venous spaces, there are 3 major differences: the absence of a medial compartment, and the existence of lateral and posterior compartments. In our opinion, the medial compartment does not have clinical utility because the medial venous space, as described by Harris and Rhoton, is frequently obliterated by the ICA, and when tumor penetrates the CS it will invade into 1 of the compartments located above, below, or behind the ICA. In cases in which just the medial wall is invaded (46 cases in this study), we prefer to classify them as medial wall invasion rather than medial compartment invasion, because they require medial wall removal rather than medial compartment tumor removal. The description of relevant surgical anatomy and nuances for medial wall removal is currently an ongoing project. Harris and Rhoton described the potential existence of a lateral venous compartment, but they stated that “the lateral space is so narrow that the sixth nerve which passes through it is adherent to the carotid on its medial side and to the sinus wall on its lateral side.” This narrow compartment, however, is greatly expanded by tumor invasion, which will cause separation of the ICA from the lateral wall of the CS. The posterior and superior compartments are considered together, as the posterior space, in the description by Harris and Rhoton and are not taken into account in radiological classifications, such as that of Knosp (see below). We believe that the separation of superior and posterior compartments is important from the clinical point of view because the posterior compartment can be invaded in isolation (4 cases) or in combination with inferior compartment invasion (9 cases). As a consequence, understanding the surgical anatomy and nuances when accessing the posterior compartment becomes surgically relevant.

The classification proposed here is not based on MRI studies but on relevant surgical anatomy, and as such it is not intended to have predictive or prognostic value. To avoid confusion, it is important to note that here we first selected patients with intraoperatively confirmed CS invasion and then retrospectively analyzed their MRI studies to correlate surgical anatomy findings with imaging findings, rather than trying to predict CS invasion based on MRI studies. We acknowledge that our report might overestimate the incidence of CS invasion per compartment, especially when multiple compartments are invaded, because imaging studies cannot always differentiate compression from true invasion of the CS. In any case, we believe that this classification helps in analyzing imaging studies with greater detail to identify the potential location of CS invasion and therefore facilitates planning the surgical approach to each involved compartment.

In 1993, Knosp et al. proposed a widely used MRI-based classification that describes 5 grades (0–4) of paraellar growth based on the intercarotid line and has predictive and prognostic intentions. The same group has recently reevaluated their MRI-based classification in an excellent article showing that the direct endoscopic view confirmed the low rate of invasion of Knosp Grade 1 adenomas but showed significantly lower rates of invasion in Knosp Grade 2 and 3 adenomas than those previously found using the microscopic technique. Consistent with the surgical anatomy–based classification proposed here, the Knosp group in 2015 suggested the addition of Grades 3A and 3B to distinguish adenomas invading the superior CS compartment from those invading the inferior CS compartment, respectively. Interestingly, they have shown that in their MRI-based classification the rate of true invasion in Grade 3A (equivalent to the superior compartment) was 26.5%, while in Grade 3B (equivalent to the inferior compartment), the rate of surgically observed invasion was 70.6%. This is probably explained by the existence of a stronger medial wall at the superior compartment than at the inferior compartment. Knosp et al. have also shown that, in their experience, the resection rates at the superior compartment were higher than those at the inferior one, with this difference becoming much more evident when comparing functional tumors. This difference could also be explained by the direct connection between inferior and lateral compartments, as shown in our study, which decreases the possibility of endocrinological remission for tumors invading the inferior but not the superior compartment. It could also reflect ease of access to the superior compartment.
compartment, which merely requires lateral extension of the sellar exposure, whereas the inferior compartment often requires clival drilling, wider exposure, and opening of the anterior wall of the CS in front of the cavernous ICA.

Here we have also intended to correlate potential adverse outcomes with the compartments where pathology was found. This was not intended as an outcomes paper, but nevertheless, we wanted to investigate the risk of CN and vascular injury when performing surgery within different compartments. Remarkably, our surgical results show that with appropriate surgical anatomical knowledge and extensive experience, good resection rates can be obtained with very low morbidity. The abducens nerve is, as expected, the one at the highest risk, but usually with good recovery. The low rate of abducens nerve palsy correlates with the high rate of residual tumor in the lateral compartment, but also suggests that surgery in the inferior and posterior compartments is safe in most instances. The risk of postoperative hematoma, on the other hand, is potentially higher in tumors with CS invasion because of venous oozing, cavernous ICA branches, and general invasiveness of tumors with greater likelihood of residual.

Limitations and Future Directions

Operative notes and preoperative MRI studies were analyzed to identify patterns of CS invasion. The Knosp group found a 16% incidence of true CS invasion among all pituitary adenomas, while here we describe a higher incidence of 37%. However, if we discount the cases of exclusive medial wall invasion, the incidence drops to 23% and is more consistent with previous descriptions. We agree with the Knosp group when they state that the endoscopic technique is the best available method for distinguishing between invasion and compression of the CS, but there remains a potential error of perception when describing intraoperatively the presence of CS invasion. Regardless, the primary aim of this work is to present a practical and surgically relevant classification of CS compartments based on meticulous surgical anatomy studies and extensive surgical experience with radiological correlation to facilitate both preoperative assessment and intraoperative performance. Even in cases in which there is compression without true invasion of the CS, it is important to identify the potentially involved compartments both in preoperative imaging studies and intraoperatively, for which the surgical anatomy–based classification presented here might be useful. This identification will help to ensure complete tumor removal when feasible. Further prospective studies are needed to elucidate the true intraoperative incidence of CS invasion per compartment as well as to evaluate the predictive and prognostic value of the classification proposed here when evaluating MRI studies.

Conclusions

We present a modified compartmental description of the CS through an EEA and include the relevant descriptive anatomy for surgical decision-making. Using the intracavernous ICA as the reference point, the CS is easily divided into 4 compartments with specific boundaries, neurovascular structures, and important landmarks. This anatomical-based classification complements current imaging-based classifications. As use of the EEA continues to increase, the surgical anatomy and relevant clinical correlations provided here may serve as a guide to others utilizing this corridor to access tumors invading the CS, in particular invasive pituitary adenomas.

References

Cavernous sinus compartments

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

Author Contributions

Supplemental Information
Videos

Correspondence
Juan C. Fernandez-Miranda, Department of Neurosurgery, UPMC Presbyterian Hospital, 200 Lothrop St., Pittsburgh, PA 15213. email: fernandezmirandajc@upmc.edu.