Microsurgical anatomy of safe entry zones to the brainstem

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OBJECT The aim of this study was to enhance the planning and use of microsurgical resection techniques for intrinsic brainstem lesions by better defining anatomical safe entry zones.

METHODS Five cadaveric heads were dissected using 10 surgical approaches per head. Stepwise dissections focused on the actual areas of brainstem surface that were exposed through each approach and an analysis of the structures found, as well as which safe entry zones were accessible via each of the 10 surgical windows.

RESULTS Thirteen safe entry zones have been reported and validated for approaching lesions in the brainstem, including the anterior mesencephalic zone, lateral mesencephalic sulcus, intercollicular region, peritrigeminal zone, supratrigeminal zone, lateral pontine zone, supracollicular zone, infracollicular zone, median sulcus of the fourth ventricle, anterolateral and posterior median sulci of the medulla, olivary zone, and lateral medullary zone. A discussion of the approaches, anatomy, and limitations of these entry zones is included.

CONCLUSIONS A detailed understanding of the anatomy, area of exposure, and safe entry zones for each major approach allows for improved surgical planning and dissemination of the techniques required to successfully resect intrinsic brainstem lesions.

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KEY WORDS brainstem; cavernous malformation; microsurgery; safe entry zones; surgical approaches; surgical anatomy

Historically, the surgical management of intrinsic brainstem lesions has been controversial. The surgical extirpation of focal gliomas, cavernous malformations, or hemangioblastomas within the brainstem has caused heated discussions in scientific meetings and the literature. In 1939, Bailey et al.3 declared this subject to be a pessimistic chapter in neurosurgery; 30 years later, Matson and Ingraham26 would still claim such lesions were inoperable. However, in 1971, Lassiter et al.25 were among the first to advocate surgical intervention. By 1986, Epstein and McCleary reported that surgery was feasible with reasonable morbidity and mortality.15 Concurrent with Epstein and McCleary’s report, Raimondi would rationally state that to have the child merely survive (i.e., with severe neurological deficits) is no justification for surgery.33 The development and improvement of complex skull base surgical approaches and incremental advances in neuroimaging, parallel to image-guided surgery, allowed a few authors to safely and effectively resect lesions in the brainstem.3,23,32

Knowledge of different skull base exposures, gained through laboratory dissections, allows neurosurgeons to approach lesions in the brainstem. Nevertheless, the brainstem, roughly the size of the human thumb, contains a rich concentration of nuclei and fibers in a small sectional area, resulting in a high likelihood of morbidity after manipulation. Awareness of the main safe entry zones on the brainstem is key to reducing morbidity for any lesion that does not emerge to the pial or ependymal surface. Such zones represent entry points and trajectories where eloquent structures and perforators are sparse and where a neurotomy would cause the least possible damage.
The aim of our study was to enhance the planning and use of microsurgical resection techniques for intrinsic brainstem lesions. We examined 13 safe entry zones on the brainstem, which have been described in the literature, and used detailed cadaveric dissections to evaluate the main surgical approaches currently employed to manage intrinsic brainstem lesions. Through detailed dissection images of these approaches, we visually demonstrate what can be seen on the brainstem surface through each of these corridors and delineate the safe entry zones provided by each approach. It is critical to note that large lesions may distort safe entry zones and that neurophysiological monitoring is a critical adjunct in these cases.36

Methods

We searched MEDLINE and Google Scholar for studies containing terms related to the surgical management of brainstem lesions to determine the most frequently discussed safe entry zones. Thirteen zones were selected: 1) anterior mesencephalic zone, 2) lateral mesencephalic sulcus, 3) intercollicular region, 4) peritrigeminal zone, 5) supratrigeminal zone, 6) lateral pontine zone, 7) supracollicular zone, 8) infracollicular zone, 9) median sulcus of the fourth ventricle, 10) anterolateral and 11) posterior median sulci of the medulla, 12) olivary zone, and 13) lateral medullary zone.5,9,14,20,23,35

Five human cadaveric heads, formalin-fixed and injected with colored silicone rubber, were carefully dissected in a simulated surgical environment at the Skull Base Laboratory of the Barrow Neurological Institute in Phoenix, Arizona. With the heads fixed with Mayfield clamps, 10 surgical approaches were performed on each head: 1) orbitozygomatic, 2) subtemporal, 3) subtemporal transtentorial, 4) anterior petrosectomy, 5) suboccipital telovelar, orbitozygomatic, 2) subtemporal, 3) subtemporal transtentorial, 4) anterior petrosectomy, 5) suboccipital telovelar, 6) median supracerebellar infratentorial, 7) extreme lateral supracerebellar infratentorial, 8) retrosigmoid, 9) far lateral, and 10) retrosylvian. The order in which the approaches were performed was altered for each head to obtain clear images of each approach. Every step was photographically registered, and the resultant surgical exposure on the brainstem surface for each approach was analyzed for both identifiable anatomical structures and the safe entry zones that were available.

Results

Safe Entry Zones

The safe entry zones discussed can be divided into 3 main regions: midbrain (Fig. 1), pons (Fig. 2), and medulla oblongata (Fig. 3).

Midbrain

Anterior Mesencephalic Zone
Lesions involving the anterior midbrain can be accessed through a limited area on the cerebral peduncle bounded medially by the oculomotor tract and nerve and laterally by the corticospinal tract (Fig. 1A and B). Such a narrow corridor takes advantage of the distribution of corticospinal tract fibers mainly in the intermediate three-fifths of the peduncle and the fact that the red nucleus and the nigrostriatal circuit are in a deep medial location.3 The entry point inside the interpeduncular cistern is limited superiorly by the posterior cerebral artery (PCA) and inferiorly by the main trunk of the superior cerebellar artery (SCA) (Figs. 4F and H and 5F).

Lateral Mesencephalic Sulcus
Hidden by the lateral mesencephalic vein, the lateral mesencephalic sulcus separates the peduncular and tegmental surfaces of the midbrain facing the middle incisural space.29 The lateral mesencephalic sulcus extends downward in a concave fashion from the medial geniculate body to the pontomesencephalic sulcus (Fig. 1A and C). Crossing the sulcus are the posterior P2 segment (P,P) superiorly, the mediolateral choroidal artery centrally, and the cerebellomesencephalic segments of the SCA, trochlear nerve, and tentorial edge inferiorly (Fig. 5G and H).

The safe entry zone runs between the substantia nigra anterolaterally and the medial lemniscus posteriorly. The oculomotor nerve fibers crossing from the red nucleus to the substantia nigra impose an anteromedial limit to dissection. Recalde et al.35 found that the average total length of the sulcus was 9.6 mm (range 7.4–13.3 mm) with an average working-channel length of 8.0 mm (range 4.9–11.7 mm).

Intercollicular Region
The quadrigeminal plate or tectum is composed of 2 superior and 2 inferior rounded eminences, designated as superior colliculi and inferior colliculi, respectively, which represent the dorsal surface of the midbrain (Fig. 1A and D).

The superior colliculi are active in the visual system; they are critical to visual fixation and saccadic eye movements.19,23 They are connected to each lateral geniculate body by a superior brachium, a path in which the retinotectal fibers run.21 Additionally, spinotectal and corticotectal fibers reach the superior colliculi, while tectospinal, tectothalamic, and tectocortical tracts leave these structures. The inferior colliculi are part of the auditory system. They receive fibers from the contralateral cochlear nucleus, dorsal and ventral nuclei of the lateral lemniscus, contralateral and ipsilateral superior olive, ipsilateral medial superior olive, and descending projections from sensory areas through the corticocollicular neurons.8,27 Commisural fibers connect 1 inferior colliculus to another.27 The inferior colliculi extend laterally through the inferior brachium to the medial geniculate body of the thalamus, which projects to the primary auditory cortex. The most appropriate area for a small neurotomy has been described as the intercollicular region, because of its sparseness of fibers (Fig. 1A and D). Bricolo and Turazzi first suggested this corridor, which has been further supported by other studies.9,22,34

Pons

Peritrigeminal Zone
The anterolateral surface of the pons has traditionally been considered a safe zone for entering the brainstem.9,17,32 Using the white fiber dissection technique, Recalde et al.35 were able to clearly quantify a safe trajectory.
FIG. 1. Safe entry zones of the midbrain. A: Cross section of the midbrain at the level of the cerebral peduncle revealing its 3 safe entry zones (white dashed lines): the lateral mesencephalic sulcus (LMS), the intercollicular region (ICR), and the anterior mesencephalic zone (AMZ). B: Anterior view of a dissected brainstem revealing the AMZ (white dashed line). C: Right postero-lateral view of the brainstem showing the LMS (black dashed line). D: Posterior exposure of the brainstem showing the ICR (black dashed line). Cerebral ped. = cerebral peduncle; CST = corticospinal tract; inf. = inferior; interped. fossa = interpeduncular fossa; mid. cerebell. ped. = middle cerebellar peduncle; pit. stalk = pituitary stalk; post. = posterior; rhomb. fossa = rhomboid fossa; sup. = superior; sup. cerebell. ped. = superior cerebellar peduncle.

FIG. 2. Safe entry zones of the pons. A: Cross section of the pons demonstrating the peritrigeminal zone (PTZ; arrow). B: Three entry zones can be used on the rhomboid fossa: the supracollicular zone (SCZ; arrow), the infracollicular zone (ICZ; arrow), and the median sulcus of the fourth ventricle (MS; dashed line). C: The arrows represent the safe entry zones for excising lateral and anterolateral pontine lesions: the supratrigeminal zone (STZ), the PTZ, and the lateral pontine zone (LPZ). Ant. med. fissure = anterior median fissure; med. long. fascicle = medial longitudinal fascicle.
in front of the trigeminal nerve (cranial nerve V [CN V]) entry zone, lateral to the corticospinal tract and anterior to the motor and sensory nuclei of the trigeminal nerve (Fig. 2A and B). On the axial plane, they found a mean distance of 4.64 mm (range 3.8–5.6 mm) between CN V and the corticospinal tract, and a mean depth of dissection of 11.2 mm (range 9.5–13.1 mm) to the trigeminal nuclei. The fibers of CNs VI, VII, and VIII run downward and are located posterior to the trigeminal nuclei.

Supratrigeminal Zone

A second entry point that has been used to manage anteriorly placed lesions in the pons is located just above the trigeminal root entry zone on the middle cerebellar peduncle (Fig. 2B). Taking advantage of the posterolateral location of the middle cerebellar peduncle and the thick pontine transverse fibers, it is possible to carefully dissect along these fibers, medially or anteromedially, posterior to the trajectory of the corticospinal tract.

Lateral Pontine Zone

In 1982, Baghai et al.² recommended a safe corridor on the junction between the middle cerebellar peduncle and the pons and between the trigeminal and the facial-vestibulocochlear complex root entry zones (Fig. 2B). Other authors have supported using the narrow corridor of the lateral pontine zone, but it restrains vertical manipulation.⁵

Supracollicular and Infracollicular Zones

The rhomboid fossa hides several structures whose manipulation may result in increased morbidity. Superficial landmarks help protect crucial structures located at the depth of the fourth ventricular floor. At the floor of the fourth ventricle, the facial nerve passes around the nucleus of the abducens nerve; this combined structure is called the facial colliculus. The medial longitudinal fascicle lies parallel to the median sulcus. Similarly, the nuclei of CNs X and XII are located just caudal to the striae medullaris.

After examining the topographic anatomy of the facial colliculi and every potential sign of neurological deficit presented after manipulating the rhomboid fossa, Kyo-shima et al.²³ described 2 safe zones through this region that minimally displace surrounding neural structures (Fig. 2C, with specific reference to SCZ and ICZ). The first safe zone is the suprafacial triangle, which is delimited caudally by the facial nerve, laterally by the cerebellar peduncles, and medially by the medial longitudinal fascicle. The second safe zone is described by the edges of the infracial triangle, which are the striae medullaris caudally, the facial nerve laterally, and the medial longitudinal fascicle medially.

However, Strauss et al.³⁷ stressed the variability of the striae medullaris and the possible damage to either the trigeminal motor nucleus or the nuclei of the lower cranial nerves when using the suprafacial or infracial triangles, respectively. They conducted a detailed morphometric study to measure the dimensions of the facial colliculus and its distance to the midline, decussation of CN IV, and vagal and hypoglossal trigones. They defined a parame-dian supracollicular area that measured 13.8 mm vertically between the facial colliculus and the decussation of...
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CN IV, 0.6 mm from the midline. The trigeminal motor nucleus limited the approach laterally, being located 6.3 mm from the midline.

A paramedian infracollicular area can be tailored between the projection of the facial nerve fibers on the facial colliculus and the superior limits of the nucleus of the hypoglossal nerve and the dorsal nucleus of the vagal nerve, extending a mean distance of 9.2 mm vertically and approximately 0.3 mm from the midline.37

**Median Sulcus of the Fourth Ventricle**

An approach through the midline, between the projection of the CN VI nuclei on the surface and the projection of the CN III nuclei on the midbrain surface, was proposed by Bricolo et al.,5 taking advantage of the sparseness of crossing fibers (Fig. 2C). Even the slightest lateral retraction may provoke extracerebral movement disorders caused by damage to the medial longitudinal fascicle.

**Medulla Oblongata**

**Anterolateral Sulcus**

Just lateral to the pyramid, the rootlets of the hypoglossal nerve leave the brainstem on the anterolateral sulcus. The short space between these rootlets and those of the C-I nerve coincides with the decussation of the corticospinal tract.9 A paramedian oblique dissection may avoid the corticospinal tract and address lesions of the anterior lower medullary region (Fig. 3A and B).

**Posterior Median Sulcus**

A neurotomy on the median sulcus provides a corri-
dor near the center of the medulla.\textsuperscript{5,9} Below the obex and restricted laterally by the clava, which covers the gracile nucleus, a surgeon can approach posteriorly placed lesions in a fashion similar to the traditional approach for intramedullary spinal cord lesions (Fig. 3C).

**Olivary Zone**

The olives are marked oval eminences on the anterolateral surface of the medulla, limited medially by the anterolateral sulcus and the pyramids and posteriorly by the posterolateral sulcus. In a cross section at the level of the inferior olivary nucleus, fibers of the hypoglossal nerve separate it from the corticospinal tract running within the pyramids. The olives are also limited medially by hypoglossal nerve fibers and the medial lemniscus and are lim-

FIG. 5. Subtemporal approach. A: Photograph showing the site of skin incision. B: A bur hole is placed just above the root of the zygomatic arch. C: A square craniotomy is made extending two-thirds in front of the bur hole and one-third behind it. The inferior edge of the craniotomy is then drilled flush with the middle fossa floor. D: The dura is elevated, exposing the temporal lobe. E: The microdissection is carried between the basal surface of the temporal lobe and the tentorial edge, through the arachnoid of the ambient cistern. F: The area of exposure provided by this approach, including part of the anterior and the lateral incisural spaces, leads to the entire lateral midbrain surface. G: Magnified view of the lateral midbrain through the opened interpuduncular and ambient cisterns. This approach also exposes 2 safe entry zones: the anterior mesencephalic zone (AMZ; green dashed line) and the lateral mesencephalic sulcus (LMS; green dashed line seen in H). H: Cutting the tentorium significantly improves visualization of the pontomesencephalic junction (PMJ) and the lateral upper pons. I: Progressive increases to a simple subtemporal approach in the area and length of exposure after adding a transtentorial extension and then an anterior petrosectomy. ICA = internal carotid artery; medial post. choroidal a. = medial posterior choroidal artery; P2A = anterior part of the P2 segment of the posterior cerebral artery; PCoA = posterior communicating artery; quad. = quadrangular; SCA = superior cerebellar artery; tent. = tentorial.
ated posteriorly mainly by the tectospinal and spinothalamic tracts.

Recalde et al.\textsuperscript{35} identified a safe depth of dissection via the olive, ranging from 4.7 to 6.9 mm, with a vertical length of 13.5 mm (Fig. 3).

**Lateral Medullary Zone “Inferior Cerebellar Peduncle Approach”**

Akin to the lateral pontine zone in the pons, the lateral medulla has recently been shown by Deshmukh et al. to be a relatively safe entry zone for resection of dorsolateral medullary lesions.\textsuperscript{14} These authors recently reported their experience with 4 patients whose lesions were approached through the foramen of Luschka with an incision in the inferior cerebellar peduncle and whose outcomes were excellent.\textsuperscript{14} We call the access through this approach the lateral medullary zone. Via a retrosigmoid approach, the foramen of Luschka is opened, and the origins of CNs IX and X are identified. Then a small vertical incision is made in the inferior cerebellar peduncle inferior to the cochlear nuclei and posterior to the origin of CNs IX and X.

**Surgical Approaches**

**Orbitozygomatic**

For neurosurgeons to perform the orbitozygomatic approach, the patient is placed supine and the head is elevated above the level of the heart, rotated 15° to 30° contralaterally, and the neck is slightly extended (Fig. 4A). A hemicoronal skin incision is performed, the skin flap is reflected, and the galeal flap is dissected and prepared. An interfascial dissection is performed, exposing the zygomatic process of the frontal bone and the frontal process of the zygomatic bone (Fig. 4B). The temporal fascia is elevated, and a subperiosteal dissection is performed, revealing the zygomatic arch. The temporal muscle is then elevated, and a subperiosteal dissection is performed, revealing the zygomatic arch.

The sylvian fissure is opened, and the dissection is carried proximally, following the M\textsubscript{1} segment of the middle cerebral artery toward the carotico-oculomotor triangle, which is entered in order to reach the crural and interpeduncular cisterns. Their arachnoid trabeculae are also opened widely. Tracking up the oculomotor nerve to its entry zone leads the surgeon to the cerebral peduncle (Fig. 4F). Possible lesions emerging on the anterior surface of the midbrain, pontomesencephalic junction, and upper pons can be accessed (Fig. 4G). This approach also provides a straight path to the aforementioned anterior mesencephalic safe entry zone between the PCA and SCA, laterally to CN III (Fig. 4H). Clinically, the ventral approaches are often avoided because of the rich motor tracts that travel ventrally in the brainstem; nonetheless, in select cases, anterior approaches may be used to resect lesions in the midbrain (Fig. 4I–J).

Depending on the anteroposterior extension of the lesion, as well as its closest point to the surface on the cerebral peduncle, a contralateral orbitozygomatic approach offers the best approach for complete resection of a midbrain lesion. Opening the Liliequist membrane allows the surgeon to reach the interpeduncular cistern, a very complex region demanding extremely delicate dissection. This small region is populated by the basilar artery bifurcation, both PCAs and SCAs, the medial posterior choroidal artery, and the thalamoperforating arteries and direct perforators of the proximal SCA, restricting surgical freedom significantly.

Lesions of the thalamomesencephalic junction are extremely challenging to expose. After widely dissecting the sylvian fissure, a small corridor is developed through the lenticulostriate arteries, between the posterior limits of both the gyrus rectus and the medial orbital gyrus, and the M\textsubscript{1}. We have described this approach—the transanterior perforating substance (TAPS) approach—previously, and it demands a small opening on the anterior perforating substance, posterior to the olfactory stria and near the optic tract.\textsuperscript{16}

**Subtemporal**

For neurosurgeons to perform the subtemporal approach, the patient is placed in a lateral decubitus position, and the sagittal suture is kept parallel to the floor. A straight vertical incision is placed in front of the tragus, and the temporal fascia and muscle are opened in the same fashion, exposing mainly the temporal bone (Fig. 5A). A bur hole is made just above the root of the zygomatic arch, and the width of the craniotomy is tailored according to a preoperative plan for the best angle of approach to the brainstem (Fig. 5B and C). The dura is opened in a U-shaped fashion, and the dissection is carried below the base of the temporal lobe until the tentorial edge is exposed (Fig. 5D and E). The anterior and middle incisural spaces are then visible. The arachnoid of the ambient, crural, and interpeduncular cisterns is opened widely (Fig. 5F). The lateral surface of the midbrain, down to the pontomesencephalic junction, occupies most of the operative field, with the anterior P\textsubscript{2} segment (P\textsubscript{2}A crural) and P\textsubscript{2}P (ambient) segments of the PCA and the middle posterior choroidal artery crossing the field. The lateral mesencephalic vein frequently covers the lateral mesencephalic sulcus (Fig. 5G). This corridor yields an oblique access to the anterior mesencephalic zone and a straight route to the lateral mesencephalic sulcus (Fig. 5H and I). When possible, care must be exercised to avoid traversing the floor of the fourth ventricle. Approaches through the floor of the fourth ventricle can result in significant lower cranial nerve deficits and respiratory and swallowing difficulties.

**Subtemporal Transtentorial**

A transtentorial extension to the subtemporal approach is obtained by sectioning and retracting the tentorium just before the trochlear nerve pierces it. The pontomesencephalic junction and an anterolateral perspective of the upper pons can then be appreciated, in addition to the SCA running in the direction of the quadrigeminal cistern (Fig. 5H).
Anterior Petrosectomy

An anterior petrosectomy or Kawase approach can be added to the subtemporal approach or performed alone when aiming for a more anterolateral view of the pons from above in order to focus on lesions anterior to the trigeminal nerve (Fig. 5I). The petrous bone in front of the internal acoustic canal is drilled away; the exposure is limited anteriorly by the V3 segment of the trigeminal nerve and laterally by the greater superficial petrosal nerve.

Suboccipital Telovelar

For neurosurgeons to perform the suboccipital telovelar approach, the patient is placed in a prone position, the head is flexed, and a straight median incision is made to expose the myofascial layer, which is opened on the midline and retracted laterally (Fig. 6A). The suboccipital area is exposed together with the C-1 posterior arch. A median suboccipital craniotomy large enough to retract both cerebellar tonsils superolaterally is tailored using 2 bur holes, which are placed laterally at the superior edge (Fig. 6B and C). A laminoplasty of the C-1 arch may be performed to significantly extend the vertical angle of approach.13

The dura is opened in a Y-shaped fashion to preserve the occipital sinus. Opening the dura exposes the cerebellar tonsils, which hide the cerebellomedullary fissure (Fig. 6D). By slightly retracting the tonsils and carefully pushing the telovelotonsillar segment of the posterior inferior cerebellar arteries laterally, it is possible to reach and open the tela choroidea. The tela choroidea, together with the inferior medullary velum, constitute the inferior half of the roof of the fourth ventricle (Fig. 6E).29 The telovelar junction attaches medially to the nodule and extends laterally into the lateral recess. Dividing the tela choroidea bilaterally is enough to bring the whole rhomboid fossa into the surgical field, as well as the lateral recesses (Fig. 6F). The safe zones above and below the facial colliculus are visible, as is the superior half of the median sulcus (Fig. 6G). Opening the inferior velum will expose the superior half of the ventricular roof beside the suprolateral recesses.

Median Supracerebellar Infratentorial

The setting for the median supracerebellar infratentorial approach is very similar to the suboccipital telovelar approach described above, except that the skin incision is extended a bit cranially to ensure that the craniotomy extends to a point just above the transverse sinuses (Fig. 7A and B). Doing so allows the tentorium to be intermittently retracted. The dura is again opened in a Y-shaped fashion, and the dissection is begun via the tentorial surface of the cerebellum, opening the supracerebellar cistern and coagulating as few bridging veins as possible to reach the cerebellomesencephalic fissure (Fig. 7E and F). Continuation of the dissection more deeply leads the neurosurgeon to the quadrigeminal plate, containing the superior and inferior colliculi and the intercollicular safe zone (Fig. 7G and H). The pulvinar and the tentorial edge laterally limit the exposure of both the superior and inferior brachia.

Extreme Lateral Supracerebellar Infratentorial

For neurosurgeons to perform the extreme lateral supracerebellar infratentorial approach, the patient is placed in a lateral decubitus position, and the head is slightly flexed and rotated ipsilaterally. A retroauricular straight skin incision is made, the myofascial layer is elevated, and the flap is retracted anteriorly (Fig. 8A). A bur hole is placed just above the asterion on the parietotemoidal suture, and a modified retromastoid craniotomy is tailored that extends across the transverse sinus, which eases surgical exposure through its intermittent retraction. The dura is opened using an inverted T-shaped incision, leaving a dural base along the transverse sinus and another along the sigmoid sinus. The dissection is made by cutting the arachnoid along the tentorial surface of the cerebellum, coagulating as few bridging veins as possible to reach the cerebellomesencephalic fissure (Fig. 8B).

The ambient cistern is then opened, exposing the trochlear nerve running along the posterolateral midbrain, frequently close to the SCA (Fig. 8C). Turning the focus to the midline and opening the quadrigeminal cistern provides an oblique approach to the collicular region, mainly to the inferior colliculus. The trochlear nerve can be traced to its origin laterally, below the inferior colliculus (Fig. 8D). retracting the cerebellum closer to the transition between the tentorial and petrosal surfaces offers a more lateral perspective of the midbrain, centered on the lateral mesencephalic sulcus. Figure 8E reveals the window on the brainstem provided by this important approach. The supracerebellar infratentorial approach is a robust approach; a more superior view can be obtained by cutting the tentorium. This addition allows the surgeon to attack lesions in the medial temporal lobe and thalamus. Figure 8F and G demonstrate a lesion resected via the extreme lateral supracerebellar infratentorial approach.

Retro sigmoid

For neurosurgeons to perform the retrosigmoid approach, the patient is placed in a lateral position with the head slightly flexed and rotated toward the ipsilateral side (Fig. 9A). A straight skin incision is placed 2 finger-breadths behind the earlobe, exposing the myofascial layer. The myofascial layer is elevated, and the intersection of the parietal, temporal, and occipital bones is exposed using a self-retractor. One bur hole located just above the asterion on the parietotemoidal suture is enough to perform a retromastoid craniotomy, with the anterior edge level with the posterior margin of the sigmoid sinus (Fig. 9B and C). The dura is opened using an inverted T-shaped incision, leaving a dural base along the transverse and the sigmoid sinuses (Fig. 9D). The microsurgical dissection starts along the petrosal surface of the cerebellum, reaching the cerebellopontine cistern (Fig. 9E). Arachnoid strands around the superior petrosal vein and its tributaries as well as around the trigeminal, facial, and vestibulocochlear nerves are cut with regard to the trajectories of the SCA and anterior inferior cerebellar artery. It is then possible to expose the middle cerebellar peduncle and the lateral pons, which contain 3 safe zones around the CN V entry zone (Fig. 9F and G), as described above. We use the retrosigmoid approach more commonly than any other ap-
FIG. 6. Median suboccipital telovelar approach. **A:** A midline vertical skin incision is made. **B:** Two bur holes are made laterally to the inion just below the transverse sinuses, and a suboccipital craniotomy is tailored. **C:** The dura is exposed. The posterior arch of C-1 was opened to enhance the vertical angle of approach to the rhomboid fossa. **D:** The dura is opened, exposing cerebellar structures such as the cerebellar tonsils and the uvula, as well as the cerebellomedullary fissure. **E:** An opened foramen of Magendie, limited laterally by the tela choroidea, the tonsils, and the posterior inferior cerebellar arteries. **F:** Dissecting the tela choroidea and the inferior medullary velum elegantly exposes the whole rhomboid fossa and cerebral aqueduct, without the associated risks of splitting the vermis. **G:** The area on the dorsal brainstem exposed by the telovelar approach is represented by the shaded area. **H:** Preoperative T2-weighted MR image in this 55-year-old male reveals a hyperintense lesion surrounded by a hypointense hemosiderin halo in the dorsal pons. The lesion was approached via a suboccipital approach with gross-total resection of the lesion. **I:** Postoperative T2-weighted MR image reveals the resection cavity. PICA = posteroinferior cerebellar artery; sup. = superior.
Fig. 7. Median supracerebellar infratentorial approach. A and B: The skin incision and craniotomy are extended farther cranially than in the median suboccipital approach to expose the transverse sinuses. C and D: After opening the dura in the customary Y-shape, the dissection is begun at the tentorial surface of the cerebellum. E: Most of the posterior incisural space is occupied by the vein of Galen complex. F: The pineal gland is exposed by dissecting downward. G: The objective is to expose the quadrigeminal plate below the pineal region at the base of the posterior incisural space. The intercollicular region (ICR) is shown in the center of the field. H: The shaded area represents the area of the dorsal brainstem exposed by this approach. IC = inferior colliculus; mesenceph. = mesencephalic; PCA = posterior cerebral artery; PG = pineal gland; SC = superior colliculus; v. = vein.
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The posterolateral view afforded by this approach allows the surgeon to remove lesions while creating few motor deficits, albeit with significant, often temporary, sensory deficits (Fig. 9H–I). The use of an endoscope can allow surgeons to visualize the lateral pons without the need for the more extensive far-lateral approach.

Far Lateral

For the far-lateral approach, the patient is placed in the park-bench position, and a classic hockey-stick skin incision allows the surgeon to promptly identify each muscular layer down to the suboccipital triangle (Fig. 10A).24 A straight incision is faster but should be reserved for surgeons who are experienced with it. The very first layer exposed is composed of the sternocleidomastoid and trapezius muscles, which when retracted expose the splenius capitis muscle. The next layer comprises the longissimus capitis muscle laterally and the semispinalis capitis mus-
cle, which when elevated bring the suboccipital triangle into the surgical field.

The superior oblique, inferior oblique, and rectus capitis posterior major muscles limit the triangle that protects the V3 segment of the vertebral artery (Fig. 10B). The rectus capitis posterior minor muscle is located medially to the rectus capitis posterior major muscle. Both of these muscles are elevated, exposing the C-1 posterior arch and the vertebral artery (Fig. 10C). The ipsilateral half of the C-1 posterior arch is removed after subperiosteal dissection of the ipsilateral half of the C-1 posterior arch is removed after subperiosteal dissection of

![Image](image_url)

**FIG. 9. Retrosigmoid approach.** A: The cadaver head is placed in the lateral position. The skin incision is usually placed 2 finger-breadths behind the pinna. B: A bur hole is drilled just cranial to the asterion, on the parietomastoid suture. C: The craniotomy is started with a C-shaped sawing line. The posterior edge of the sigmoid sinus as well as the transverse-sigmoid junction is skeletonized. D: The dura is opened and the cerebellar surface is exposed. E: The microsurgical dissection starts along the petrosal surface of the cerebellum, reaching the cerebellopontine cistern. The approach also provides access to the supratrigeminal (STZ) and the lateral pontine (LPZ) safe zones but provides a suboptimal angle of attack for the peritrigeminal zone. F: Lesions abutting the middle cerebellar peduncle or the lateral pontine surface can be resected using this route. G: The shaded area represents the area of exposure on the lateral brainstem produced by the retrosigmoid approach. H and I: This pontomedullary cavernous malformation in a 10-year-old male was approached via a retrosigmoid approach through the lateral medullary zone. H: Preoperative T2-weighted MR image demonstrates the lesion. I: Postoperative T2-weighted MR image reveals gross-total resection of this lesion. AICA = anteroinferior cerebellar artery; LPZ = lateral pontine zone; mid. cerebell. ped. = middle cerebellar peduncle; PICA = posterior inferior cerebellar artery; STZ = supratrigeminal zone; sup. = superior; transv. = transverse; v = vein.
the vertebral artery. The posterior root of the transverse foramen may be drilled away to mobilize the vertebral artery, although this is not required for most brainstem lesions.

A lateral suboccipital craniotomy is then tailored to the craniocaudal extension of the lesion, exposing the posterior margin of the sigmoid sinus (Fig. 10D). The posterior third of the occipital condyle may also be drilled away, widening the angle of attack for anterolateral medullary lesions. The dura is then opened. The posterolateral medulla is exposed for access to superficial lesions, including exposure of the trajectory of the lower cranial nerves to the jugular foramen, the vertebral artery, and posterior inferior cerebellar artery. The cervicomedullary junction is also exposed. Changing the angle of the microscope allows visualization of the anterolateral surface of the medulla. The shaded area correlates with the area of exposure on the brainstem accessed by the far-lateral approach. The patient underwent a right far-lateral approach and resection of the lesion via the lateral pontine zone. Postoperative T2-weighted MR image reveals gross-total resection of the lesion. ALS = anterolateral sulcus safe zone; C2 spin. proc. = C-2 spinous process; inf. oblique m. = inferior oblique muscle; PICA = posterior inferior cerebellar artery; post. = posterior; rectus cap. post. major m. = rectus capitis posterior major muscle; sup. oblique m. = superior oblique muscle; transv. proc. of C1 = transverse process of C-1; TS/SS junction = transverse sinus/sigmoid sinus junction; V2 = V2 segment of the vertebral artery; V3 = V3 segment of the vertebral artery; V4 = V4 segment of the vertebral artery.

**Fig. 10.** Far-lateral approach. A: The classic hockey-stick incision with the patient in the park-bench position. B and C: A meticulous muscle dissection exposes the suboccipital triangle, covering the V3 segment of the vertebral artery (VA). D: A lateral suboccipital craniotomy and a C-1 laminotomy. The posterior root of the transverse foramen may be drilled away to mobilize the vertebral artery, a step not required for most brainstem lesions. E: The posterior third of the occipital condyle may also be drilled away, widening the angle of attack for anterolateral medullary lesions. The dura is then opened. F: The posterolateral medulla is exposed for access to superficial lesions, including exposure of the trajectory of the lower cranial nerves to the jugular foramen, the vertebral artery, and posterior inferior cerebellar artery. The cervicomedullary junction is also exposed. Changing the angle of the microscope allows visualization of the anterolateral surface of the medulla. G: The shaded area correlates with the area of exposure on the brainstem accessed by the far-lateral approach. H: T1-weighted postcontrast MR image of the brain in a 67-year-old female reveals a lesion consistent with a cavernous malformation. I: Postoperative T2-weighted MR image reveals gross-total resection of the lesion. J Neurosurg October 9, 2015 13
The arachnoid covering the cerebellopontine cistern can be divided to approach the pontine surface. Continuing the dissection ventrally leads to the premedullary cistern, allowing access to the anterolateral sulcus and the olivary zone (Fig. 10G). Figure 10H and I illustrates removal of a lesion via the far lateral approach.

Retrolabyrinthine

For neurosurgeons to perform the retrolabyrinthine approach, the patient can be positioned supine using a thick roll under the ipsilateral shoulder, rotating the head contralaterally and flexing it. The surgery starts with a retroauricular C-shaped incision, followed by elevation and anterior retraction of the myofascial flap to expose the spine of Henle and the posterior margin of the external acoustic canal (Fig. 11A). Macewen’s triangle is a landmark for identifying the mastoid antrum 1.5 cm below the surface and is limited superiorly by the suprameatal crest, anteroinferiorly by a line running along the superior and posterior margins of the external auditory canal and crossing the spine of Henle, and posteriorly by a tangential line from the posterior margin of the canal crossing the first line.

A mastoidectomy is the first step to this transpetrosal presigmoid approach. The suprameatal crest is the superior limit for the initial drilling, the posterior wall of the canal is the anterior limit, the mastoid tip is the inferior limit, and the sigmoid sinus is the posterior limit. The drilling should start by drawing an inverted L over the cortical bone, exposing the first air cells, and employing a uniform depth of dissection (Fig. 11B). The next objective is to reach the mastoid antrum cranially and expose the Trautmann’s triangle caudally (Fig. 11C). This triangle represents an area of the posterior fossa dura limited by the sigmoid sinus posteriorly; the jugular bulb inferiorly; the sigmoid sinus posteriorly; the jugular bulb inferiorly; the petrosal surface of the cerebellum is initially exposed; however, after cerebrospinal fluid is drained from the cerebellopontine cistern, the surgeon can observe the posterior petrosal sinus, middle fossa dura, and otic capsule superiorly (Fig. 11D).

The dura is opened along the sinuses and retracted anteriorly. The petrosal surface of the cerebellum is initially exposed; however, after cerebrospinal fluid is drained from the cerebellopontine cistern, the surgeon can observe the flocculus behind the CN VII/VIII complex and the anterior inferior cerebellar artery (Fig. 11E and F). After dissecting the cistern widely, the surface of the middle cerebellar peduncle and the root entry zone of the trigeminal nerve can be seen (Fig. 11F). Its smaller motor root exits the pons superomedial to the larger sensory root. This approach provides a significantly more lateral approach to the supratrigeminal, peritrigeminal, and lateral pontine safe zones (Fig. 11G).

Discussion

The brainstem had been considered an untouchable region for decades, protected anteriorly by the clivus, laterally by the petrous bones, posteriorly by the cerebellum, and superiorly by the diencephalon. Because it harbors significant cranial nerve nuclei and tracts in a small sectional area, any manipulation can cause an elevated risk of morbidity.

Almost concurrently, Pool in 1968 and Lassiter et al. in 1971 reported their pioneering surgical series that offered a surgical option for managing intrinsic brainstem pathology. The following decades were marked by strong discussions on the indications and feasibility of brainstem surgery. But the expertise gained by select groups of neurosurgeons using an essential combination of progress in microsurgical instruments and techniques, skull base surgery, surgical planning with magnetic resonance imaging and image guidance, neuroanesthesia and neurointensive care, and intraoperative monitoring produced significantly better results and outcomes for patients with brainstem lesions. For instance, Bricolo et al. have published extensive work on brainstem tumors, introducing and discussing different safe entry zones. Similarly, the senior author of this paper (R.F.S.) has published a number of studies on the evolution of surgery for cavernous malformations of the brainstem. Finally, other select groups have contributed meaningful additions to the surgical management of brainstem hemangioblastomas.

Experience in multiple surgical routes is key to selecting the right approach to different locations within the brainstem. A detailed review of the lesion on thin-cut T1-, T2-, and susceptibility-weighted MRI sequences is required. Image guidance supports anatomical and radiological knowledge, ensuring a perfect trajectory to the lesion. Nevertheless, whenever lesions do not rise to the pial or ependymal surface, it is essential to have a fundamental understanding of the concept of safe entry zones. Such landmarks have been described in surgical series and neuroanatomy studies (Tables 1 and 2). They represent small regions between vital neural structures and take advantage of the sparseness of perforators. Moreover, manipulation through these corridors is believed to minimize deficits when performed by experienced surgeons.

It is important to note that large intrinsic lesions may

<table>
<thead>
<tr>
<th>Lesion Location</th>
<th>Anterior</th>
<th>Lateral</th>
<th>Posterior</th>
</tr>
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<tbody>
<tr>
<td>Midbrain</td>
<td>OZ, mini-OZ, PT</td>
<td>Anterolateral: OZ, mini-OZ, ST</td>
<td>Median SCIT</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Posterolateral: paramedian or extreme lateral SCIT</td>
<td></td>
</tr>
<tr>
<td>Pons</td>
<td>ST ± TT ± AP, RL, RS</td>
<td>RS</td>
<td>SOTV ± C-1 laminoplasty</td>
</tr>
<tr>
<td>Medulla</td>
<td>FL</td>
<td>Upper Medulla: FL, RS</td>
<td>SOTV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lower Medulla: FL</td>
<td></td>
</tr>
</tbody>
</table>

AP = anterior petrosectomy; FL = far lateral; OZ = orbitozygomatic; PT = pterional; RL = retrolabyrinthine; RS = retrosigmoid; SCIT = supracerbellear infratentorial; SOTV = suboccipital telovelar; ST = subtemporal; TT = transtentorial.
Surgical approaches to the brainstem

Fig. 11. Retrolabyrinthine approach. A: The patient is positioned supine, and the head is rotated toward the contralateral side. A retroauricular C-shaped incision is placed on the left side; the skin flap is reflected forward. Exposure of the lateral surface of the mastoid bone with its landmarks is shown. B: Initial mastoid cortical drilling initiated just posterior to the spine of Henle. The mastoidectomy starts by drilling a straight cut along the temporal line aiming toward the sinodural angle. A second perpendicular line is drilled from the initial point toward the mastoid tip, bounded by the external auditory canal anteriorly. C: The mastoid cortex was removed and the air cells are open. Koerner’s septum is thinned, unveiling the mastoid antrum, which is the largest mastoid cell. D: The semicircular canals are identified. The dura in front of the sigmoid sinus and above the jugular tubercle delineates Trautmann’s triangle. E: The posterior fossa dura is then opened, taking into consideration the anatomy of the endolymphatic sac. The petrosal surface of the cerebellum comes to view, with the flocculus behind the CN VII/VIII complex. The distal anterior inferior cerebellar artery is also noted in relation to such complex. F: This presigmoid approach provides a straighter route to the lateral surface of the pons, although it results in a limited view and requires time-consuming drilling. The superior and middle neurovascular complexes of the cerebellopontine angle are exposed. The trigeminal nerve root entry zone determines 3 safe entry zones on the lateral pons: the lateral pontine (LPZ), peritrigeminal (PTZ), and supratrigeminal (STZ) zones. G: The area of exposure on the lateral pons that is provided by the retrolabyrinthine approach is shown by the shaded area. LSC = lateral semicircular canal; m. = muscle; mid. = middle; mid. cerebell. ped. = middle cerebellar peduncle; PSC = posterior semicircular canal; SSC = superior semicircular canal; supramast. = supramastoid.
distort the present surgical windows and their landmarks and safe entry zones provided by each approach.

**Midbrain Lesions**

Both pterional and orbitozygomatic approaches provide a straightforward route to the ipsilateral cerebral peduncle (Table 1). The orbitozygomatic approach offers the widest vertical angle of attack and surgical freedom in the peduncular region. Lesions surfacing anteriorly on the peduncle, pontomesencephalic junction, or upper pons can be managed through these approaches. The anterior mesencephalic zone can also be nicely exposed when neither color nor volume alteration is visible on the pial surface. We currently use keyhole approaches rather than extensive dissections and large craniotomies whenever possible. The mini-modified orbitozygomatic (mini-OZ) approach generally replaces full orbitozygomatic craniotomies. The mini-OZ requires a significantly smaller skin incision, just behind the hairline, and the bone opening is reduced to a 3-cm bone piece, starting just lateral to the supraorbital notch and extending to a point just lateral to the frontozygomatic suture (Fig. 12). Our group described the same anatomical exposure when quantitatively comparing the mini-OZ, pterional, and orbitozygomatic approaches.\(^1\)

Another interesting option is the transcalvarial supraorbital approach, which utilizes a discreet eyebrow incision and provides a similar bone opening and corridor as that of the mini-OZ (Fig. 12 inset).\(^1\)

The subtemporal approach exposes the entire lateral surface of the midbrain. With proper planning, the craniotomy will provide an adequate anterior or posterior view of the middle incisural space. However, the extreme lateral supracerebellar infratentorial approach provides an angled view of the posterolateral surface of the midbrain, without the drawbacks of a posterior subtemporal microdissection and retraction. The 2-point method may aid such decision making when approaching lesions on the midbrain tegmentum.\(^7\)

Lesions that are deeper and closer to the lateral surface should be approached through the lateral mesencephalic sulcus. The long axis of the lesion will dictate whether the subtemporal or extreme lateral supracerebellar infratentorial corridors are used. Lesions within the tegmentum that are closer to the ventral surface may be best approached through the anterior mesencephalic zone via a pterional or orbitozygomatic approach.

Finally, tectal plate lesions may be reached through any variation of the supracerebellar infratentorial approach, depending on where the lesion is closest to the pial surface.\(^1\) The median supracerebellar infratentorial approach is employed for midline lesions or when a dissection through the intercollicular region is necessary. The extreme lateral approach is reserved for lateral lesions on the tectal plate that occur on the surface of either the superior or inferior colliculus. This approach provides a wide horizontal angle of approach to any lesion on the posterolateral midbrain surface including the lateral mesencephalic sulcus. The exit of the trochlear nerve is an important landmark; dissecting this nerve within the ambient cistern medial to its exit within the quadrigeminal cistern will lead to the inferior colliculus, which is superomedially placed.

**Pontine Lesions**

As previously mentioned, the pterional and the orbitozygomatic approaches offer some exposure of the ventral upper pons. The transtentorial extension of the subtemporo-

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### TABLE 2. Accessible safe entry zones by surgical approach

<table>
<thead>
<tr>
<th>Approach</th>
<th>Safe Entry Zones</th>
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<tbody>
<tr>
<td>Orbitozygomatic</td>
<td>AMZ</td>
</tr>
<tr>
<td>Subtemporal</td>
<td>AMZ</td>
</tr>
<tr>
<td>Subtemporal transtentorial</td>
<td>AMZ, STZ</td>
</tr>
<tr>
<td>Anterior petrosectomy</td>
<td>AMZ, STZ, PTZ</td>
</tr>
<tr>
<td>Suboccipital telovelar</td>
<td>MS</td>
</tr>
<tr>
<td>Median SCIT</td>
<td>LMS, IC, SC, IF</td>
</tr>
<tr>
<td>Extreme lateral SCIT</td>
<td>LMS, IC, SC, IF</td>
</tr>
<tr>
<td>Retrosigmoid</td>
<td>LMS, STZ, PTZ, LPZ, AL, PM, LMZ</td>
</tr>
<tr>
<td>Far lateral</td>
<td>AL, PM, LMZ, olivary</td>
</tr>
<tr>
<td>Retrolabyrinthine</td>
<td>LMS, STZ, PTZ, LPZ, AL, PM, LMZ, olivary</td>
</tr>
</tbody>
</table>

AL = anterolateral sulcus of medulla; AMZ = anterior mesencephalic zone; IC = intercollicular; IF = infracollicular; LMS = lateral mesencephalic sulcus; LMZ = lateral medullary zone; LPZ = lateral pontine zone; MS = median sulcus of fourth ventricle; PM = posterior median sulcus of medulla; PTZ = peritrigeminal zone; SC = supracollicular; SCIT = supracerebellar infratentorial; STZ = supratrigeminal zone.
ral approach allows exposure of the lateral upper pons as well as the pontomesencephalic junction. However, the trigeminal nerve entry zone is actually the major landmark in approaching most of the anterolateral pontine lesions. Thus, approaches that aim toward the emergence of CN V represent the main routes to managing pontine lesions.

Despite the complexity of dissection and drilling work, the anterior petrosectomy offers the best direct anterior view of the peritrigeminal zone. The retrolabyrinthine approach is also time consuming and provides a limited posterolateral view of the CN V entry zone. However, the retrosigmoid approach is the workhorse for managing anterior and lateral pontine and high-riding medullary lesions, while providing a more posterolateral exposure of the pons and the middle cerebellar peduncle than other approaches (Fig. 13). Additionally, its widespread use in managing vestibular schwannomas and neurovascular conflicts provides experience for those who employ it to attack pontine lesions directly or through the peritrigeminal, supratrigeminal, and lateral pontine safe zones.

Dorsal pontine lesions abutting or close to the rhomboid fossa can be reached through a suboccipital telovelar approach. The depth of the rhomboid fossa is rich in nuclei and tracts, which limits free manipulation. The facial colliculus is the major landmark and guides the surgeon to the supracollicular and infracollicular safe zones when the lesion does not reach the surface. Lastly, cranial lesions can be resected through the median sulcus.

**Medullary Lesions**

The far-lateral approach is chosen to manage anterolateral lesions within the medulla. Cranial lesions not abutting the pial surface are reached through the olivary safe zone. Otherwise, caudal lesions are approached through the anterolateral sulcus between the emergence of the hypoglossal and C-1 spinal nerve rootlets.

Lateral lesions close to the pontomedullary junction require mainly a retrosigmoid approach. This craniotomy can also be employed to manage some lateral caudal lesions if the long axis of the lesion is amenable to the oblique angle of view provided by the retrosigmoid approach (Fig. 13).4 Deeper dorsolateral lesions can be managed by tailoring an incision over the lateral medullary zone. Finally, posterior lesions can be directly accessed via a median suboccipital approach. The neurosurgeon should avoid any manipulation on the calamus scriptorius, an extremely eloquent region, populated by the nuclei of the lower cranial nerves. A posterior midline medullary incision below the obex is advised instead.

**A Note of Caution**

Brainstem lesions represent some of the most challenging entities faced by neurosurgeons. In this article, we have summarized the approaches and safe entry zones into the brainstem. However, no region in the brainstem is truly “safe” for entry. The zones presented in this paper represent the regions through which lesions can be accessed with the least morbidity. As clinical experience from our group has demonstrated, surgery in the brainstem is associated with a high rate of temporary, but real, deficits.1 Practitioners with limited experience operating in the posterior fossa and the brainstem should consider referring these patients to high-volume centers with the requisite experience.

**Conclusions**

Progress in medical technology combined with the experience and dissemination of knowledge regarding microsurgery and brainstem pathology changed the paradigm that the brainstem represented a “no man’s land” for neurosurgeons.

Our revisit of the main safe entry zones provided by each major surgical approach to the brainstem, which includes detailed dissection images and shows areas of exposure, may allow better planning to approach lesions of the brainstem and may help disseminate the techniques for successful resection of intrinsic brainstem lesions.

**Acknowledgments**

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**References**


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**FIG. 13.** Illustration of a retrosigmoid craniotomy and microsurgical resection of an intrinsic lesion in the posterolateral medulla. The flocculus and choroid plexus protruding through the foramen of Luschka are mobilized, and the lateral medullary zone is entered to gain access to the lesion. Reproduced with permission from Barrow Neurological Institute, Phoenix, Arizona. First published in Deshmukh et al: *J Neurosurg* 121:723–9, 2014.

Disclosure

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

Author Contributions

Conception and design: Cavalcanti. Acquisition of data: Cavalcanti. Analysis and interpretation of data: Cavalcanti. Drafting the article: Cavalcanti, Kalani. Critically revising the article: Preul, Kalani, Spetzler. Reviewed submitted version of manuscript: Preul, Kalani, Spetzler. Administrative/technical/material support: Preul. Study supervision: Preul, Spetzler.

Correspondence

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Objective: To report a technique of endoscopic transclival resection of a hemorrhagic brainstem cavernous malformation manifesting in the ventral pons.

Methods: A 29-year-old woman presented with numbness and tingling of the right arm and leg and loss of fine motor control. Magnetic resonance imaging revealed a cavernoma in the ventromedial brainstem on the ventral surface. A purely endoscopic, endonasal, transclival approach was used to resect this cavernoma. Computed tomography/magnetic resonance imaging merged navigation (StealthStation, Medtronic) was used.

Results: The patient had no neurologic deficits postoperatively. The motor control loss and tingling disappeared. She did not experience any complications. Cerebrospinal fluid leakage appeared to result from using the very small opening of the skull base and dura mater and was the reason for the use of a lumbar drain for several days. At the 6-week follow-up examination, the patient was in excellent condition with no neurologic deficits and had returned to her full-time job.

Conclusions: Successful endoscopic, endonasal, transclival resection of a brainstem cavernous malformation was described. This patient experienced improvement in neurologic symptoms after surgery without morbidity. Technologic advances in endoscopic skull base approaches provide access to lesions of the brainstem that previously required more invasive approaches. The endonasal transclival approach provides the most direct route to ventral pontine lesions. Early intervention in brainstem cavernous malformation is indicated and should be performed with an individualized approach taking into consideration the possible complications.

Introduction

Brainstem cavernous malformations (BSCMs) exhibit more frequent symptomatic hemorrhages than supratentorial cavernous malformations. Generally, BSCMs represent about 10% of all vascular lesions of the brain. They occur equally among male and female patients and usually manifest between the ages of 20 and 40 years. Patients with cavernous malformations can present with headaches, seizures, or neurologic deficits, or the lesions can be found incidentally. BSCMs in particular pose a difficult problem for surgeons and patients. The natural history of cavernous malformations has been studied in detail and is still debated. When hemorrhages occur, cavernous malformations have a high risk of rebleeding, with rebleeding rates of BSCM of 5%–35% per year.

Surgical intervention is indicated in patients with hemorrhages and a BSCM that manifests on the pial surface. The surgical approach is dictated by the location of the cavernous malformation within the brainstem. The main goal is to minimize the amount of healthy tissue that must be traversed to achieve a complete resection. The risks and benefits of surgical treatment must be weighed against possible morbidity resulting from surgery. However, brainstem hemorrhages and repeat hemorrhages can also result in a very poor condition.

Although surgical resection of BSCM is challenging, as a result of modern magnetic resonance imaging (MRI), excellent neuronavigation systems, and new surgical tools in the last decade, surgery is considered more frequently.

Key words
- Brain stem
- Cavernous malformation
- Endonasal
- Endoscopy
- Transclival

Abbreviations and Acronyms
BSCM: Brainstem cavernous malformation
CSF: Cerebrospinal fluid
CT: Computed tomography
MRI: Magnetic resonance imaging
Endoscopic procedures are increasingly used for skull base surgery. Many publications on endonasal endoscopic surgery stress the less invasive nature of these techniques and the feasibility of approaching the clivus. We report our technique of endoscopic transclival resection of a BSCM manifesting on the ventral pons and compare our case with related cases reported more recently in the literature. To our knowledge, this is the first reported successful resection of a BSCM via an endoscopic transnasal transclival approach without any postoperative complications and with no neurologic deficits.

**CASE REPORT**

**Presentation of Clinical Case**

A 29-year-old woman presented with numbness and tingling of the right arm and leg. She also described loss of fine motor control of the right hand and transient diplopia. She reported experiencing a transient headache 2 weeks ago. MRI performed after the patient arrived in our department revealed an enhancing lesion in the ventromedial brainstem on the ventral surface (Figure 1). It was decided to offer the patient surgical resection because this was the first episode of symptomatic bleeding, and there was a high risk of rebleeding resulting in a deteriorating condition. We considered approaching the lesion using an endoscopic, endonasal, transclival approach (Video 1). We believed that we would minimize the amount of intact neural tissue with this approach. Via an endonasal transclival approach, we had a direct angle to the ventral brainstem and the lesion, which was closed to the surface (Figure 1).

**Surgical Setting and Technique**

The patient was placed supine with the upper part of the body slightly elevated to about 20° and the head tilted to the left. The patient’s head was fixed with a 3-pin head-fixation system; general anesthesia was administered with oro-tracheal intubation. Lateral fluoroscopy (C-arm) was used for intraoperative imaging. An intraoperative computed tomography (CT) scan with Siemens CT suite (Siemens Healthcare GmbH, Erlangen, Germany) was used for MRI/CT-based merged neuro-navigation with StealthAir System (Medtronic, Minneapolis, Minnesota, USA) to achieve the most accurate navigation in the high-risk area of the lesion in the brainstem (Figure 2). Our surgical setting included intraoperative neurophysiologic monitoring of somatosensory evoked potentials and auditory evoked potentials.

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**Figure 1.** Preoperative magnetic resonance imaging revealed an enhancing lesion in the ventromedial brainstem close to the ventral surface in sagittal (A) and axial (B) views. In the axial view, the basilar artery is in the middle of the ventral surface of the brainstem in front of the lesion. Axial T2 fluid attenuation inversion recovery image (C) indicated a cavernous malformation most likely. The arrows demonstrate the most direct approach and angle to the lesion with minimal opening of the brainstem surface via the endonasal transclival route.
The endoscopic equipment consisted of a series of various rigid-rod lenses Hopkins optics, a Xenon cold light source, a digital 1-chip camera, a high-resolution video monitor screen, and a digital recording system (AIDA; KARL STORZ GmbH & Co., Tutlingen, Germany).

The nose and the nasal cavities were prepared with application of a nasal decongestant and an alcohol-based disinfectant. Mepivacaine with 1:100,000 epinephrine was injected into nasal mucosa for hemostasis. The nasal approach was performed by the authors. An endonasal approach to the clivus was used initially with the same technique as reported previously by the authors in a large series of sellar pathologies.15,21

RESULTS

Detailed Account of Surgical Approach and Technique

The nasal approach was performed by the authors without preparation of a nasoseptal flap. Initially, we decided to use a mononostril endonasal approach to the clivus with the same technique as we reported previously in a large series of sellar pathologies.15,21 Via the right mononostril approach with careful

Figure 2. Use of merged neuronavigation with magnetic resonance imaging (A) and computed tomography (B). We achieved excellent accuracy of neuronavigation using merged images at the skull base and brainstem.
insertion of the speculum under direct endoscopic control, we passed the inferomedial aspect of the middle turbinate under lateral fluoroscopy to the sellar floor until the sphenoid sinus was reached. The nose was carefully dilated in several steps. With this use of the speculum, the nasal mucosa can be preserved through the whole surgical procedure, and almost any mucosal bleeding can be prevented. After exploration of both sphenoid ostia, the anterior face of the sphenoid sinus was removed with Kerrison rongeurs to expose the complete sphenoid sinus and clivus. CT/MRI merged neuronavigation and anatomic landmarks were used to identify the carotid arteries bilaterally. Because of a narrow corridor of the clivus between the internal carotid arteries (Figure 3), we had to change to a binostril approach without a speculum. Otherwise, the surgeon was unable to handle the endoscope and instruments effectively and safely within this narrow space. A 2-handed technique with a fixed endoscope was used during the procedure in this case. The clivus was drilled down to the dura mater in the midline with high-speed electric diamond drill. The sellar floor and the basion were the superior and inferior limitation of the bone resection. The lateral extent of drilling was limited by the petrous part of the internal carotid arteries bilaterally. Dura mater was opened in the midline. The basilar artery could be directly identified slightly diverted to the left as expected in the neuronavigation. Using image-guided navigation, the bleeding was located to the right of the basilar artery. A small corticectomy was made, and dark blood drained out of the cavernoma cavity without manipulation of the perforating arteries of the brainstem. With gentle suction and dissection, the cavernoma was completely removed. A 0° endoscope was used for inspection of the cavity as far as possible. There was no remnant cavernoma. After confirmation of excellent hemostasis, closure of the dura mater was performed with autologous periumbilical fat graft, TachoSil, and fibrin glue. No attempt was made to reconstruct the clival bone. The bone and dural opening was very small, so we decided not to use a nasoseptal flap for additional closure. After repositioning of the nasal septum, nasal packing was placed. After the procedure, a lumbar drain was inserted directly and was continued for 5 days. An intraoperative CT scan was performed at the end of the procedure for resection control (Figure 4). Surgical time was 189 minutes. Histopathologic analysis revealed a cavernous malformation as demonstrated in Figure 5.

Postoperative Course
The patient was extubated immediately after the procedure and admitted to the intensive care unit for neurologic monitoring for 24 hours. She was speaking and tolerating a regular diet on postoperative day 1. The patient reported reduction of the numbness and tingling of the right arm and leg within 12 hours postoperatively. No new neurologic deficits were detected postoperatively.

Lumbar drainage was continued postoperatively for 5 days with bed rest. After removing the lumbar drain, the patient was mobilized successfully. She had no ataxia and no fine motor skill
hemorrhage, and 7 died after subsequent hemorrhages. Many studies have been performed of BSCMs to understand the pathology better and to decide when which kind of surgery is indicated. Some studies showed that the rates of hemorrhage are similar for cavernous malformations in the supratentorial and infratentorial compartments.6 However, 1 series showed that the rates of hemorrhage for infratentorial lesions were 30 times greater in prospectively followed patients with BSCMs having a 5% per years per lesion rate of hemorrhage.5 Fritschi et al.22 reported a series of 41 patients. Their retrospective series estimated a minimum bleeding rate of 2.7% per year and an average rebleeding rate of 21% per year per lesion. Of 12 patients who died after a hemorrhage, 5 died after the first hemorrhage, and 7 died after subsequent hemorrhages. BSCMs are difficult to treat because of their location in an eloquent area. Resection of BSCMs is associated with significant morbidity. However, total resection is curative. Additionally, cavernomas displace, rather than invade—especially after bleeding with a hemorrhagic edge—nervous tissue, making it possible to resect lesions that manifest on the pial surface with minimal risk of a persistent neurologic deficits. Surgical treatment should be considered in every BSCM with an individualized approach that takes in consideration the possible complications.

The ideal approach to the brainstem and the lesion provides the best visualization, minimizes retraction, and provides a good working angle to the cavernoma resulting in good postoperative results with reduction of the surgical morbidity. Many surgical approaches have been proposed to access cavernomas in this location, including the lateral transpeduncular route,23 the presigmoid approach,24 the extradural25 and intradural26 transpetrosal approaches, the retrosigmoid or extended retrosigmoid approach,27 and the combined retrosigmoid-subtemporal approach.28,29 All of these approaches provide access to the anterolateral brainstem but are suboptimal for addressing lesions that manifest on the pontine surface at or near the midline. The lateral or posterolateral approaches, particularly the transpetrosal approaches, require extensive drilling of bone and manipulation and retraction of cranial nerves and vascular structures. None of these approaches provide a direct working angle to a BSCM on the ventromedial pons. Also, large new series show up to a 30% risk of motor deficits after resection of pontomedullary junction cavernomas when approached laterally caused by irritation of the corticospinal tracts that run longitudinally in the ventromedial pons.

Reisch et al.20 presented 2 cases of anterior cavernous malformations resected using a microscopic technique through a transoral translacical technique, allowing direct access to the ventral brainstem. Both patients had an improved neurologic examination relative to their baseline at the 3-month follow-up evaluation, although 1 patient required reoperation for a CSF leak. This technique has been used infrequently since then.

At the present time, many lesions of the skull base can be accessed and removed via an endoscopic endonasal approach. It is important to determine preoperatively that the entire lesion is accessible via an endoscopic approach and that the surgical tools are adequate. The surgeon has to balance the advantages of a direct vector to the lesion and minimizing surgical trauma and the known risks of CSF leaks and potentially dealing with bleeding with endoscopic instruments.

New developments in endoscopic techniques have made it possible to perform a transclival approach with endoscopic visualization. The endoscopic, transnasal, transclival approach to BSCMs has previously been described in case reports.17–20 In the presented cases, 2 of 4 patients had persistent CSF leakage and underwent revision surgery using different surgical techniques than described in the case reports. In 1 patient, there was a residual cavernous malformation on follow-up MRI. Nayak et al.19 described endoscopic resection of BSCM in 4 patients via endonasal and retrosigmoidal approaches. They pointed out that they will consider prophylactic CSF drainage in future cases using an endonasal transclival approach. In Table 1, we compare the published cases and our case. In general, the authors pointed out the importance of significant experience of

deficits. No cerebrospinal fluid (CSF) leak was appreciated. Postoperative MRI demonstrated complete resection of the cavernous malformation and bleeding (Figure 6). The patient was discharged to home on postoperative day 7 in good condition without any neurologic deficits.

At 6-week follow-up examination, the patient presented in excellent condition without any neurologic symptoms. No CSF rhinorrhea had developed. She had returned to her full-time job as laboratory technical assistant.

Before the present case, 4 comparable case reports were published in the literature. Two patients had persistent CSF leakage postoperatively and underwent revision surgery using different surgical techniques. Remnant cavernous malformation was detected on follow-up MRI in 1 case. No morbidity was reported. The reported cases from the literature are compared with the present case in Table 1.

DISCUSSION

Many studies have been performed of BSCMs to understand the pathology better and to decide when which kind of surgery is indicated. Some studies showed that the rates of hemorrhage are similar for cavernous malformations in the supratentorial and infratentorial compartments. However, 1 series showed that the rates of hemorrhage for infratentorial lesions were 30 times greater in prospectively followed patients with BSCMs having a 5% per years per lesion rate of hemorrhage. Fritschi et al. reported a series of 41 patients. Their retrospective series estimated a minimum bleeding rate of 2.7% per year and an average rebleeding rate of 21% per year per lesion. Of 12 patients who died after a hemorrhage, 5 died after the first hemorrhage, and 7 died after subsequent hemorrhages.

Figure 5. Histopathologic analysis with elastica van Gieson staining revealed typical findings of a cavernous malformation with large pathologic vessels with fibrotic vascular wall and hemosiderin in the surrounding tissue in the resected tissue (magnification × 100).
the surgeon with respect to relevant anatomy, endoscopic techniques, and endoscopic instruments.\textsuperscript{17–19}

The biggest concern we had before surgery using an endoscopic skull base approach was the risk of CSF leak. CSF leak is still the most common complication in endoscopic skull base surgery, and although there has been dramatic improvement, this complication is underreported in the literature. Since we began our endoscopic technique, we have improved our CSF leak rate.

Table 1. Comparison of Clinical Course, Complications, and Dimension of Lesion in Reported Cases of Endonasal Transclival Resection of Brainstem Cavernous Malformations

<table>
<thead>
<tr>
<th>Case 1 (Sanborn et al., 2012\textsuperscript{20})</th>
<th>Case 2 (Kimball et al., 2012\textsuperscript{18})</th>
<th>Case 3 (Dallan et al., 2015\textsuperscript{17})</th>
<th>Case 4 (Present Case)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)/sex</td>
<td>17/male</td>
<td>59/female</td>
<td>15/male</td>
</tr>
<tr>
<td>Presenting symptoms</td>
<td>Acute onset of headache, facial numbness, left-sided hemiparesis, right sixth cranial nerve palsy, dysphagia</td>
<td>Intermittent dysarthria, right facial weakness, left arm and leg weakness, loss of fine motor control</td>
<td>Acute onset of headache, vomiting, diplopia, hearing loss, facial palsy</td>
</tr>
<tr>
<td>Dimensions (mm)</td>
<td>$17 \times 12$</td>
<td>$20 \times 20 \times 20$</td>
<td>$10 \times 10$</td>
</tr>
<tr>
<td>Complications</td>
<td>CSF leak</td>
<td>CSF leak</td>
<td>Small residual of CM</td>
</tr>
<tr>
<td>Postoperative neurologic deficits</td>
<td>Worsening of left-side motor function, restricted horizontal gaze; improved in follow-up</td>
<td>Remained at preoperative neurologic baseline; improved in follow-up</td>
<td>Recovered after 2 years</td>
</tr>
</tbody>
</table>

CSF, cerebrospinal fluid; CM, cavernous malformation.
with application of an autologous periumbilical fat graft for dural closure and use of lumbar drainage after dural repair in all cases of endonasal surgery. Aggressive lumbar CSF drainage is needed for at least 5 days postoperatively. Otherwise, the risk of a persistent CSF leak is very high independent of the applied technique for dural and skull base repair. A second method to minimize the risk of CSF leakage is the reduction of bone and dural opening. We used the merged CT/MRI neuronavigation to access the cavernoma via a minimized opening of the clivus and a small opening of the dura mater. The opening of the clivus is only 7 mm (Figure 4). In consequence of the very small bone opening and consequently small dural opening, we had a low risk of CSF leakage postoperatively, and there was no need for a nasoseptal flap.

Significant bleeding after opening of the premonate dura mater as described before did not occur. In general, the control of bleeding during the approach to the brainstem is essential for a successful resection of BSCM or other lesions of the brainstem under endoscopic view. Manipulation with instruments and especially bipolar electrocautery near the brainstem or into the brainstem must be minimized to avoid operative morbidity.

CONCLUSIONS
We have described in detail our surgical technique of endoscopic, endonasal, transclival resection of a BSCM manifesting on the ventral surface of the pons. The endonasal transclival approach provides the most direct route to ventral pontine lesions. A major step to prevent postoperative persistent CSF leakage is the insertion of a lumbar drain for several days and a minimalized opening of the skull base and dura mater. Early intervention in BSCM is indicated and should be performed with an individualized approach taking into consideration the possible complications.

ACKNOWLEDGMENTS
We thank Y. J. Kim for providing the histopathologic image of the removed brainstem cavernous malformation in the presented case.

REFERENCES


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The utility of preoperative diffusion tensor imaging in the surgical management of brainstem cavernous malformations

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Objective Resection of brainstem cavernous malformations (BSCMs) may reduce the risk of stepwise neurological deterioration secondary to hemorrhage, but the morbidity of surgery remains high. Diffusion tensor imaging (DTI) and diffusion tensor tractography (DTT) are neuroimaging techniques that may assist in the complex surgical planning necessary for these lesions. The authors evaluate the utility of preoperative DTI and DTT in the surgical management of BSCMs and their correlation with functional outcome.

Methods A retrospective review was conducted to identify patients who underwent resection of a BSCM between 2007 and 2012. All patients had preoperative DTI/DTT studies and a minimum of 6 months of clinical and radiographic follow-up. Five major fiber tracts were evaluated preoperatively using the DTI/DTT protocol: 1) corticospinal tract, 2) medial lemniscus and medial longitudinal fasciculus, 3) inferior cerebellar peduncle, 4) middle cerebellar peduncle, and 5) superior cerebellar peduncle. Scores were applied according to the degree of distortion seen, and the sum of scores was used for analysis. Functional outcomes were measured at hospital admission, discharge, and last clinic visit using modified Rankin Scale (mRS) scores.

Results Eleven patients who underwent resection of a BSCM and preoperative DTI were identified. The mean age at presentation was 49 years, with a male-to-female ratio of 1.75:1. Cranial nerve deficit was the most common presenting symptom (81.8%), followed by cerebellar signs or gait/balance difficulties (54.5%) and hemibody anesthesia (27.2%). The majority of the lesions were located within the pons (54.5%). The mean diameter and estimated volume of lesions were 1.21 cm and 1.93 cm³, respectively. Using DTI and DTT, 9 patients (82%) were found to have involvement of 2 or more major fiber tracts; the corticospinal tract and medial lemniscus/medial longitudinal fasciculus were the most commonly affected. In 2 patients with BSCMs without pial presentation, DTI/DTT findings were important in the selection of the surgical approach. In 2 other patients, the results from preoperative DTI/DTT were important for selection of brainstem entry zones. All 11 patients underwent gross-total resection of their BSCMs. After a mean postoperative follow-up duration of 32.04 months, all 11 patients had excellent or good outcome (mRS Score 0–3) at the time of last outpatient clinic evaluation. DTI score did not correlate with long-term outcome.

Conclusions Preoperative DTI and DTT should be considered in the resection of symptomatic BSCMs. These imaging studies may influence the selection of surgical approach or brainstem entry zones, especially in deep-seated lesions without pial or ependymal presentation. DTI/DTT findings may allow for more aggressive management of lesions previously considered surgically inaccessible. Preoperative DTI/DTT changes do not appear to correlate with functional postoperative outcome in long-term follow-up.

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Key words cavernous malformations; brainstem; diffusion tensor imaging; diffusion tensor tractography; resection; outcome; vascular disorders

Abbreviations BSCM = brainstem CM; CM = cavernous malformation; CST = corticospinal tract; DTI = diffusion tensor imaging; DTT = diffusion tensor tractography; FA = fractional anisotropy; ICP = inferior cerebellar peduncle; ML = medial lemniscus; MLF = medial longitudinal fasciculus; mRS = modified Rankin Scale.

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Disclosure The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.
Cavernous malformations (CMs) are uncommon lesions, with an estimated prevalence of 0.4%–0.8%. They represent 10%–20% of all CNS vascular malformations, with the majority of cases involving supratentorial structures. Approximately 10%–35% of CMs arise in the brainstem and may be associated with initial hemorrhage and rebleeding rates higher than those occurring with supratentorial and spinal cord lesions. Resection may reduce the risk of a stepwise neurological deterioration, but the complexity of brainstem anatomy makes this task technically demanding and is associated with the risk of additional brainstem injury.

Several adjuvant techniques have been implemented in the surgical management of brainstem lesions, such as functional MRI, intraoperative frameless stereotactic navigation, and intraoperative MRI. None of those methods can precisely visualize white matter tracts or define essential aspects of tract location or displacement. Diffusion tensor imaging (DTI) and diffusion tensor tractography (DTT) are promising neuroimaging techniques that help overcome some of those limitations. They have become useful clinical tools that can delineate functionally important white matter tracts for surgical planning. Tractography based on diffusion MRI explores the correlation between water diffusion and brain structure to delineate the course of white matter pathways. Diffusion tensor tractography (DTT) follows a white matter tract from voxel to voxel in 3 dimensions by assuming that the direction of least restricted diffusion corresponds to the orientation of axons. As a result of this predictable pattern of diffusion, which is orientation dependent (or anisotropic), location and orientation of white matter tracts can be determined.

Several articles have described the implementation of DTI for a multitude of neurological diseases and neuroanatomical studies; however, none has addressed its specific application in the management of brainstem cavernous malformations (BSCMs).

The goals of the present study were to determine if preoperative DTI and DTT can clearly identify relevant fiber tracts adjacent to BSCMs and to evaluate their roles in surgical planning. We analyze the correlation of DTI and DTT findings with known microsurgical anatomy of the brainstem safe entry zones, and their implications for the selection of surgical approaches. Finally, we attempt to correlate preoperative changes in DTI and DTT and functional outcome after resection of these lesions.

Methods

Patients

All patients who were evaluated for a BSCM at the University of Texas Southwestern Medical Center between July 2007 and July 2012 were screened for inclusion into the study. Eleven patients who underwent resection of a symptomatic BSCM and had a preoperative DTI scan were identified. Retrospective chart review was used to identify patients with a minimum of 6 months of clinical and radiographic follow-up. Surgical intervention was considered in cases of 1) BSCMs with pial presentation, independent of the number of hemorrhages preoperatively; or 2) history of BSCMs and progressive neurological deficits, with or without radiographic evidence of rehemorrhage. Detailed neurological examination and brain MRI gradient echo and gadolinium contrast-enhanced sequences were obtained. All patients were reassessed daily during hospital admission, then routinely during outpatient clinic visits for a minimum of 6 months postoperatively. Retrospective analysis and data collection were approved by the institutional review board at our institution.

Conventional MR and DTI

All patients underwent initial brain MRI with and without gadolinium contrast as part of their diagnostic workup. Once the patients were selected for surgical intervention, additional brain MRI with fast imaging employing steady state acquisition (FIESTA) and DTI protocol were performed (Signa HDxt 3.0T, GE Medical Systems; FOV 16.0 cm, matrix size 320 × 256, slice thickness 2.00 mm). DTI was performed using single-shot spin-echo planar imaging (TR 8,500–12,000 msec, TE 75–85 msec, matrix 128 × 128, slice thickness 2.4 mm, gap 0 mm). Nineteen diffusion directions at b = 1000 sec/mm² were acquired in addition to b = 0 images. All images were reviewed by one of the senior authors (A.R.W.). A default fractional anisotropy (FA) threshold of 0.20 and minimum fiber length of 50 mm were used for construction of DTT, as validated by Kunimatsu et al. Patterns of fiber tract alterations (based on morphological appearance on color map FA threshold and reconstructed 3D tractography) were classified into 4 groups, as described by Lazar et al. (Table 1). Areas of interest were limited to the neuroanatomical region of the brainstem correlating to the BSCM site and its hemorrhage. The following major fiber tracts were selected for evaluation: 1) corticospinal tract (CST), 2) medial lemniscus (ML) and medial longitudinal fasciculus (MLF), 3) inferior cerebellar peduncle (ICP), 4) middle cerebellar peduncle, and 5) superior cerebellar peduncle (Fig. 1). Scores of 0–4 were applied according to the degree of distortion seen in each of the involved tracts, and the sum of individual fiber tract scores was used for univariate analysis.

Initial postoperative imaging follow-up consisted of noncontrast head CT scanning, completed up to 24 hours after resection. Postoperative brain MRI with gadolinium contrast was obtained during the hospital stay or the subsequent week.
DTI in the surgical management of brainstem cavernomas

after discharge, but no longer than 6 months postoperatively. If no evidence of a recurrent or residual lesion was identified on initial brain MRI, this study was repeated at 6-month intervals for the first 2 postoperative years and at 2-year intervals thereafter.

Anatomical Location and Hemorrhage Status

Cavernous malformation location was stratified into 5 categories: mesencephalic, pontomesencephalic, pontine, pontomedullary, and medullary. Sizes were measured on thin-slice T1- or T2-weighted sequences, including the extralesional hematoma cavity (if present). The volume (including BSCM and surrounding hematoma) was calculated assuming an approximate ellipsoid lesional shape: 

$V = \frac{4}{3} \pi r_1 r_2 r_3$

Clinical criteria to determine evidence of hemorrhage were 1) acute onset of neurological deficit that persisted for more than 24 hours and 2) deterioration of preexisting symptoms or development of new neurological deficits in patients with previously ruptured BSCMs.

Surgical Principles and Technique

Several surgical approaches were used (Fig. 2). To minimize local tissue trauma, the hemosiderin-stained surrounding parenchyma is not routinely resected in our practice. Developmental venous anomaly was preserved in all identified cases. 

The 2-point method was used when feasible to guide the surgical decision-making process, as described elsewhere. The selected surgical approach was correlated with the results from preoperative DTI/DTT and the initial surgical plan adjusted if the findings showed discrepant results or potential risk to the integrity of major long fiber tracts. Somatosensory, motor, and brainstem auditory evoked potential monitoring, as well as electromyographic recordings of specific cranial nerves, were performed selectively based on CM location. A perioperative lumbar drain was used only once for adequate brain relaxation (subtemporal approach for a mesencephalic CM). Histopathological confirmation was obtained for all surgical specimens.
Clinical and/or radiographic follow-up was obtained at the first postoperative clinic evaluation and subsequent clinic visits. Neurological examination findings at the time of discharge and the first and most recent postoperative visits were reviewed. Functional outcomes were measured independently by 2 separate observers at the time of admission, discharge date, and last clinic visit using the modified Rankin Scale (mRS) score. Excellent (mRS Score 0–1), good (mRS Score 2–3), or bad (mRS Score 4–6) outcome was determined preoperatively and at the time of the last clinic visit. No patients were lost to follow-up.

Statistical Analysis
Patient data including age, sex, medical and neurosurgical history, number of hemorrhages before surgical intervention, and length of hospital and inpatient rehabilitation stays were collected. Mean, standard deviation, and range were determined for all the demographic data analyzed. Fisher’s exact test, independent samples t-test, or Mann-Whitney U-test was performed as indicated for categorical and continuous variables. A test probability value < 5% was considered significant.

Results

Patient Characteristics and Presentation
Between November 2007 and March 2012, 11 patients with surgically treated BSCMs were identified and fulfilled the enrollment criteria (Tables 2 and 3). The mean age at presentation was 49 years, with a male-to-female ratio of 1.75:1. Cranial nerve deficits were the most common presenting symptoms (81.8%), followed by cerebellar signs and gait/balance difficulties (54.5%) and hemi-body numbness/hemianesthesia (27.2%). Headaches were infrequent complaints at initial presentation (9%); only 1 patient (with a left posterior pontine tegmental lesion) presented with hemiparesis.

Lesion Characteristics and Location
The majority of the lesions were located within the pons (72.7%). The remaining lesions were mesencephalic (n = 2) and medullary (n = 1). Seven patients (63.6%) underwent resection of the CM after a single symptomatic event; 3 patients (27.3%) were submitted to resection after a second symptomatic event. One patient with a CM located on the posterolateral aspect of the midbrain (epicenter on lateral mesencephalic sulcus) had 3 hemorrhages before surgical intervention (including a remote episode 10 years before his presentation to our institution).

The mean size of symptomatic lesions was 1.21 cm, and the mean estimated volume was 1.93 cm³. No statistical difference was seen for mean size and volume between patients with 1 or 2 or more hemorrhagic episodes (p = 0.842 and p = 0.963, respectively). The mean elapsed times from symptom onset to surgical intervention were 103.86 days and 120.50 days for patients with 1 or more than 1 hemorrhagic episode, respectively.

Diffusion Tensor Imaging and Diffusion Tensor Tractography
The mean time from DTI data acquisition to operative intervention was 24.45 days. All patients had changes in DTI and DTT involving at least 1 major fiber tract; 82% showed involvement of 2 or more fiber tracts. Overall, a total of 32 fiber tracts in all 11 patients were found to have some degree of disturbance caused by a BSCM and associated hemorrhage. CST and ML/MLF were the most commonly affected (n = 8 and n = 9, respectively). The majority of changes were displacement (n = 14) or partial interruption and distortion (n = 14). Complete interruption was seen in 4 cases (2 pontine, 1 pontomedullary, and 1 medullary lesion), 3 of those involving the CST (Table 4).

The results obtained from DTI and DTT were cross-referenced with the planned surgical approach. Four cases with radiographic evidence of pial presentation on preoperative MRI underwent surgery through the originally selected surgical approach. This paramount principle of resection of brainstem lesions is associated with a better postoperative neurological outcome and lower incidence of new neurological deficits, in part because it minimizes normal brainstem tissue retraction, avoids ex-
tensive parenchymal surgical corridors, and utilizes the local surface changes caused by the underlying lesion and hemorrhage as a reliable marker for entry zone selection.1,2,7,9,11,27,28,45,52,60 The pial presentation on MRI correlated with DTI/DTT findings (fiber tract deviation or interruption at the selected brainstem entry point) as well as the intraoperative findings during initial microscopic dissection. In 4 patients with no clear evidence of pial presentation on preoperative MRI studies, the decision-making process was influenced by the results of DTI/DTT. A 50-year-old patient presenting after second hemorrhage from a known right pontine cavernous malformation diagnosed after new onset of left facial weakness and hemifacial numbness (Fig. 4A) underwent a far-lateral transcondylar transpeduncular approach instead of a transventricular/posterior approach after DTI/DTT showed the cavernous malformation to displace the ML, ICP, and the facial colliculus posteromedially (Fig. 4B and C). Postoperative MRI showed gross-total resection of her CM with a peritrigeminal area brainstem entry point (Fig. 3D). In a similar situation, a 15-year-old boy with a posteriorly located left pontomedullary junction cavernous malformation diagnosed after new onset of left facial weakness and hemifacial numbness (Fig. 4A) underwent a far-lateral transcondylar transpeduncular approach instead of a transventricular/posterior approach after DTI/DTT showed the cavernous malformation to displace the ML, ICP, and the facial colliculus posteromedially (Fig. 4B and C). Postoperative MRI showed gross-total resection of his CM with a peritrigeminal area brainstem entry point.

**TABLE 2. Brainstem cavernous malformations: general patient demographic data**

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Age (yrs)</th>
<th>Sex</th>
<th>No. of Preop Hemorrhages</th>
<th>Location</th>
<th>Anteroposterior Size (mm)</th>
<th>Volume (cm³)</th>
<th>LOS (days)</th>
<th>LOS Rehab (days)</th>
<th>Surgical Approach</th>
<th>Follow-Up (mos)</th>
<th>Initial mRS Score</th>
<th>Last mRS Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40, F</td>
<td>1</td>
<td>1</td>
<td>Pons</td>
<td>12</td>
<td>1.04</td>
<td>5</td>
<td>—</td>
<td>Far lateral</td>
<td>59.00</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>44, F</td>
<td>1</td>
<td>1</td>
<td>Pons</td>
<td>5</td>
<td>0.07</td>
<td>7</td>
<td>—</td>
<td>Transvermian</td>
<td>53.60</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>48, F</td>
<td>2</td>
<td>1</td>
<td>Pons</td>
<td>6</td>
<td>0.20</td>
<td>7</td>
<td>—</td>
<td>Transpetrosal presigmoid</td>
<td>45.93</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>15, M</td>
<td>1</td>
<td>2</td>
<td>Pons</td>
<td>12</td>
<td>0.97</td>
<td>6</td>
<td>—</td>
<td>Far lateral transcondylar</td>
<td>39.83</td>
<td>1</td>
<td>2</td>
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<tr>
<td>5</td>
<td>70, M</td>
<td>1</td>
<td>1</td>
<td>Pons</td>
<td>9</td>
<td>0.62</td>
<td>21</td>
<td>22</td>
<td>Telovelar</td>
<td>35.90</td>
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</tr>
<tr>
<td>6</td>
<td>29, M</td>
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<td>1</td>
<td>Pons</td>
<td>19</td>
<td>5.69</td>
<td>8</td>
<td>—</td>
<td>Telovelar</td>
<td>32.37</td>
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<tr>
<td>7</td>
<td>67, F</td>
<td>1</td>
<td>1</td>
<td>Midbrain</td>
<td>12</td>
<td>1.04</td>
<td>38</td>
<td>23</td>
<td>Subtemporal</td>
<td>22.20</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>62, M</td>
<td>3</td>
<td>1</td>
<td>Midbrain</td>
<td>10</td>
<td>0.58</td>
<td>17</td>
<td>57</td>
<td>Subtemporal</td>
<td>28.17</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>55, M</td>
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<td>1</td>
<td>Pons</td>
<td>6</td>
<td>0.53</td>
<td>8</td>
<td>29</td>
<td>Far lateral</td>
<td>20.47</td>
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<td>2</td>
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<tr>
<td>10</td>
<td>50, M</td>
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<td>2</td>
<td>Pons</td>
<td>29</td>
<td>9.84</td>
<td>6</td>
<td>12</td>
<td>Transpetrosal presigmoid</td>
<td>16.30</td>
<td>2</td>
<td>2</td>
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<tr>
<td>11</td>
<td>59, M</td>
<td>1</td>
<td>1</td>
<td>Medulla</td>
<td>13</td>
<td>0.67</td>
<td>21</td>
<td>—</td>
<td>Far lateral transcondylar</td>
<td>6.00</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

LOS = length of stay; — = not applicable.

**TABLE 3. Descriptive analysis of 11 patients who underwent resection of symptomatic BSCMs**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
<td>15</td>
<td>70</td>
<td>49.00 (16.535)</td>
</tr>
<tr>
<td>Time btwn diagnosis/presentation and surgery in days</td>
<td>39</td>
<td>224</td>
<td>109.91 (56.749)</td>
</tr>
<tr>
<td>Bleeding episodes until surgery</td>
<td>1</td>
<td>3</td>
<td>1.45 (0.688)</td>
</tr>
<tr>
<td>Anteroposterior size (mm)</td>
<td>5</td>
<td>29</td>
<td>12.09 (6.877)</td>
</tr>
<tr>
<td>Volume (cm³)</td>
<td>0.07</td>
<td>9.84</td>
<td>1.932 (3.045)</td>
</tr>
<tr>
<td>Time btwn DTI acquisition and surgery in days</td>
<td>1</td>
<td>69</td>
<td>24.45 (21.135)</td>
</tr>
<tr>
<td>Hospital LOS (days)</td>
<td>5</td>
<td>38</td>
<td>13.09 (10.261)</td>
</tr>
<tr>
<td>Rehab LOS (days)</td>
<td>12</td>
<td>57</td>
<td>28.06 (17.009)</td>
</tr>
<tr>
<td>Follow-up (mos)</td>
<td>6</td>
<td>58</td>
<td>32.04 (16.209)</td>
</tr>
<tr>
<td>Initial mRS score</td>
<td>0</td>
<td>3</td>
<td>1.45 (0.820)</td>
</tr>
<tr>
<td>Last mRS score</td>
<td>0</td>
<td>2</td>
<td>1.45 (0.688)</td>
</tr>
</tbody>
</table>

Surgical Approaches

Four patients (36.3%) underwent a far-lateral approach and its variations for resection of lesions located at the pons or pontomedullary junction. Three patients (27.4%) had large CMs abutting the floor of the fourth ventricle, with intraventricular pial presentation, and underwent a midline suboccipital craniotomy. Table 5 summarizes the remaining surgical approaches used for the resection of the BSCMs.

Outcomes

All 11 patients had gross-total resection of their BSCMs. The mean overall hospital length of stay was 13.09 days. Six patients (54.5%) were discharged home after recovering from the surgical procedure; 5 patients (45.5%) required admission to an inpatient rehabilitation facility, with a mean length of stay of 28.60 days; all 5 patients
were eventually discharged home. Need for inpatient rehabilitation admission postoperatively did not predict worse outcome \( (p = 0.137) \). As observed in various other studies, most patients had transient worsening of preoperative neurological deficits or development of new neurological symptoms; nonetheless, all 11 patients had improvement in neurological function by the first postoperative outpatient visit; the improvement continued over the first 24 months. The mean length of postoperative follow-up was 32.04 months. There were no deaths during long-term follow-up.

Two patients developed postoperative CSF leak. One of the cases resolved after lumbar drain placement and temporary CSF diversion; the second patient required reoperation for an enlarging pseudomeningoele and wound infection with early meningitis. One patient required temporary tracheostomy/gastrostomy tube placement that was discontinued 3 months postoperatively (Table 6).

Five patients (45.5%) had excellent outcomes (mRS

### TABLE 4. DTI/DTT changes and attributed DTI score stratified by brainstem location

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Medulla Oblongata</th>
<th>Pons</th>
<th>Midbrain</th>
<th>DTI Score</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ICP</td>
<td>CST</td>
<td>ML/MLF</td>
<td>ICP</td>
</tr>
<tr>
<td>1</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>8</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>9</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>3</td>
</tr>
<tr>
<td>11</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>—</td>
</tr>
</tbody>
</table>

ICP = inferior cerebellar peduncle; MCP = middle cerebellar peduncle; SCP = superior cerebellar peduncle.
Score 0–1) at the time of their last outpatient clinic evaluation. Six patients (54.5%) had good outcomes (mRS Scores 2–3). No patients had an mRS score of 4 or 5 at last follow-up. Compared with preoperative assessment, 5 patients (45.5%) had improvement of neurological function; 2 patients (18.2%) remained stable, and 4 patients (36.3%) had some degree of neurological decline postoperatively. Except for the number of preoperative bleeding episodes \((p = 0.047, 95\% CI 0.015–1.413)\) and initial mRS score \((p = 0.021, 95\% CI 0.210–2.005)\), no other independent variable was associated with long-term outcome.

The mean DTI scores for patients with a stable/improved or worse mRS score postoperatively were 8.00 and 7.50, respectively \((p = 0.724)\). The results were similar after stratification by brainstem location for pontine lesions \((p = 0.687)\); small sample size prevented statistical analysis of mesencephalic lesions. The only patient with a medullary BSCM had overall improvement and mRS Score 1 postoperatively, despite significant changes seen on DTI.

**Discussion**

Cavernous malformations are discrete, lobulated, well-circumscribed lesions consisting of dilated and thin-walled capillaries with simple endothelial lining and variably thin fibrous adventitia. The typical CM has no interwalled capillaries with simple endothelial lining and variable morphology. The best treatment option for accessible brainstem lesions once they bleed, because it may prevent neurological decline due to recurrent hemorrhages.

**Natural History**

There is variable risk of hemorrhage reported in the literature, partially due to preselection of patients in retrospective studies and variations in the definition of hemorrhagic episodes. An overall hemorrhage rate of 2.4%–4.6% per patient-year appears to be an adequate estimate from various natural history studies, with higher numbers \(2.6%–7%\) per patient-year obtained from surgical series. After an initial event, bleeding rates are generally higher \(5%–34.7%\).

**TABLE 5. Surgical approaches for resection of BSCMs**

<table>
<thead>
<tr>
<th>Surgical Approach</th>
<th>No. of Patients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Far lateral</td>
<td>1</td>
</tr>
<tr>
<td>Transcondylar</td>
<td>3</td>
</tr>
<tr>
<td>Suboccipital</td>
<td>1</td>
</tr>
<tr>
<td>Transvermian</td>
<td>2</td>
</tr>
<tr>
<td>Telovelar</td>
<td>1</td>
</tr>
<tr>
<td>Transpetrosal presigmoid</td>
<td>1</td>
</tr>
<tr>
<td>Frontotemporal transylvian</td>
<td>1</td>
</tr>
<tr>
<td>Supracerebellar-infratentorial*</td>
<td>1</td>
</tr>
<tr>
<td>Subtemporal</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>12</td>
</tr>
</tbody>
</table>

* Aborted due to inadequate exposure and prominent venous anatomy precluding safe resection.

**TABLE 6. Perioperative complications in 11 patients undergoing resection of BSCMs**

<table>
<thead>
<tr>
<th>Complications</th>
<th>No. of Patients</th>
</tr>
</thead>
<tbody>
<tr>
<td>New transient CN deficit</td>
<td>6</td>
</tr>
<tr>
<td>CN III</td>
<td>1</td>
</tr>
<tr>
<td>CN VI</td>
<td>3</td>
</tr>
<tr>
<td>CN VII</td>
<td>1</td>
</tr>
<tr>
<td>CN VIII</td>
<td>1</td>
</tr>
<tr>
<td>New permanent CN deficit</td>
<td>3</td>
</tr>
<tr>
<td>CN VII</td>
<td>2</td>
</tr>
<tr>
<td>CN VIII</td>
<td>1</td>
</tr>
<tr>
<td>New motor deficit</td>
<td>1</td>
</tr>
<tr>
<td>New sensory deficit</td>
<td>1</td>
</tr>
<tr>
<td>Thalamic ischemic infarct</td>
<td>1</td>
</tr>
<tr>
<td>Need for tracheostomy &amp;/or gastrostomy tube placement</td>
<td>1</td>
</tr>
<tr>
<td>CSF leak</td>
<td>2</td>
</tr>
<tr>
<td>Meningitis</td>
<td>1</td>
</tr>
<tr>
<td>Ventilator-associated pneumonia</td>
<td>1</td>
</tr>
</tbody>
</table>

**Study Population**

The study population was slightly older (mean age 49 years) than reported in surgical literature. Most lesions were located in the pons; this neuroanatomical distribution of BSCMs in our study is similar to the one reported by Dukatz et al. Headaches were usually not a predominant complaint and cranial nerve deficits were the most prevalent presentation. Postoperatively, clinical symptoms improved or remained stable in 63.7% of the patients. Four patients’ conditions (36.3%) deteriorated or they developed new neurological deficit; overall, these results are similar to those described in the literature. Patients who improved or remained stable had more hemorrhages and higher initial mRS scores preoperatively, which did not reflect negatively on final functional outcome. All 11 patients had mRS scores of 2 or lower at 32 months. No rehemorrhages were documented over a mean follow-up of 32 months.

**DTI/DDT Data**

Since the advent of DTI 2 decades ago, there has been significant interest in its potential clinical applications. The physical principles and rationale of this technique have been extensively debated, and a more profound discussion is beyond the scope of the current study.
Wu et al. showed that DTI-based functional neuronavigation contributed to maximal safe resection of cerebral gliomas and decreased postoperative motor deficits while increasing high-quality survival. Lower rates of postoperative deficit and dependency as well as higher median survival rates were reported in 118 patients who underwent surgery with DTI-integrated neuronavigation compared with 120 patients who underwent surgery with standard techniques. Others have shown good concordance between tractography results and intraoperative direct electric stimulations.

Despite good data on DTI use for supratentorial lesions, there have been only a limited number of studies regarding its application in brainstem pathologies, partially because of known technical difficulties intrinsic to this location. Kovanlikaya et al. investigated the role of DTI and DTT on the CST alterations caused by space-occupying lesions in the brainstem before and after resection in 14 patients. All of the patients with normal CST on DTT presented without motor deficit on neurological examination. DTT was shown to have high sensitivity (100%) and negative predictive value (100%), but high false-positive results (positive predictive value of 42.9%) in preoperative evaluation, related to lesion artifact. In 2 separate articles, Chen et al. acknowledged that, compared with conventional MRI, DTI and DTT provided superior quantification and visualization of lesion involvement in eloquent fiber tracts of the brainstem. Moreover, DTI and DTT were found to be beneficial for white matter recognition in the neurosurgical planning and postoperative assessment of brainstem lesions.

In our study, 82% of the patients presented with DTI changes involving 2 or more major fiber tracts. Most disturbances were displacements or partial interruptions and involved the CST and ML/MLF complex. Sensitivity and negative predictive value were excellent and similar to the ones presented by Kovanlikaya et al. Positive predictive values as low as 37.5% were also observed in our study. Preoperative DTI was not shown to correlate with postoperative outcome, as determined by the mRS score. These findings suggest that preoperative DTI/DTT may not be a useful tool for prediction of neurological deficits or long-term outcome after resection of BSCMs. Part of the explanation could reside in the fact that the majority of preoperative symptoms in our population were cranial nerve deficits (81.8%), which are not well delineated by DTI/DTT. Another explanation derives from limitations in the technique itself. The hemosiderin rim is well known to cause local modifications in tissue anisotropy and to falsely disrupt tractography maps. Additionally, echo planar imaging–based DTI is hindered by susceptibility distortions at the proximity of the skull base air-filled spaces, partially secondary to pulsatile cardiac and respiratory motion artifacts.

DTI could represent, however, a valuable tool in preoperative and intraoperative planning for resection of specific subtypes of lesions. Cavernous malformations are thought to displace rather than infiltrate surrounding structures. Some neurological deficits observed preoperatively could be attributed to tissue expansion and displacement caused by blood contained in the hemorrhagic cavity; resorption of blood products correlates positively with neurological improvement and is one of the reasons why some authors recommend resection in a delayed fashion. This delay allows for partial liquefaction of the hematoma, which facilitates resection and minimizes surgery-related trauma. In cases in which the BSCM has pial or ependymal presentation, the lesion itself provides the surgical access route.

To our knowledge, this is the largest study published to date involving brainstem cavernous malformations and DTI. Our results confirm the feasibility of DTI and DTT on preoperative assessment of patients with brainstem space-occupying lesions such as BSCMs. In selected cases, DTI/DTT could provide useful information preoperatively that may influence surgical results in deep-seated brainstem lesions without pial or ependymal presentation. In this subtype of BSCMs, DTI/DTT may assist in the selection of the surgical approach and brainstem entry zone. In the future, intraoperative DTT visualization for neurosurgical planning can be integrated with the neurosurgical microscope and real-time querying tractography obtained, maximizing resection while preserving structure and, subsequently, function. DTI/DTT could be a potential tool for preoperative counseling of patients with critically located lesions, anticipating neurological deficits that—even transiently—can impact negatively on quality of life. The long follow-up demonstrated well the remarkable functional recovery those patients can attain after an initial expected postoperative neurological decline. Dukatz et al., in a study published in 2011, emphasized the importance of the quality-of-life assessment after resection of BSCMs. In that study, 87% of the individuals who underwent surgical treatment for BSCMs pursued the same professional activity as before surgery at last follow-up. Of all 71 patients, 58 (82%) felt good or better after surgery and 63 (89%) stated that they had experienced emotional relief postoperatively.

Several factors need to be taken into account when evaluating the results of this study. The small sample size and the retrospective nature of our data collection incur a strong selection bias. The absence of a control group is an important limiting factor for the analysis of our surgical results. We did not routinely obtain postoperative DTI in our patients; different authors have shown improved DTI signal or correction of distortion on major fiber tracts postoperatively, with possible correlation of those findings with final neurological symptoms. Finally, there are limitations of the technique itself. DTI is still highly operator dependent and subject to interobserver variability. Its information is limited to long fiber tract alterations, and the technique does not provide information on brainstem substructures such as nuclei, their interconnecting fibers, and cranial nerve trajectories. Artifacts caused by
the BSCM itself, hemorrhage, and hemosiderin deposits as well as surrounding blood vessel pulsations can limit adequate imaging acquisition. Some of these obstacles can be overcome with ongoing improvements in the technique, such as high angular resolution diffusion imaging and q-ball reconstruction of high angular resolution diffusion imaging information.6,37 Tract-based spatial statistics is a promising approach that can improve the sensitivity, objectivity, and interpretability of the analysis of multisubject diffusion imaging studies.54,55 However, its use for large space-occupying lesions on the brainstem is still limited.

Conclusions
Diffusion tensor imaging and DTT are potentially useful preoperative tools that could be considered when evaluating patients with deep-seated, symptomatic BSCMs. In patients with no clear radiographic evidence of pial or ependymal presentation is seen, DTI and DTT could influence the selection of surgical approach or brainstem entry zone. In our series, preoperative DTI/DTT changes did not appear to correlate with patients’ functional postoperative outcome on long-term follow-up.

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References


Author Contributions
Conception and design: Flores, Barnett. Acquisition of data: Flores, Whittemore. Barnett. Analysis and interpretation of data: all authors. Drafting the article: Flores, Samson, Barnett. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Flores. Statistical analysis: Flores. Administrative/technical/material support: Whittemore. Study supervision: Flores, Samson, Barnett.

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