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Moving toward the petroclival region: a model for quantitative and anatomical analysis of tumor shift

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Object. The authors quantitatively assessed the effects of balloon inflation as a model of tumor compression on the brainstem, cranial nerves, and clivus by measuring the working area, angle of attack, and brain shift associated with the retrosigmoid approach.

Methods. Six silicone-injected cadaveric heads were dissected bilaterally via the retrosigmoid approach. Quantitative data were generated, including key anatomical points on the skull base and brainstem. All parameters were measured before and after inflation of a balloon catheter (inflation volume 4.8 ml, diameter 20 mm) intended to mimic tumor compression.

Results. Balloon inflation significantly shifted ($p < 0.001$) the brainstem and cranial nerve foramina (mean [$\pm$ standard deviation] displacement of upper brainstem, 10.2 ± 3.7 mm; trigeminal nerve exit, 6.99 ± 2.38 mm; facial nerve exit, 9.52 ± 4.13 mm; and lower brainstem, 13.63 ± 8.45 mm). The area of exposure at the petroclivus was significantly greater with balloon inflation than without (change, 316.26 ± 166.75 mm^2; $p < 0.0001$). Before and after balloon inflation, there was no significant difference in the angles of attack at the origin of the trigeminal nerve ($p > 0.5$).

Conclusions. This study adds an experimental component to the emerging field of quantitative neurosurgical anatomy. Balloon inflation can be used to model the effects of a mass lesion. The tumor simulation created "natural" retraction and an opening toward the upper clivus. The findings may be helpful in selecting a surgical approach to increase the working space for resection of certain extraaxial tumors. *(DOI: 10.3171/JNS-07/10/0797)*

KEY WORDS • petroclival region • quantitative anatomical study • retrosigmoid approach • tumor model

CHOOSING a surgical approach to access lesions of the posterior fossa and petroclival region requires careful preoperative analysis. Because of the narrow working space and restricted angles of approach, surgical planning in this area can be extremely important. Tumors in this region were once considered inoperable[1,52] and remain challenging.[5,9,19,32,41] With the advent of diagnostic neuroimaging tools and skull base surgery as a discipline, improvements in neuroanesthesia and neurophysiological monitoring, and refinements in neurosurgical instrumentation, lesions of the posterior fossa and petroclival region can now be treated surgically with acceptable morbidity and mortality rates.[1–5,9,10,17,19–21,23,32,34,35,37,40,46,47] An improved understanding of the radiosurgical management of these lesions has also contributed to their cure.

The development of skull base approaches, including the introduction of contemporary transpetrosal approaches and their combinations, has created many options for achieving wide surgical exposure of the petroclival region[1–4,9,10,17,19–21,34,35,46,47] and thus has led to considerable improvement in the surgical treatment of petroclival meningiomas. Note, however, that a subset of patients with petroclival lesions can be treated via the simple retrosigmoid approach.[6,7,10,15,23,35–38,40,44,51–53] In these patients, the tumor displaces the brainstem to create a 3D corridor that widens access and increases the maneuverability of instruments.[37,48] In such cases, tumor compression causes displacement or "natural retraction" of the brainstem, which opens a surgical corridor toward the petroclival region. These lesions can be managed via a traditional retrosigmoid approach. We introduce a novel tumor model designed to imitate and quantify such mass lesions.

Materials and Methods

Six cadaveric heads with colored silicone–injected arterial and venous systems and no known brain pathophysiology were used to obtain bilateral measurements, yielding 12 data sets. Dissections were performed, and quantitative data were acquired using standard microsurgical instruments while the cadaveric heads lay under the surgical microscope (Leica Microsystems Group). A high-speed drill (Midas Rex, L.P.) was used to drill the bone. Medi-tech Equalizer balloon catheters (Boston Scientific) were used to create a mass intended to mimic a tumor. The balloon, constructed of flexible latex, was mounted on the tip of a multilumen, nylon, nontapered catheter shaft. A 50-ml syringe was used to inflate the balloon catheter and

Abbreviation used in this study: CPA = cerebellopontine angle.

inject a specially prepared pink dye to improve visualization of the mass (Fig. 1).

Retrosigmoid Approach

The first stage of the experimental procedure consisted of the suboccipital retrosigmoid approach, which is detailed elsewhere[26,37,43] and reviewed only briefly here. Before the bilateral dissections were performed, the cadaveric head specimens were placed in a 90° lateral position and were rigidly fixed in a Mayfield headholder. A curvilinear skin incision was placed behind the ear, 1.5 to 2 cm medial to the mastoid process. The excision reached from just above the superior nuchal line to the level of C-1. The trapezius and splenius capitis muscles were detached from the superior nuchal line. A suboccipital craniectomy was performed. Important landmarks included the external occipital protuberance that overlies the confluence sinuum and the superior nuchal line overlying the transverse sinus. A single bur hole was placed below the Frankfurt horizontal line and 3 cm behind the external auditory canal. The dura mater was separated carefully, and the bone was removed using rongeurs to enlarge the craniectomy to 3 to 4 cm^2. The transverse sinus superiorly and its junction with the sigmoid sinus laterally were thus exposed. The dura was opened to form a triangular flap based on the sigmoid sinus.

Quantitative Assessments of the Working Area and Brainstem Displacement

Brain retraction remained constant, and the cadaveric heads were rigidly fixed to ensure the validity of the quantitative assessments. As in the clinical setting for the retrosigmoid approach, the cerebellum was retracted and supported medially to expose the entry and exit zones of the cranial nerves. The cerebellar hemisphere was held 1.5 cm away from the sigmoid sinus.

The working area was measured in each specimen before and after balloon inflation (catheter size, 2.3 mm; inflated balloon diameter, 20 mm; and balloon inflation volume, 4.8 ml). The balloon was always inserted under microscopic visualization between the lower cranial nerves and vestibulocochlear–facial nerve complex (Fig. 1). The *black mark* at the site of attachment between the balloon and catheter was placed at the level of the seventh and eighth cranial nerve complex. The balloon was placed above these nerves at the level of the fifth cranial nerve.

Operative approaches to the CPA and petroclival region were divided into three categories: the upper region around the trigeminal nerve, the middle area around the vestibulocochlear–facial nerve complex, and the lower region around the lower cranial nerves.[29,31] To determine and compare working areas, with and without balloon inflation, we defined three triangles (upper, middle, and lower) among the relevant structures of the posterior fossa. Using these anatomical landmarks, a polygonal construct was delineated to define the total working area. For the petroclival perspective, the focus consisted of the area anterior to the cranial nerve roots and foramina at the upper, middle, and lower thirds of the clivus. The anatomical points of interest chosen for the petroclival region therefore included the Meckel cave, the uppermost constant landmark; the internal auditory meatus, the middle constant landmark; the jugular foramen, the lowermost constant landmark; the maximal medial exposure of the uppermost point on the clivus; and the maximal medial exposure of the lowest point on the clivus. The latter two points were variable.

The working area on the brainstem was mapped by assigning the following points: A, the apparent origin of the trigeminal nerve on the brainstem, the upper constant landmark; B, the facial nerve exit point, the middle constant landmark; C, the exit of the glossopharyngeal nerve on the brainstem, the lower constant landmark; D, the maximal medial exposure of the uppermost point of the brainstem at the level of the petrous ridge, the upper variable; E, the maximal medial exposure of the lowest point on the brainstem, a lower variable; and F, the lowest visible point of the accessory nerve, a lower variable. The constant landmarks were marked for repeated use for subsequent measurements after balloon inflation (Figs. 1–5).

The Optotrak 3020 system (Northern Digital) with a six-marker digitizing probe and accompanying software was used to measure the area of exposure. Heads were immobilized in a rigid headholder clamped to an operating table, with cameras positioned 1.5 m away. A data point was acquired by touching the tip of the digitizing probe to the anatomical points of interest under the operating microscope while the markers on the probe were in view of the cameras. Rigid fixation of the head ensured that it remained in the same Cartesian coordinate system as the Optotrak. The Optotrak system, which was connected to a personal computer, stored data files in the form of x, y, and z coordinates (in millimeters) of each vertex. Brain retractors remained rigidly fixed and permanently secured while the points of interest were relocated for each exposure to prevent measurement errors while the points were located spatially.

These three described triangles shared certain sides. If the adjacent triangles were considered as a unit, the polygonal surface they

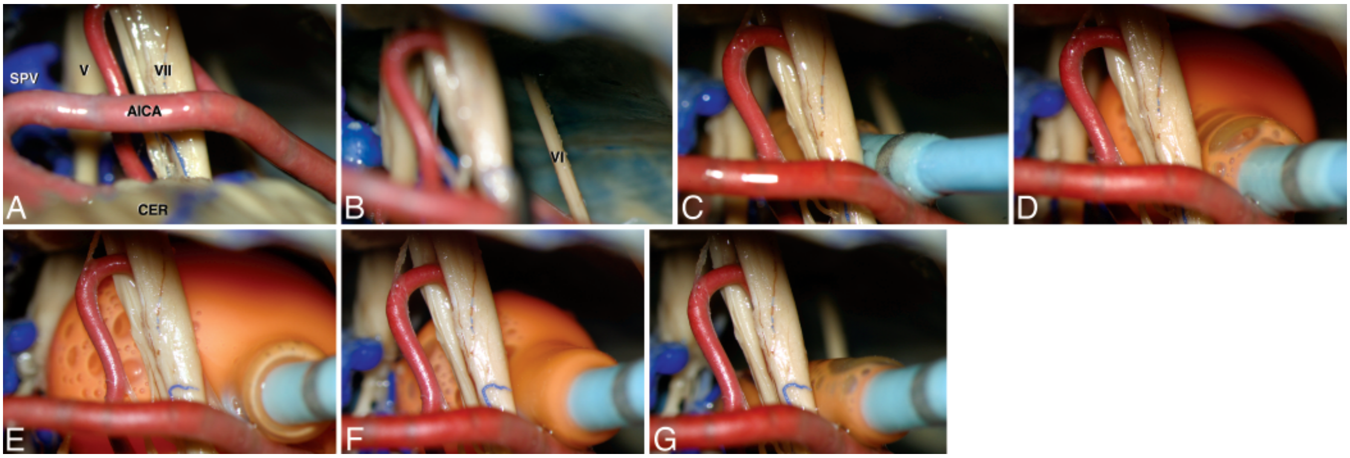

FIG. 1. Photographs depicting balloon inflation in the petroclival region and CPA. A: The middle and upper neurovascular complex before insertion of the balloon catheter. B: The location of the abducens nerve (VI). C: The balloon catheter has been inserted. The *black mark* where the balloon attaches to the catheter is positioned at the level of the seventh and eighth cranial nerve complex. The balloon is inserted behind and at the level of the trigeminal nerve. D: Injection of dye to improve visualization of the balloon. E: Inflation of the balloon. F: Partial deflation of the balloon. G: Complete deflation of the balloon. AICA = anterior inferior cerebellar artery; CER = cerebellum; SPV = superior petrosal vein; V = fifth cranial nerve; VII = seventh and eighth cranial nerve complex.

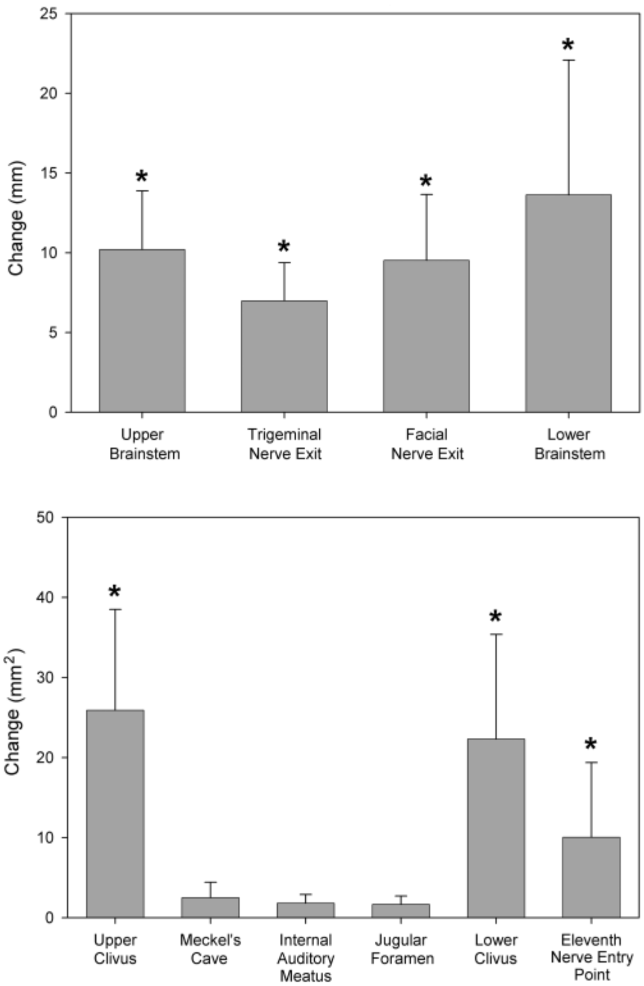

FIG. 2. *Upper:* Bar graph demonstrating brainstem and cranial nerve displacement. Balloon inflation produced a significant shift *(asterisks)* of the upper and lower brainstem and the origins of the trigeminal and facial nerves. *Lower:* Bar graph revealing changes in the accessibility of the upper and lower clivus and the accessory nerve entry zone but no significant change in the access to the cranial nerve foramina. *Asterisks* represent statistically significant changes, $p < 0.05$. All *error bars* represent standard deviations.

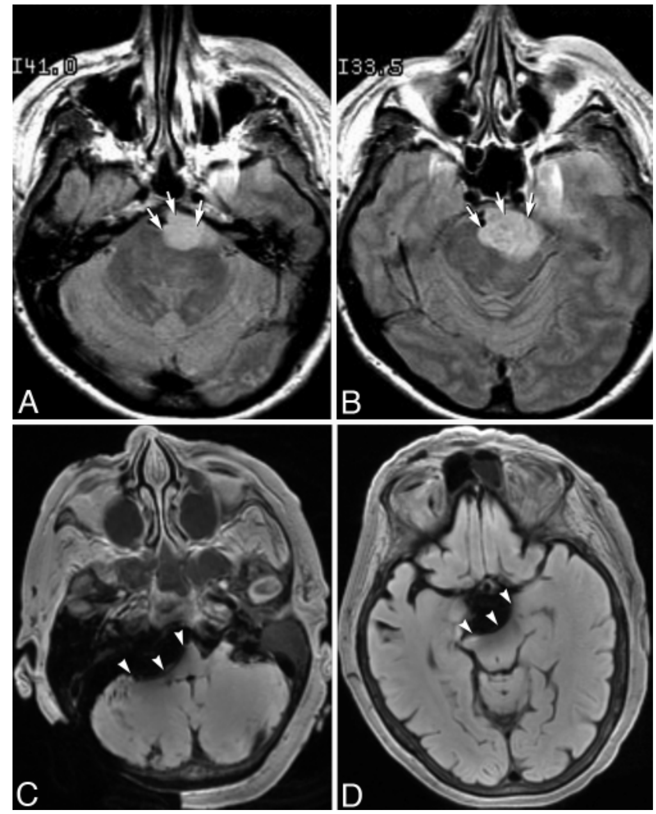

FIG. 3. Magnetic resonance images. A and B: Contrast-enhanced T1-weighted images obtained in a 59-year-old woman with a left-sided petroclival meningioma, demonstrating infratentorial brainstem compression (A) as well as supratentorial displacement of the upper pons and midbrain (B). The patient was treated via a simple retrosigmoid approach followed by an orbitozygomatic approach and Gamma Knife surgery for the residual tumor. *Arrows* indicate tumor compression and displacement of the brainstem. C and D: Axial T1-weighted images obtained in the cadaveric head of a 62-year-old man, revealing balloon inflation on the right side to simulate the effects of a petroclival tumor. As in the clinical case, the lower portion of the balloon (tumor) compresses the pons (*arrowheads* in C) and opens a corridor toward the upper clivus (compare with panel A), whereas the upper portion of the balloon extends supratentorially (D) and displaces the upper brainstem (compare with panel B).

formed represented the working area. Triangular areas were calculated as half the magnitude of the vector cross product of any two vectors forming two sides of a triangle (for example, the area of the triangle ABC = 1/2[AB × AC]). The mean of the sum of the polygonal constructs defined the total working area.

Determining Angles of Approach

The angle of attack was determined using a robotic surgical microscope (Surgiscope, Elekta Instruments, Inc.) moving in a spherical mode. The cadaveric head was fixed in a Mayfield headholder. The longitudinal axis of the clivus was in the same plane as that of the microscope's vertical axis of movement. The longitudinal axis of the fifth to the 11th cranial nerve was in the microscope's horizontal axis of movement. The same 10 anatomical landmarks were defined and marked as the target points for assessment on the clival and brainstem sides (Fig. 6). The target was identified and brought into focus by the microscope's laser beams at a focal length of 300 mm. Keyhole-point fixation movement of the microscope enabled determination of angles. After this protocol was completed, the horizontal and vertical angles of attack on the target points were measured before and after balloon inflation in all specimens bilaterally.

Statistical Analysis

The working area and angle of attack associated with each approach were compared using one-way repeated-measures analysis of variance followed by the Holm–Sidak method of pairwise comparisons. When data failed a test of normal distribution, the Friedman repeated measures analysis on ranks was used followed by the Dunn method. In all comparisons, a probability value less than 0.05 was considered significant. Values are expressed as the means ± standard deviations.

Results

Area of Surgical Exposure and Tumor Displacement

Balloon inflation significantly shifted ($p < 0.001$; Figs. 1 and 5) the brainstem and cranial nerve origins (mean displacement of upper brainstem, 10.2 ± 3.7 mm; trigeminal nerve exit, 6.99 ± 2.38 mm; facial nerve exit, 9.52 ± 4.13

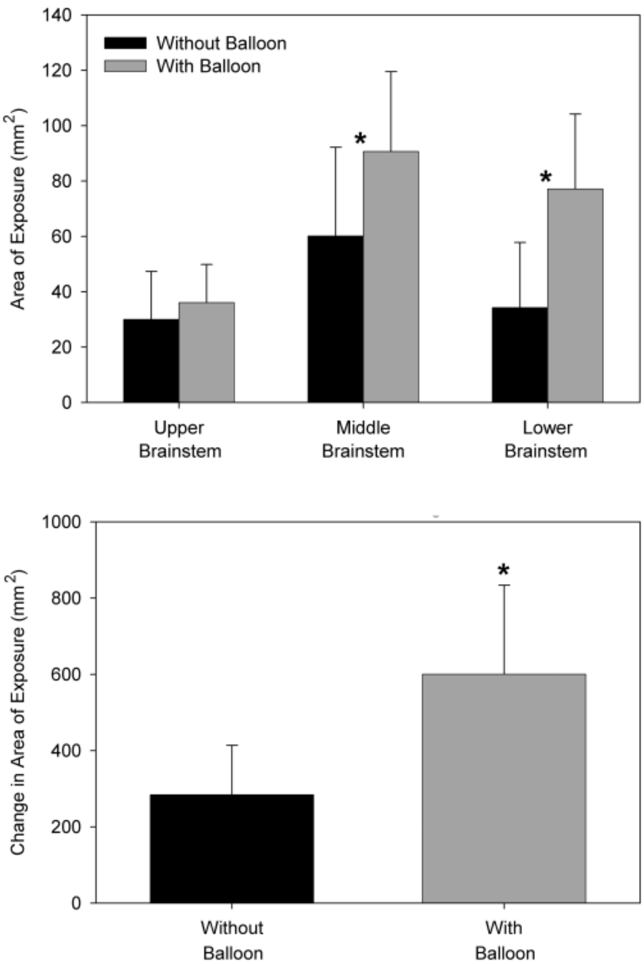

FIG. 4. Bar graphs depicting the working area for the brainstem *(upper)* and petroclival surface *(lower)* with and without balloon inflation. With balloon inflation, there was a significant increase in the area of exposure of the middle and lower brainstem but not in that of the upper brainstem. With balloon inflation, there was a significant increase in the total area of exposure of the clivus. *Asterisks* represent a statistically significant increase, $p < 0.05$.

mm; and lower brainstem, 13.63 ± 8.45 mm; Fig. 2 *upper*). Accessibility to the lower and upper petroclival surfaces increased significantly ($p < 0.001$; change in accessibility to upper clivus, 25.88 ± 12.61 mm^2; change in accessibility to lower clivus, 22.31 ± 13.06 mm^2; Fig. 2 *lower*). There was also a significant change ($p < 0.001$) in access to the 11th cranial nerve. However, accessibility to the Meckel cave, internal auditory meatus, and jugular foramen did not change significantly ($p > 0.05$). Magnetic resonance images were obtained while the balloon was inflated to verify the relationship of the tumor to the clivus and the brainstem (Fig. 3C and D).

The total petroclival area of exposure increased significantly ($p < 0.0001$) after balloon inflation (change, 316.26 ± 166.75 mm^2; before balloon inflation, 284.15 mm 2 ± 129.38 mm^2; after balloon inflation, 600.41 ± 233.50 mm^2; Figs. 4 and 5). After balloon inflation, the working area and accessibility were greatest at the middle and lower brainstem surface ($p = 0.0308$ and $p = 0.0001$) and smallest at the upper brainstem ($p > 0.05$).

Angles of Approach

The three neurovascular complexes at the CPA are located within the same vertical and horizontal planes, and the angular values of these anatomical structures were almost analogous. Thus, the value for the (vertical and horizontal) angles of approach to these structures is represented by the exit of the trigeminal nerve. The angles of approach for the following five landmarks are presented: upper clivus, upper brainstem, fifth cranial nerve exit, lower brainstem, and lower clivus.

The angles of attack were not significantly different at the clivus and origin of the trigeminal nerve before and after balloon inflation ($p > 0.05$; Fig. 6). The horizontal angle of approach was significantly greater at the lower brainstem ($p = 0.0054$), and the vertical angle of approach was significantly greater at the upper brainstem ($p = 0.0296$; Fig. 6). These differences became particularly visible when the angular differences before and after balloon inflation were calculated and compared.

Discussion

Emerging Field of Applied Quantitative Neurosurgical Anatomy

With the advent of microsurgery and the development of skull base approaches, surgeons have a wide range of available approaches to manage tumors at various locations. Today's neurosurgeon must select the optimal treatment and most advantageous surgical approach for a particular lesion.[11,22,24–27,29–31,42,50] A better understanding of the effects of tumor displacement on exposure and the selection of surgical approach is necessary.

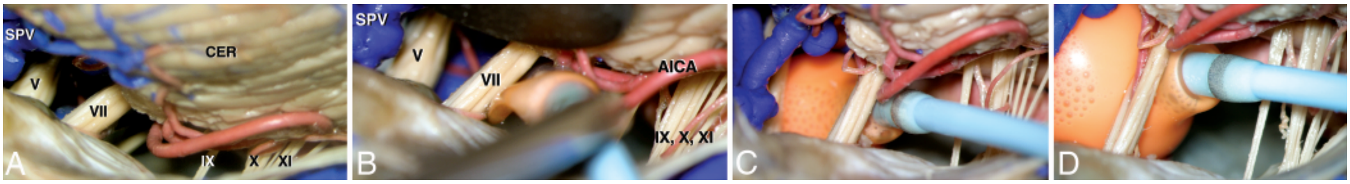

FIG. 5. Photographs showing the posterior fossa anatomy. A: Note the relationship of the cerebellum and the various cranial nerves. B: The balloon catheter was inserted with microscopic visualization. C and D: Partial (C) and maximal (D) inflation of the balloon. Note the gradual displacement of brainstem and soft tissue and the stretching of the cranial nerves. IX, X, XI = lower cranial nerve complex.

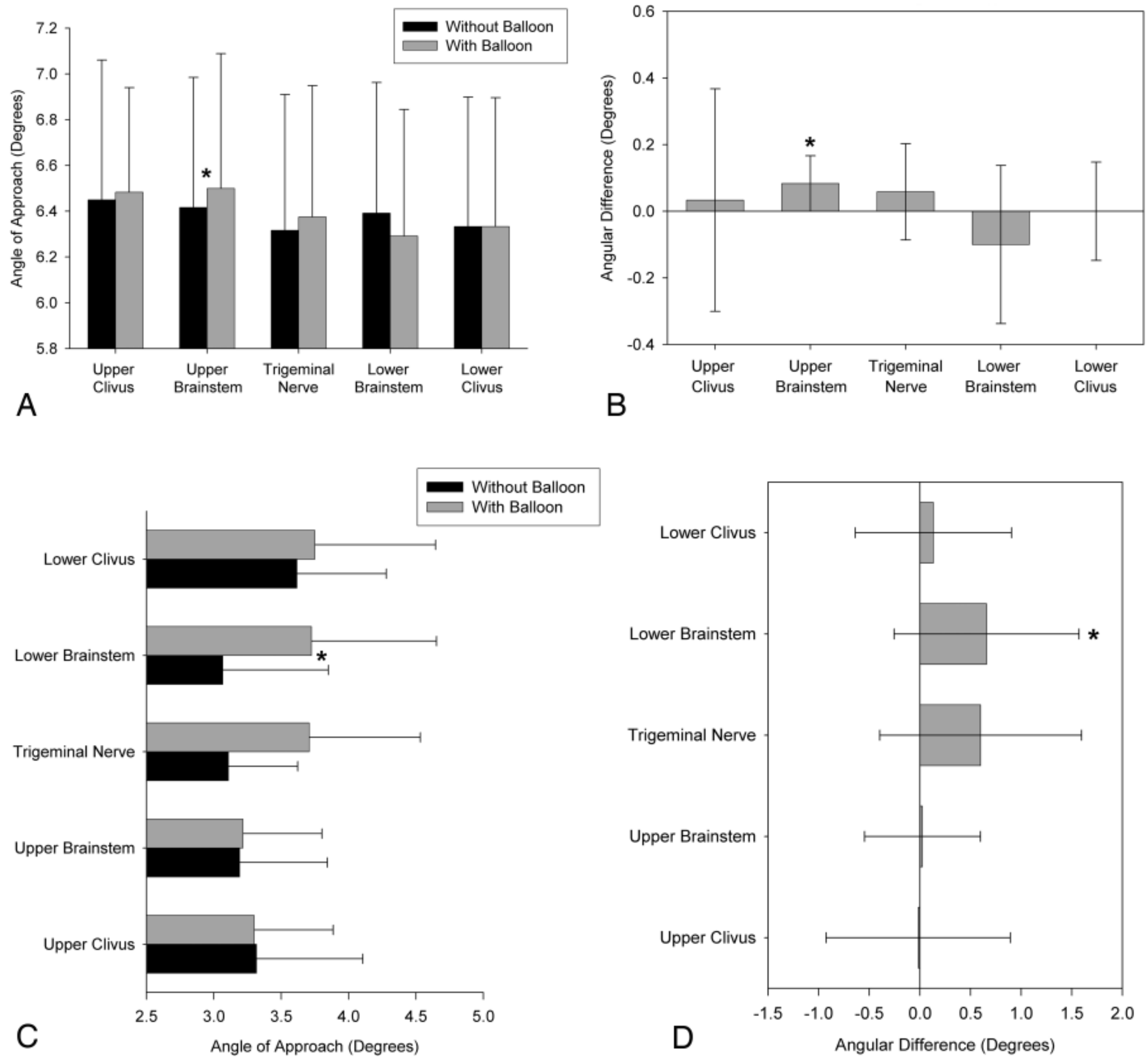

FIG. 6. Bar graphs revealing angles of approach and angular differences with and without balloon inflation. A: Vertical angle of approach to five representative posterior fossa structures without and with balloon inflation. B: The differences in the vertical angle of approach are clearer once they are plotted. C: The horizontal angle of approach with and without balloon inflation. D: Calculated differences in the horizontal angle of approach. *Asterisks* represent a statistically significant angular difference, $p < 0.05$.

Authors of recent studies have used stereotactic techniques to quantify and compare surgical approaches.[8,18,28,33,45,49] In the present study we used the same quantitative methods we used in earlier studies;[12–14,16,43] however, we added a new component to create and quantitatively assess tumor compression through a balloon-inflation model (Figs. 1 and 3). Our results demonstrate that experimental simulation of a tumor mass and quantitative anatomical assessment of tumor compression and nervous tissue shift are feasible and open the door to additional comparative studies to increase the selection of operative approaches.

Definition of the Petroclival Region

The definition of what constitutes the petroclival region, especially with regard to the classification of posterior fossa meningiomas, varies from author to author and study to study.[6,10,39] Al Mefty and associates[2] have defined petroclival meningiomas as arising from the upper two thirds of the clivus, at the petroclival junction, and medial to the trigeminal nerve. Similarly, Couldwell et al.[10] have defined petroclival tumors as those with a basal attachment medial to the skull base foramina of the fifth and ninth through the 11th cranial nerves. In some studies, however, lesions classified as petroclival meningiomas have been considered CPA lesions in others.[2,10,39,40,46,52] Yaşargil and colleagues[52] noted that “the separation into topographical areas such as clival, cerebellopontine angle, etc., is artificial because there are always transitional cases.” Analogously, Spetzler et al.[46] have described “meningiomas involving the clivus and cerebellopontine angle.”

In vivo these tumors may grow supratentorially and involve the Meckel cave, cavernous sinus, middle cranial fossa, and sellar and parasellar areas. We did not evaluate this growth pattern, originally differentiated by Yaşargil and colleagues[52] as sphenopetroclival. In the present study we evaluated displacement of the brainstem and cranial nerves by a tumor mass originating in the petroclival region, with lateral extension into the posterior fossa and CPA.

Retrosigmoid Approach for Petroclival Tumors

Depending on the study, the retrosigmoid approach has been used to treat 20 to 70% of petroclival meningioma cases.[6,7,10,15,23,35–38,40,44,51–53] In their experience with 41 patients harboring petroclival meningiomas, Sekhar et al.[40] pointed out that the retrosigmoid route is the simplest approach to these lesions and primarily appropriate for centrolateral (rather than purely central) lesions. This less aggressive management philosophy has gained popularity, especially in terms of the availability of adjuvant stereotactic radiosurgery.[23,51] In a review of the petroclival meningiomas encountered over the past 20 years, we found that our treatment regimen and preferred approaches for the management of these lesions has changed over time.[5] In the past 10 years, we have moved away from the complex transpetrosal exposures to one- or two-stage exposures using the retrosigmoid approach alone or combined with another (for example, combined with an orbitozygomatic approach) to treat these challenging lesions.

The retrosigmoid approach plays a major role in the management of two groups of patients.[6,7,10,15,23,35–38,40,44,51–53] The first group consists of those with large petroclival tumors that extend into the CPA, middle fossa, and cavernous sinus. Infiltration of the cavernous sinus precludes complete tumor removal, and the goal of surgery is brainstem decompression rather than radical resection. The second group includes patients harboring large petroclival tumors with a major extension into the posterior fossa, some extension into the middle fossa, and no involvement of the cavernous sinus. In such cases, total resection can be achieved via a simple retrosigmoid approach. A number of authors have pointed out that the retrosigmoid approach may be most suitable in the latter group when the tumor "points" to the CPA.[15,37,38] In such cases, the tumor may act as a "natural retractor," opening a surgical corridor (Fig. 3) that increases exposure and obviates the need for extensive bone drilling.[15,23,38,40,48]

Modeling Effect of Tumor Mass in the Petroclival Region

In this study the inflation of a balloon was used to simulate the effect of tumor mass (Fig. 3). Taking into consideration the various definitions of petroclival tumors, we positioned the balloon at the level of the trigeminal nerve, above and posterior to the seventh and eighth cranial nerve complex (Fig. 5). The maximum size of the inflated balloon was 2 cm, which is within the reported size range of 1 to 5 cm for petroclival meningiomas.[23,38,40] On magnetic resonance images of the cadaveric specimens, the simulated in vitro tumor looked remarkably like an actual petroclival lesion in vivo. We did not evaluate the effect of tumor size on exposure in this study, choosing instead to keep the size of the inflated balloon constant to simulate a medium-sized tumor. A balloon inflated to this size created significant shifts between the brainstem and cranial nerve foramina (Fig. 2 *upper*).

Effect of Balloon Inflation on Retrosigmoid Exposure

Balloon inflation significantly increased accessibility to the lower and upper petroclival surfaces (Fig. 2 *lower*). As would be expected, there was no significant change in accessibility to fixed landmarks such as the Meckel cave, internal auditory meatus, and jugular foramen.

Inflation of the balloon significantly increased exposure to the middle and lower brainstem (Fig. 4 *upper*) and to the total working area of the clivus (Fig. 4 *lower*). A similar finding was not observed for the upper brainstem because the large mass of the inflated balloon prevented access to this area for measurements (Figs. 3C and D and 5D).

Study Limitations

Our study involves a simple model of a mass lesion. Preserved cadaveric specimens cannot precisely simulate the consistency of a living brain. The effect of draining cerebrospinal fluid and brain swelling associated with mass lesions, which are major considerations in the clinical setting, could not be addressed in this study. Our focus was the brainstem/cranial nerve surface and clival bone interface. We assessed the compression and displacement caused by a balloon intended to mimic a tumor. Encroachment of vessels and cranial nerves and violation of the arachnoid surface by tumor are other significant clinical problems that were not assessed. Furthermore, the balloon was inflated acutely, whereas tumors grow over longer periods.

Conclusions

This study adds tumor simulation as a new component to the emerging field of quantitative neurosurgical anatomy. Using a balloon-inflation model, we showed that quantitative assessment of tumor compression and displacement of nervous tissue is possible. In this model, simulation of a petroclival tumor mass produced significant displacement of brainstem structures and significantly increased the surgical exposure offered by the retrosigmoid approach to the lower and middle brainstem as well as the clivus. The findings support the concept that a tumor mass in this region can act as a "natural retractor," opening a surgical corridor that increases exposure and obviates the need for more extensive skull base approaches. In future studies we plan to evaluate the effect of the size and location of extraaxial masses on surgical exposure in the posterior fossa by using a variety of approaches.

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