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Original

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Original Investigation

Morphometric and Radiomorphometric Study of the Correlation Between the Foramen Magnum Region and the Anterior and Posterolateral Approaches to Ventral Intradural Lesions

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ABSTRACT

AIM: To identify the range of dimensional morphometric variability correlated to the basilar and condylar part of the occipital bone, which may affect the choice of approach to ventral intradural foramen magnum (FM) lesions.

MATERIAL and METHODS: In total, 25 dry skulls and 50 head computed tomography (CT) scan results have been assessed in detail, focusing on the FM, occipital condyles, jugular tubercles (JT), and hypoglossal canals (HC). A morphometric analysis has been carried out using linear and angular measurements to estimate the range of the dimensional variability of these structures. Data were presented as mean \pm standard deviation, ranges, and interquartile range on a boxplot. The sagittal intercondylar angle (SICA) and anterior condylar angle (ACA) have been found to be important in estimating the axial orientation of the condyles, whereas the JT–HC interline ratio has indicated the prominence of the tubercles.

RESULTS: The SICA and ACA have exhibited high variability. The average JT–HC interline ratio was 0.8. Wider SICA–ACA and higher JT–HC interline ratio make the posterolateral approach advantageous. An anterior medial or far-medial endoscopic route is indicated in opposite conditions. In this study, two illustrative cases have been reported.

CONCLUSION: A cautious preoperative morphometric evaluation of the FM region must be considered prior to using tailored and safe anterior endoscopic and posterolateral approaches to ventral intradural lesions to identify the advantages of a certain corridor as much as possible, thereby minimizing the risk of complications.

KEYWORDS: Far-lateral approach, Foramen magnum, Jugular tubercle, Occipital condyles, Transclival approach

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■ INTRODUCTION

Due to the extremely complex anatomy, peculiar biomechanics, and deep location of the involved neurovascular structures, the ventral foramen magnum (FM) region is universally considered a formidable area to deal with. Numerous approaches with advantages and disadvantages are commonly used in daily practice to treat extradural and intradural lesions, including those in the anterior border of the FM and lower clivus. Basically, these corridors can be classified into two main groups, namely, the anterior (Figures 1, 2A-D) (10,13,15,22,33,46,53), and posterolateral approaches (Figure 3) (2,3,17,20,21,25,30,31,40-43,47,54). Although the anterior intradural approaches allow direct ventral access to the brainstem and upper cervical cord with zero retraction of the neurovascular structures, they are often too narrow and inadequate for the treatment of lesions with relevant lateral extension. Moreover, the use of such approaches puts patients at high risk for cerebrospinal fluid leaks. Conversely, posterolateral routes offer more surgical freedom but involve working corridors, which are performed across the plane of the lower cranial nerves in most cases. Numerous posterolateral approaches involve the medial transposition of the vertebral artery and encompass drilling of the condyle and the jugular tubercle (JT); therefore, they are associated with the increased risk of mechanical instability or neurovascular iatrogenic injury.

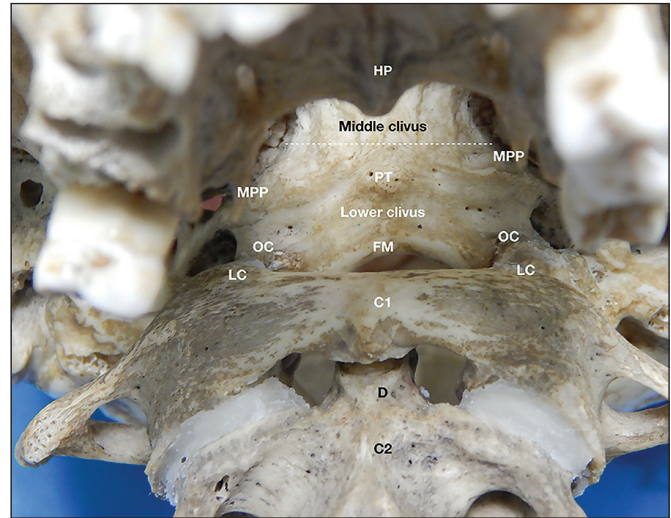


Figure 1: Transoral perspective of the foramen magnum region. The transoral approach allows direct midline access to the foramen magnum region. Mouth-opening capacity, integrity of the temporomandibular joint, macroglossia, dentation, and jaw length may be important limiting factors. **HP:** Hard palate; **OC:** occipital condyle; **LC:** lateral condyle; **FM:** foramen magnum; **PT:** pharyngeal tubercle; **C1:** atlas; **D:** dens of the axis; **C2:** axis; **MPP:** medial pterygoid plate. The dotted line refers to the inferior clival line and marks the limit between the middle and lower clivus.

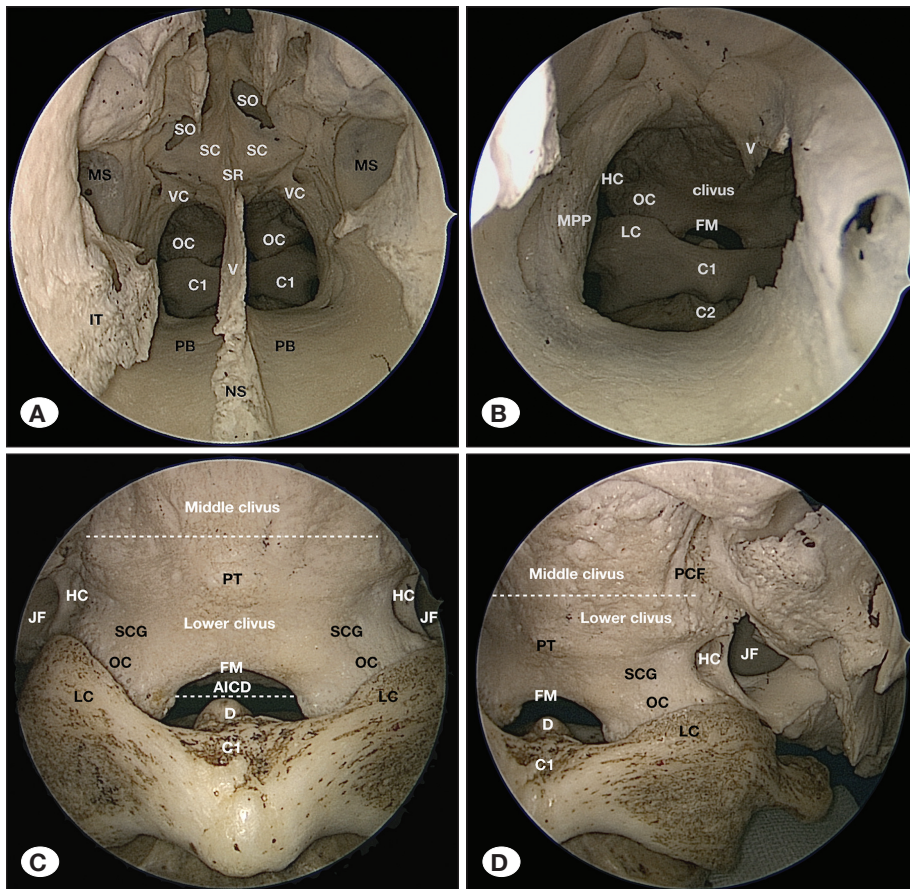


Figure 2: Extended endoscopic endonasal perspective of the medial and far-medial approaches. **A)** Nasal stage of the extended endoscopic endonasal medial and far-medial approaches. **B)** Endoscopic view of the choana and rhinopharynx. **C-D)** Medial and far-medial vision of the foramen magnum region. **NS:** Nasal septum; **V:** vomer; **SR:** sphenoid rostrum; **IT:** inferior turbinate; **PB:** palatine bone; **MS:** maxillary sinus; **SC:** sphenoid conchae; **SO:** sphenoid ostium; **VC:** vidian canal; **OC:** occipital condyle; **LC:** lateral condyle; **FM:** foramen magnum; **D:** dens of the axis; **C1:** atlas; **C2:** axis; **MPP:** medial pterygoid plate; **HC:** hypoglossal canal; **PT:** pharyngeal tubercle; **AICD:** anterior intercondylar distance; **SCG:** supracondylar groove; **JF:** jugular foramen; **PCF:** petroclival fissure.

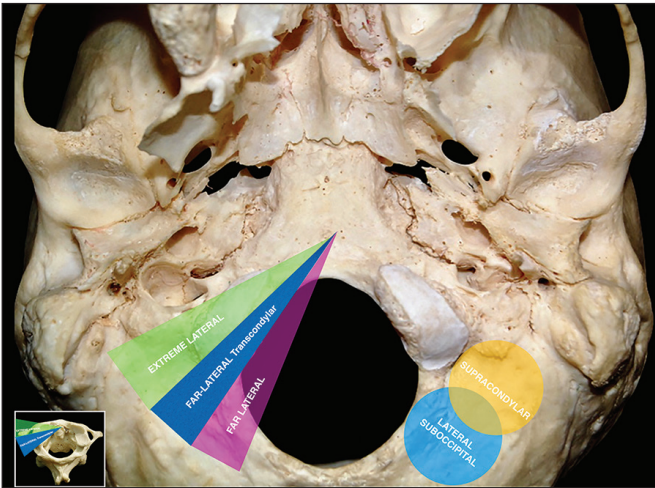


Figure 3: Posterolateral approaches. The lateral suboccipital approach involves craniotomy or craniectomy of the most lateral part of the occipital squama. The far-lateral approach consists of an infero-lateral extension of the lateral suboccipital approach that also involves C1 hemilaminectomy. The far-lateral transcondylar approach comprehends a partial condylectomy, where the hypoglossal canal is generally preserved, which increases the angle of attack to the target. The supracondylar approach is also referred to as the supracondylar trans-condylar fossa trans-jugular tubercle approach. In this approach, the condyle is completely preserved, and the area of exposure is at the level of the jugular tubercle. The extreme lateral approach is considered a pure lateral route to the lower clivus. Total condylectomy offers a maximal tangential view of the entire basilar part of the occipital bone up to the contralateral petroclival fissure.

The approach of choice to ventral FM pathologies is classically based on lesion-, patient-, and surgery- related factors, and the latter comprehends the confidence and experience the surgeon possesses about specific surgical routes.

An equally paramount aspect regarding the patient and lesion to be treated involves the existence of specific anatomical conditions or variations, which can theoretically make a surgical corridor to ventral FM easier or safer to be performed based on both morphologic and morphometric data.

This study aimed to identify morphometric parameters correlated to the basilar and condylar part of the occipital bone, which are associated with the highest rate of dimensional variability. These may affect the choice of approach to intradural lesions involving the ventral FM and lower clivus.

■ MATERIAL and METHODS

This study was approved by the institutional review board of our institution and was reported based on the Strengthening the Reporting of Observational Study in Epidemiology statement (52).

Morphometric and Radiomorphometric Evaluation

Twenty-five dry skulls of unknown age and gender and 50 adult head computed tomography (CT) scan results have

been used to assess the normal dimensional anatomy and the range of anatomical variability of the basilar and condylar parts of the occipital bone. CT scan results were reviewed anonymously, and the need for informed consent was waived. The skulls were measured using a Vernier caliper. CT scans (Toshiba Aquillion® 64, Milwaukee, Wisconsin, the USA) were performed according to the following parameters: 0.5-mm thick slices, 0.3-mm interval, FOV of 240 mm, matrix of 512 × 512, pixel size of 0.46 mm, 230 mA, and 120 kV. Data have been transferred to a medical imaging work station (Osirix DICOM Viewer®, Pixmeo, Bernex, Switzerland) and reviewed with bone setting in sagittal, coronal, axial, and oblique planes according to the different anatomical structures that should be measured. Three-dimensional rendering of the images was also assessed in detail. The FM, condyle, JT, and hypoglossal canal (HC) have been evaluated in detail. All data were reported as mean ± standard deviation (SD). For paired structures, a t-test between the left- and right side measurements has been performed. A p-value ≤0.05 was considered statistically significant.

Analysis of the Dimensional Variability of the FM Region

The analysis of the dimensional variability of each morphometric parameter has been carried out by calculating SD, range, and interquartile range reported as a boxplot.

Foramen Magnum

The longest sagittal axis of the FM has been calculated as the distance between the basion and the opisthion, whereas the largest axial axis coincided with an intercondylar line traced at the level of the posterior tip of each condyle. An FM index dividing the sagittal axis by the axial one has also been obtained. An index ≥1.2 indicated an oval-shaped foramen; otherwise, it was assumed to be round shaped. The FM area has been calculated using the Radinsky (39), and Teixeira methods (50) based on the maximum diameters. These results have been compared with data reported in the literature.

Condyle

The length and width of the condyles have been measured on the skulls and CT scans, whereas the height has been assessed only on the skulls at the midlevel of each condyle for accuracy purposes. The distances between the anterior condylar tip and the basion (ACT-B) as well as between the anterior condylar tip and the opisthion (ACT-O) have been calculated only on the skulls.

The same procedure has been repeated for the evaluation of the distances between the posterior condylar tip and the basion (PCT-B) and between the posterior condylar tip and the opisthion (PCT-O).

The anterior intercondylar distance (AICD) and the posterior intercondylar distance (PICD) have been calculated at the level of the anterior and the posterior tip of the condyles. The anterior condylar angle (ACA) has been calculated on both the skulls and CT scans at the level of the intersection between the longest axis of each condyle and the midsagittal plane, whereas the sagittal intercondylar angle (SICA) has been evaluated at the intersection between the longest axes of both condyles.

HC (Anterior Condylar Canal)

Its inner and outer diameter have been measured on both sides. The distance between the inner orifices has also been calculated and reported as an HC interline. On CT scan, the HC interline has been evaluated on the coronal plane. In addition, the distance between the posterior tip of the condyle and the midportion of the medial, intermediate, and lateral third of the canal length has been reported as PCT-HC zone 1, PCT-HC zone 2, and PCT-HC zone 3, respectively.

Jugular Tubercle

The JT interline has been described as the distance between the uppermost part of the tips of the JTs. On CT scan, it has been measured on the coronal plane. The JT interline has been assumed as an indirect estimation of the prominence of the tubercles at the level of the FM area. The JT interline has been correlated to the HC one and reported as the JT-HC interline ratio, assuming that this parameter can indicate the prominence of the tubercles.

Middle and Lower Clivus

All morphometric data about the clivus have been obtained from the skulls. The total clival length was reported as the sagittal midline distance between the dorsum sellae of the sphenoid bone and the basion. According to the Funaki's study about the demarcation between the superior, middle, and lower clivus, the length of the middle clivus has been measured as the distance between the superior line located 3.4 mm below the upper edge of the petrous apex and the inferior line crossing the glossopharyngeal nerve notch of the jugular foramen (15). The number of skulls where a central clival depression could be appreciated has also been reported as the percentage of their overall number.

RESULTS

Dimensional Anatomy of the FM Region

Foramen Magnum

The longest sagittal axis of the FM measured 35.3 ± 4 mm, where as the largest axial axis was 30.4 ± 3 mm (Figure 4).

The FM index was 1.16, and none of the specimens had an index ≥ 1.2 .

The FM area was 842.3 mm^2 with the Radinsky method, and 846.5 mm^2 with the Teixeira method.

Table I shows the average FM diameters, index, and area, and their comparison with data reported in or obtained from the literature.

Condyle

The length, width, and height of the condyles were 23.5 ± 1 , 11.3 ± 1 , and 9 ± 1 mm on the left side and 23.6 ± 1 , 11.7 ± 1 , and 9.3 ± 1 mm on the right side, respectively. No differences were found between the left and right sides. The ACT-B was 10 ± 2 mm on both sides. The ACT-O was 38.9 ± 6 and 38.7 ± 6 mm on the left and right sides, respectively. The PCT-B measured 28.3 ± 4 on the left side and 28 ± 4 mm on the right

side. The PCT-O was 26.7 ± 6 mm on the left side and 26.8 ± 6 mm on the right side. The AICD and PICD were 20 ± 5 and 41 ± 6 mm, respectively. The ACA was $34.8 \pm 5^\circ$ on the left side and $35 \pm 5^\circ$ on the right side with a left-right average of $34.9 \pm 5^\circ$. No differences were found between the left and right sides in all condylar parameters. The SICA measured $69.8^\circ \pm 11$ (Figure 5).

Table II shows the summary of the morphometric and radiomorphometric data correlated to the occipital condyles.

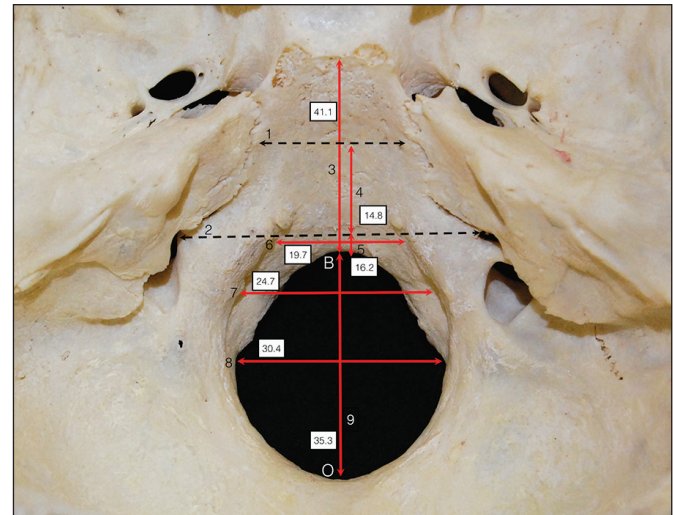


Figure 4: Morphometric analysis of the foramen magnum and the middle and lower clivus. **B:** basion; **O:** opisthion; **1:** superior clival line; **2:** inferior clival line; **3:** total clival length; **4:** middle clivus length; **5:** lower clivus length; **6:** jugular tubercle interline; **7:** hypoglossal canal interline; **8:** axial diameter of the foramen magnum; **9:** sagittal diameter of the foramen magnum. All measurements have been reported as average in mm.

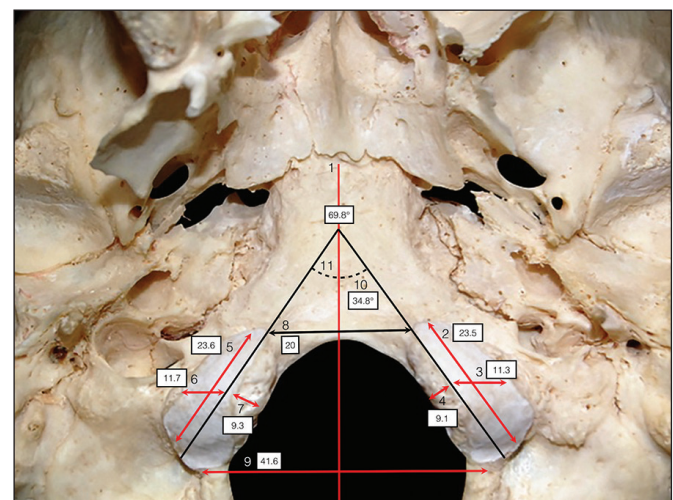


Figure 5: Morphometric analysis of the jugular tubercle. **1:** midline; **2-4:** length, width, and height of the left occipital condyle; **5-7:** length, width, and height of the right occipital condyle; **8:** anterior intercondylar distance; **9:** posterior intercondylar distance; **10:** anterior condylar angle; **11:** sagittal intercondylar angle. All measurements have been reported as average in mm.

HC (Anterior Condylar Canal)

The inner diameter of the HC was 4.4 ± 1 mm on the left side and 4.5 ± 1 mm on the right side, whereas the mean outer diameter was 6.8 ± 1 mm on the left side and 7.1 ± 1 mm on the right side. The PCT-HC zone 1, PCT-HC zone 2, and PCT-HC zone 3 were 6.8 ± 1 , 15.4 ± 1 , and 17.8 ± 1 mm on the left side and 6.7 ± 1 , 15.5 ± 1 , and 17.7 ± 1 mm on the right side. No differences were found between the left and right sides for all measurements. The HC interline measured 24.7 ± 1 mm (Figure 6).

Table III shows the morphometric and radiomorphometric data correlated to the HC.

Jugular Tubercle

The JT interline measured 19.7 ± 3 mm, and the JT-HC interline ratio was 0.8.

Middle and Lower Clivus

The total clival length was 41.1 ± 4 mm. The lengths of the middle and lower clivus were 14.8 ± 1 and 16.2 ± 0.8 mm, respectively (Figure 4). An evident central clival depression was found in 36% of the skulls.

Table IV presents the morphometric data of the middle and lower clivus and a comparison with the data reported in the literature.

Dimensional Variability of the Condylar and Basilar Part

The analysis of SDs, ranges, and interquartile ranges has shown a higher variability in the SICA, ACA, PICD, AICD, ACT-B, ACT-O, PCT-B, PTC-O, and JT interline. The boxplot,

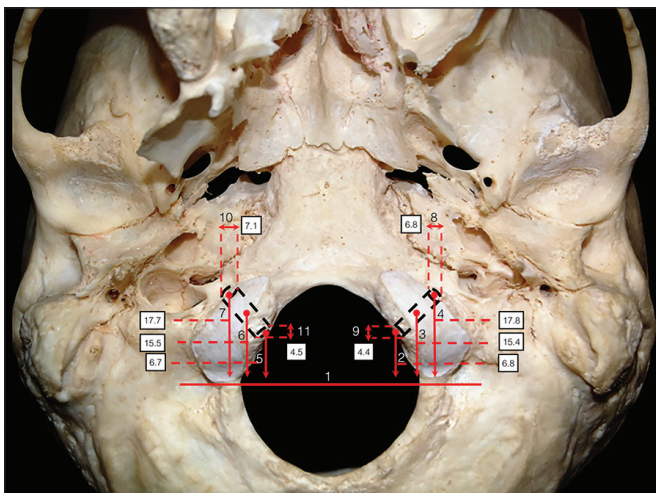


Figure 6: Morphometric analysis of the hypoglossal canal. **1:** line marking the posterior limits of the occipital condyles; **2–4:** distance between the posterior tip of the condyle and the medial, intermediate, and lateral third lengths of the left canal; **5–7:** distance between the posterior tip of the condyle and the medial, intermediate, and lateral third lengths of the right canal; **8–9:** outer and inner diameter of the occipital left condyle; **10–11:** outer and inner diameter of the occipital right condyle. All measurements have been reported as average in mm.

Table I: Foramen Magnum: Diameters, Index and Area Reported in the Present Study and Their Comparison with Data Reported in or Derived from Literature

Author	Sagittal diameter (mm)			Axial diameter (mm)			FM index			FM Area (mm ³)							
	Average	Min	Max	Average	Min	Max	Average	Min	Max	Average	Min	Max					
	Range	Range	Range	Range	Range	Range	Range	Range	Range	Range	Range	Range					
Olivier, 1975 (37)	35.7 [§]	33	38.4	5.4	30.3 [§]	28.2	32.4	4.2	1.17	849.1	730.5	966.4	235.9	854.8	735	972.6	237.6
de Oliveira, 1985 (11)	34.5 [§]	29.2	40.5	11.3	29.4 [§]	26.2	37	10.8	1.17	816.9	596.4	1190.8	594.4	826	597.9	1193.9	596
Catalina-Herrera, 1987 (6)	35.3 [§]	30	41	11	29.6 [§]	21.4	37.6	16.2	1.19	820.2	503.9	1210.1	706.1	826	518.4	1212.4	693.9
Bozbuğa, 1999 (5)	36.6 [^]	27.8	43.2	15.4	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr
Muthukumar, 2005 (34)	33.3 [^]	27	39	12	27.9 [^]	23	32	9	1.19	729.3	468.4	979.6	511.2	735	490.6	989.2	498.6
Naderi, 2005 (35)	34.7 [^]	29.5	43.5	14	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr
Ozer, 2011 (38)	37.2 [^]	27	45	18	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr
Cirpan, 2016 (9)	34.3 [^]	29	43.6	14.6	28.9	24.2	35	10.8	1.18	783.6	569.1	1122.6	553.4	790.4	572.2	1145.5	573.2
Lyrtzis, 2017 (29)	35 [^]	26.7	42.9	16.2	30.1 [^]	22.1	36.6	14.5	1.16	826.9	468.4	1235.4	767	831.1	472.7	1243.4	770.7
Present Study	35.3 [§]	28.2	41.4	13.2	30.4 [§]	26	36.8	10.8	1.16	842.3	575.5	1184.4	608.8	846.5	576.5	1187.8	611.3

FM: Foramen magnum; **SD:** Standard deviation; [§]: measured on the intracranial side; [^]: measured on the esocranial side; **nr:** not reported.

Table II: Morphometric and Radiomorphometric Data of the Occipital Condyle

L condyle		R condyle		AICD (mm ± SD)	PICD (mm ± SD)	ACT-B (mm ± SD)		ACT-O (mm ± SD)		PCT-B (mm ± SD)		PCT-O (mm ± SD)		ACA (° ± SD)		SICA (° ± SD)		
Length (mm ± SD)	Width (mm ± SD)	Length (mm ± SD)	Width (mm ± SD)			L	R	L	R	L	R	L	R	L	R		L	R
Average	23.5 ± 1	11.3 ± 1	9 ± 1	23.6 ± 1	11.7 ± 1	9.3 ± 1	20 ± 5	41 ± 6	10 ± 2	38.9 ± 6	38.7 ± 6	28.3 ± 4	28 ± 4	26.7 ± 6	26.8 ± 6	34.8 ± 5	35 ± 5	69.8 ± 11
Min	21	8	6.5	21.1	8.5	6.5	13.5	30.7	6.8	27.2	27	21.6	21.3	18.2	18.3	23.7	24	47.7
Max	25.4	14.1	11.2	25.9	14.9	11.3	32.7	49.6	16.4	47	47	34.5	34	37.2	37.4	43.6	43.8	87.4
Range	4.4	6.1	4.7	4.8	6.4	4.8	19.2	18.9	9.6	19.8	20	12.9	12.7	19	19.1	19.9	19.8	39.7

L: left; **R:** right; **SD:** standard deviation; **AICD:** Anterior Inter-Condylar Distance; **PICD:** Posterior Inter-Condylar Distance; **ACA:** Anterior Condylar Angle; **SICA:** Sagittal Inter-Condylar Angle; **ACT-B:** distance between the anterior tip of the condyle and the basion; **ACT-O:** distance between the anterior tip of the condyle and the opisthion; **PCT-B:** distance between the posterior tip of the condyle and the basion; **PCT-O:** distance between the posterior tip of the condyle and the opisthion.

Table III: Morphometric and Radiomorphometric Data of the Hypoglossal Canal

HCs interline (mm ± SD)	HC inner diameter (mm ± SD)		HC outer diameter (mm ± SD)		PCT-HC zone 1 (mm ± SD)		PCT-HC zone 2 (mm ± SD)		PCT-HC zone 3 (mm ± SD)		
	L	R	L	R	L	R	L	R	L	R	
Average	24.7 ± 1	4.4 ± 1	4.5 ± 1	6.8 ± 1	7.1 ± 1	6.8 ± 1	6.7 ± 1	15.4 ± 1	15.5 ± 1	17.8 ± 1	17.7 ± 1
Min	23.1	2.6	2.7	5.0	5.3	4.8	4.6	13.2	13.0	15.6	15.4
Max	27.3	6.8	7.0	9.0	9.7	8.5	8.2	17.8	18.2	20.6	20.7
Range	4.2	4.2	4.3	4.0	4.4	3.7	3.6	4.6	5.2	5.0	5.3

HC: hypoglossal canal; **SD:** standard deviation; **L:** left; **R:** right; **PCT-HC zone 1:** distance between the posterior tip of the condyle and the HC calculated at the medial third of the length of the HC; **PCT-HC zone 2:** distance between the posterior tip of the condyle and the HC calculated at the middle third of the length of the HC; **PCT-HC zone 3:** distance between the posterior tip of the condyle and the HC calculated at the lateral third of the length of the HC.

Table IV: Morphometric Data of the Middle and Lower Clivus and Comparison with Data Reported in Literature

Author	Clivus (total) (mm)			Middle clivus (mm)			Lower clivus (mm)				
	Average	Min	Max	Average	Min	Max	Average	Min	Max		
de Oliveira, 1985 (11)	41.8	32	53	21	nr	nr	nr	nr	nr		
Lang, 2001 (24)	45	37	52	15	nr	nr	nr	nr	nr		
Funaki, 2013 (15)	46.8	54	71	17	21.4	19	24	25.4	23	30	7
Present study	41.1	35.5	52.2	16.7	14.8	13	16.2	16.2	14.5	17.4	2.9

nr: not reported.

as shown in Figure 7, summarizes the dimensional variability of all the considered morphometric parameters (Figure 7).

Illustrative Cases

Case 1

A 38-year-old woman presented with neck pain, tetraparesis, and difficulties in swallowing. Magnetic resonance imaging (MRI) has revealed a midline ventral FM meningioma causing severe cervico-medullary compression. The ACA calculated on preoperative axial CT scan was 75.7° , where as the JT-HC interline ratio was 0.9. Therefore, a transcranial left far-lateral approach was performed while the patient was in modified park-bench position. The postoperative course was uneventful, and the condition of the patient gradually improved. The tumor histology was grade I meningotheliomatous meningioma, based on the World Health Organization (WHO) classification. A Postoperative MRI after three months has revealed the complete removal of the tumor without complications (Figure 8A-E).

Case 2

A 52-year-old man presented with severe neck pain and ataxia. MRI showed a midline ventral FM meningioma with initial bilateral encasement of the vertebral arteries. The ACA calculated on preoperative axial CT scan was 62.4° , and the JT-HC interline ratio was 0.6. The endoscopic endonasal transclival far-medial intradural approach was used in the tumor. A pedicled nasal septal flap and autologous fascia lata were utilized for dural closure. During the postoperative course, the patient presented with transient dysphagia and completely recovered after six months of follow-up. Histology confirmed a grade I meningotheliomatous meningioma based on the WHO classification. Postoperative CT scan showed the surgical corridor with total removal of the tumor (Figure 9A-E).

DISCUSSION

The acquisition of greater confidence with the anatomy of the esocranial skull base using the extended endoscopic endonasal approaches (EEEAs), along with the deeper knowledge of the biomechanics of the craniovertebral junction,

and the significant improvement of reconstructive techniques have significantly extended the endoscopic option beyond the limits of the extradural compartments. In fact, the use of the EEEAs has recently been proposed for intradural lesions, such as meningiomas involving the ventral FM and the petroclival region (4,19,23,53), and ventrally located ponto-medullary cavernomas (12,18,27,36,44,51), or even aneurysms of the vertebrobasilar system (14,26,45,48,49). Due to the lower rate of infection or functional complications with the use of EEEAs, such approaches are more preferred than purely microscopic or endoscope-assisted transoral approaches (7). However, at least as far as intradural pathologies affecting the perimedullary cisterns and the brainstem are concerned, EEEAs are still considered pioneering because they still pose a non-negligible rate of complications; thus, transcranial posterolateral approaches are generally preferred. In addition to key factors, such as site, volume, type, and consistency of the lesion; the relationship with the neighboring neurovascular structures; and the surgeon's confidence with a specific corridor, choosing the appropriate approach should also include a cautious evaluation of the posterolateral skull base radiomorphometric parameters. Indeed, in the context of specific patient-related anatomy, a corridor may be safer and more effective than others. This concept is essential in the planning of the approach to extradural FM lesions, but it becomes paramount when dealing with intradural pathologies. The results of the present study confirmed the existence of a dimensional variability within the FM region that mainly involves the axial orientation of the condyle and the prominence of the JT.

Furthermore, the SICA, ACA, PICD, AICD, ACT-B, ACT-O, PCT-B, and PCT-O are all correlated to the orientation of the condyle on the axial plane: the longer the PICD, PCT-B, and PCT-O, the shorter the ACT-B and ACT-O, and the wider the SICA and ACA. Considering these reciprocal relationships, the preoperative evaluation of angular measurements, such as the ACA and SICA, can anticipate the degree of encroachment that the anterior tips of the condyles will have within the anterior medial or far-medial corridor. An ACA and SICA wider than 35° and 70° , respectively, reduce the surgical freedom of the anterior approaches to the ventral intradural FM lesions and

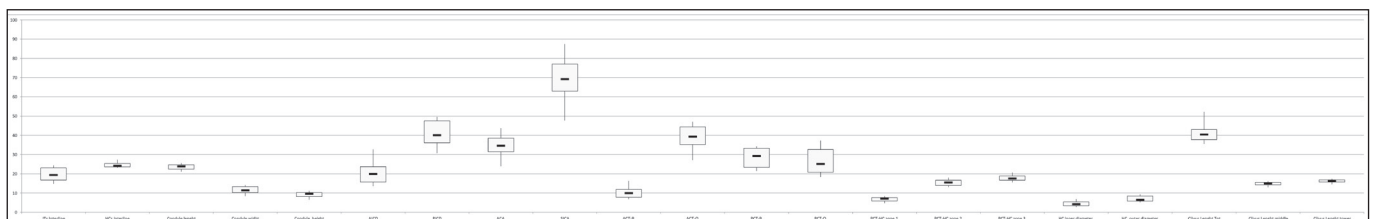


Figure 7: Boxplot reporting the dimensional variability of all the considered morphometric parameters. Solid lines inside the box indicate the median values. **JT:** Jugular tubercle; **HC:** hypoglossal canal; **AICD:** anterior intercondylar distance; **PICD:** posterior intercondylar distance; **ACA:** anterior condylar angle; **SICA:** sagittal intercondylar angle; **ACT-B:** distance between the anterior condylar tip and the basion; **ACT-O:** distance between the anterior condylar tip and the opisthion; **PCT-B:** distance between the posterior condylar tip and the basion; **PCT-O:** distance between the posterior condylar tip and the opisthion; **PCT-HC zone 1:** distance between the posterior tip of the condyle and the midportion of the medial third of the hypoglossal canal length; **PCT-HC zone 2:** distance between the posterior tip of the condyle and the midportion of the intermediate third of the hypoglossal canal length; **PCT-HC zone 3:** distance between the posterior tip of the condyle and the midportion of the lateral third of the hypoglossal canal length.

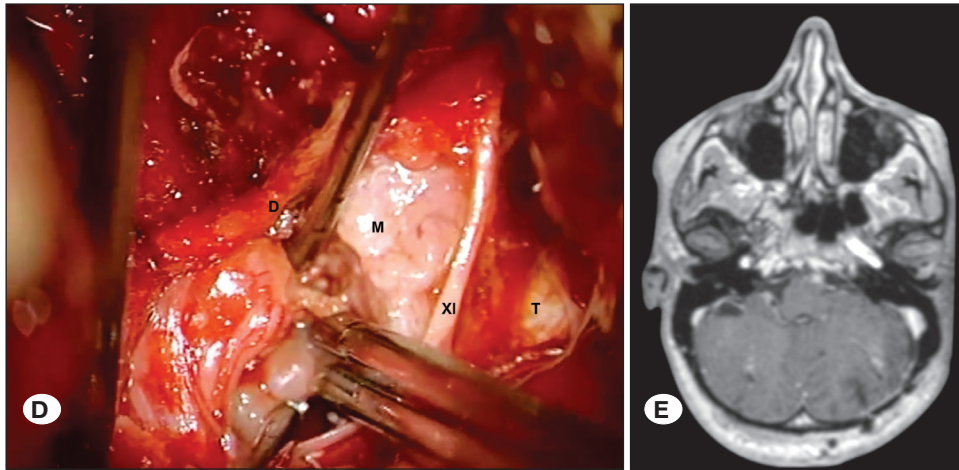
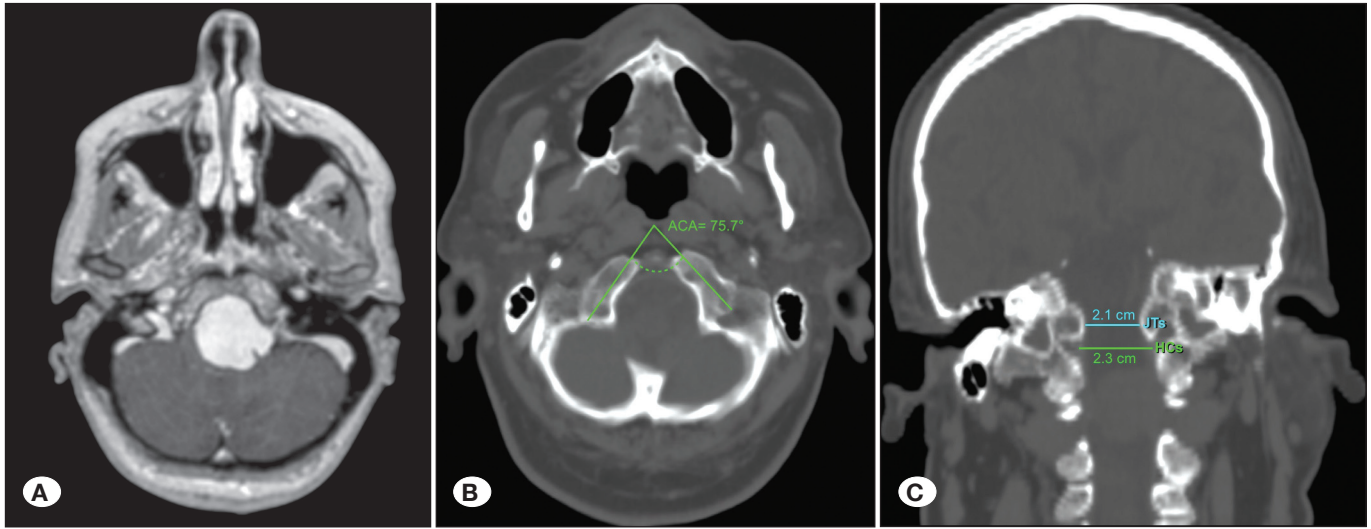


Figure 8: Case 1. **A)** T1-weighted, contrast-enhanced magnetic resonance imaging (MRI) revealing a midline ventral foramen magnum meningioma. **B)** Anterior condylar angle measurement on a preoperative axial computed tomography (CT) scan. **C)** Jugular tubercles–hypoglossal canals interline ratio calculated on a coronal CT scan. **D)** Intraoperative view of the tumor exposed through a left far-lateral approach in a patient who is in modified park-bench position. M: meningioma; D: dura mater; XI: left accessory nerve; T: left cerebellar tonsil. **E)** T1-weighted contrast-enhanced MRI revealing the complete removal of the tumor after 3 months.

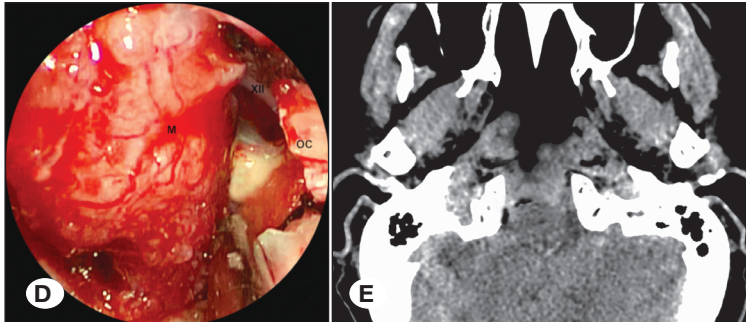
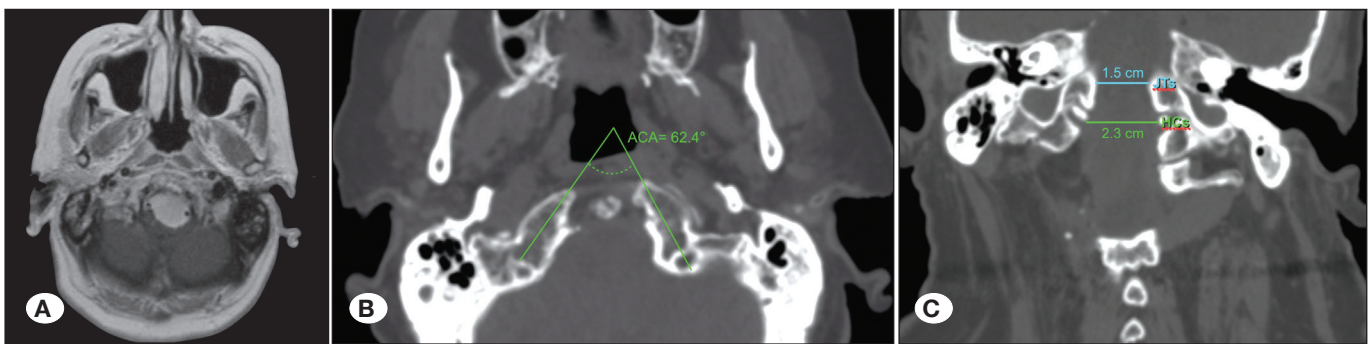


Figure 9: Case 2. **A)** T1-weighted contrast-enhanced magnetic resonance imaging showing a midline ventral foramen magnum meningioma with initial bilateral encasement of the vertebral arteries. **B)** Anterior condylar angle measurement on preoperative axial computed tomography (CT) scan. **C)** Jugular tubercles–hypoglossal canal interline ratio calculated on a coronal CT scan. **D)** Intraoperative view of the meningioma exposed via an endoscopic endonasal transclival far-medial intradural approach. M: meningioma; XII: left hypoglossal nerve; OC: left occipital condyle. **E)** Postoperative axial CT scan showing the transclival midline corridor.

often cause the need for a partial anterior condylectomy with all the related biomechanical consequences. In these cases, a posterolateral intradural approach could be recommended because it may be simpler and less invasive from both an anatomical and biomechanical standpoint. Conversely, an anterior route may be advantageous in cases of narrower ACA and SICA (Figure 10A-D). Naderi et al. have reported a minor average SICA ($59.3^\circ \pm 13.6$ vs. 69.8 ± 11), despite its association with high variability in this study (35). This difference may be due to the fact that they considered the SICA as the angle formed by the intersection between two converging lines traced at the midportion of each condyle, which is different from the present study, in which SICA has been calculated based on the midline intersection of the longest axes of the condyles.

Regarding the JT, equally wide variability was identified from the present data about its prominence within the FM area. Mintelis et al. have reported that the average length, width, and thickness of the JT were 16.5, 11.5, and 0.61 mm, respectively (32). However, these measurements were challenging to obtain directly from CT scans during preoperative planning. That is the main reason why the indirect measures of JT prominence as JT interline and JT-HC interline ratio have been reported in this study. In daily clinical practice, preoperative evaluation

of the relationships between the JT and the vertebrobasilar junction is of utmost importance in planning a posterolateral corridor for a wide range of aneurysms in this area (8,16,28). The same concept is also applicable to meningiomas of the lower clivus or petroclival area, particularly if the existence of a central clival depression or an oval-shaped configuration of the FM (FM index ≥ 1.2) lengthens and deepens the surgical corridor (1). A prominent JT obviously makes the far-medial and far-lateral transtuberular approach more complex. Nevertheless, endoscopic extradural drilling of the tubercle is theoretically associated with a lower risk of mechanical and thermal injury to the lower cranial nerves because the bony work is performed forward to the plane of the nerves. The far-medial approach must be chosen especially when a prominent JT is associated with a narrower ACA and SICA.

In these cases, the need for extradural or intradural drilling of the tubercle adds to that of performing a partial or complete condylectomy to achieve an adequate working angle and ultimately to increase surgical freedom. Our results indicated that a JT-HC interline ratio significantly < 0.8 can predict a high degree of obstruction in the surgical corridor in the far-lateral approach due to the prominence of the tubercle itself (Figure 11A-D).

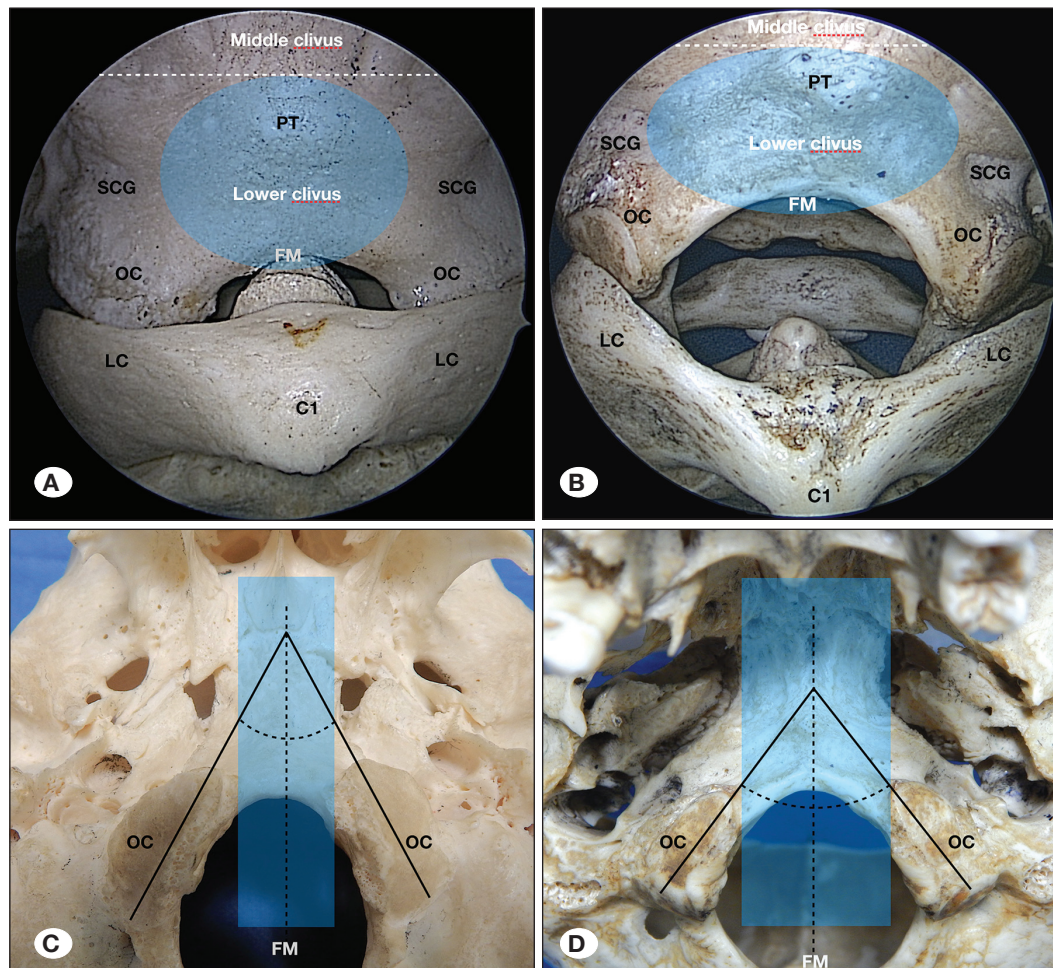


Figure 10: **A)** Endoscopic endonasal midline view of the foramen magnum region in a skull with a narrow anterior intercondylar distance and a narrow sagittal intercondylar angle **(C)**. **B)** Same endoscopic view of a skull with a wider anterior intercondylar distance and a wider sagittal intercondylar angle **(D)**. **OC:** occipital condyle; **LC:** lateral condyle; **FM:** foramen magnum; **D:** dens of the axis; **C1:** atlas; **PT:** pharyngeal tubercle; **AICD:** anterior intercondylar distance; **SCG:** supracondylar groove. The dotted line in figure A and C the inferior clival line and marks the limits between the middle and lower clivus.

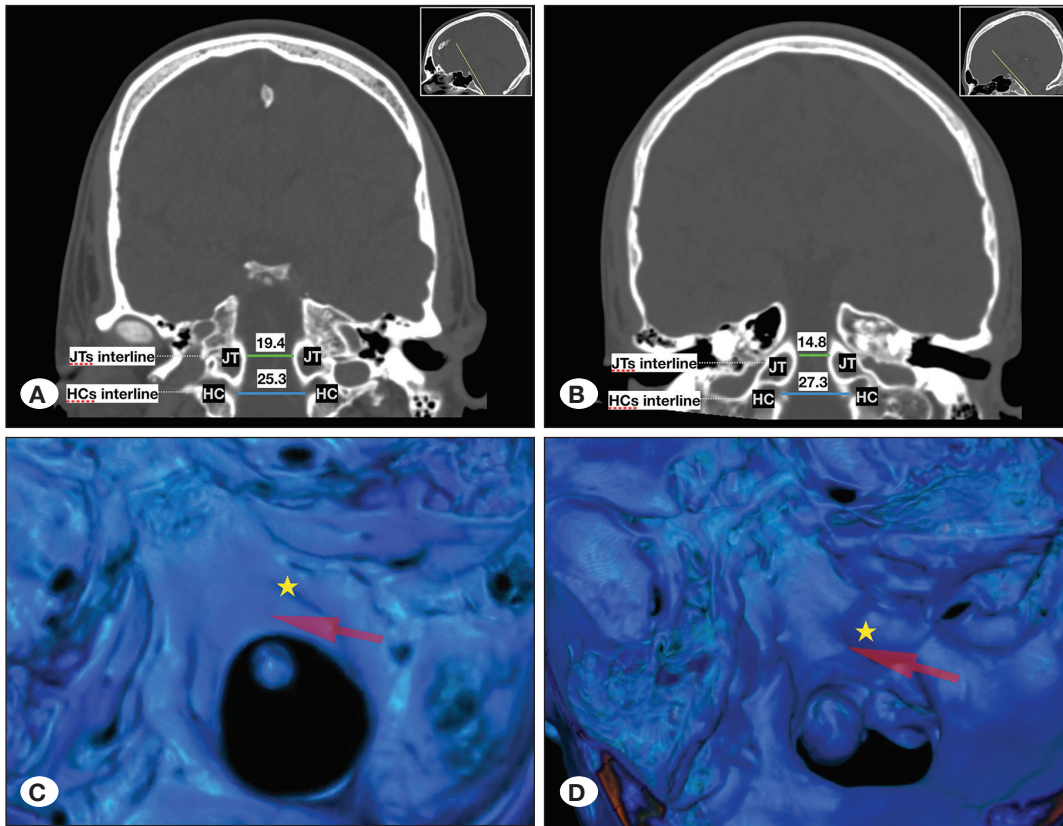


Figure 11: **A)** Bone window coronal computed tomography (CT) scan of a patient with a jugular tubercles–hypoglossal canal interline (JT–HC) ratio of 0.7 compared with that of another patient with a JT–HC interline ratio of 0.5 **(B)**. The squared areas on the upper right-hand side of both images report the sagittal CT scans of the same patients also showing the gantry tilt (yellow line) that was set parallel to the clivus. **(C–D)** 3D rendered CT scan of patients (a) and (b), respectively. The yellow star marks a flat (c) and prominent (d) JT, whereas the red arrow indicates the line of sight of the far-lateral approach. **JT:** jugular tubercle; **HC:** hypoglossal canal.

As far as the clivus is concerned, its middle and lower third length were lower in the present study compared with data obtained by Funaki and colleagues, and this difference may be attributed to the limited number of skulls that were analyzed, resulting in reduced dimensional variability (15).

Limitations

Although it was established that the skulls were not pediatric, no further information about the dry skulls in terms of age, sex, and ethnicity is available, and such factors may cause bias. Nevertheless, a Gaussian distribution has been considered based on the sample size, which is non-negligible.

A further source of bias should be assumed for what has affected the presumed lesser accuracy of the measurements performed using the means of the digital tools of the imaging workstation, compared with the direct measurements performed with the caliper.

Further clinical studies must be conducted to validate the reported data.

CONCLUSION

A comprehensive case-by-case morphometric analysis of the FM region is *important* not only for planning and using individualized and safe anterior and posterolateral approaches to ventral intradural lesions but also for identifying all the advantages of a specific corridor as much as possible while minimizing the risk of complications.

Preoperative evaluation of the ACA, SICA, and JT–HC interline ratio, along with other fundamental lesion-related aspects, may be a discriminating factor in choosing between an anterior versus posterolateral surgical route.

In an ACA and SICA narrower than 35° and 70° , respectively, an anterior approach may be more advantageous. Conversely, a posterolateral corridor must be chosen in cases of wider ACA and SICA, particularly if they are associated with a JT–HC interline ratio ≥ 0.8 .

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