Approaching Intradural Lesions of the Anterior Foramen Magnum and Craniocervical Junction: Anatomical Comparison of the Open Posterolateral and Anterior Extended Endonasal Endoscopic Approaches

(Article begins on next page)

Approaching intradural lesions of the anterior foramen magnum and cranio-cervical junction: anatomical comparison of the open postero-lateral and the anterior extended endonasal endoscopic approaches

Guillaume Dannhoff[1-3] MD, Paolo Gallinaro[1] MD*, Julien Todeschi[1] MD, Mario Ganau[1]MD-PhD, Giorgio Spatola[1] MD, Irène Ollivier[1] MD, Hélène Cebula[1] MD, Charles-Henry Mallereau[1], Seyyid Baloglu[2] MD, Raoul Pop[2] MD, Francois Proust[1] MD-PhD, Salvatore Chibbaro[1-3] MD-PhD.

*The first 2 authors have equally contributed to the study

[1] Department of Neurosurgery, Strasbourg University Hospital, Strasbourg France

[2] Neuroradiology Unit, Strasbourg University Hospital, Strasbourg France

[3] Skull Base ENT-Neurosurgery Laboratory of the University Hospital of Strasbourg, France

Key words: Chordoma, Cranial base approaches; Far Lateral Approach; Far Medial Endonasal Approach; Foramen Magnum; Meningioma; Skull base surgery.

Short title: Anatomical comparison of anterior and postero-lateral approaches to the foramen magnum

Corresponding Author:

Dr. Guillaume Dannhoff MD
Strasbourg University Hospital
1, Av. Moliere, 67098 – Strasbourg France
guillaume.dannhoff@neurochirurgie.fr
guillaume.dannhoff@chru-strasbourg.fr

ABSTRACT

Background: Lesions of the foramen magnum (FM) and cranio-cervical junction (CCJ) area are traditionally managed surgically through anterior, antero-lateral and postero-lateral skull-base approaches. This anatomical study aimed to compare the usefulness of a modified extended endoscopic approach (EEA), the so-called far-medial endonasal approach (FMEA), versus the traditional posterolateral far-lateral approach (FLA).

Material and Methods: Ten fixed silicon injected heads specimens were used in the Skull Base ENT-Neurosurgery Laboratory of the University Hospital of Strasbourg, France. A total of 20 FLA and 10 FMEA were realized. A high-resolution CT scan was performed for a quantitative analysis of the different approaches. The analysis aimed to estimate the extent of surgical exposure and the freedom of movement (manoeuvrability) through the operating channel, using a polygonal surface model to get a morphometric estimation of the area of interest (surface and volume) on post-dissection CT scan using Slicer 3D software.

Results: FMEA allows a more direct route to the anterior FM, with a wider brainstem exposure compared to the FLA, and an excellent visualization of all anterior midline structures. Limitations of FMEA include the deep and narrow surgical corridor, and the difficulty to reach lesions located laterally over the jugular foramen and the hypoglossal canal.

Conclusion: FMEA and FLA are both effective surgical routes to reach FM and CCJ lesions; a good command of both should be enrooted in any modern skull base surgeon as they appear complementary. This anatomical study provides tools to comprehensive preoperative evaluation and selection of the most appropriate surgical approach.

INTRODUCTION

The occipital bone surrounding the foramen magnum is made of three portions, the basilar part or clivus anteriorly, the squamous part posteriorly and the condylar part in-between, protruding inferiorly to form the atlanto-occipital joint. Together, these portions encompass various neurovascular structures in a complex anatomical display (Fig. 1). Surgical areas surrounding the foramen magnum, i.e. retro-clival area and cranio-cervical junction (CCJ) can be affected by various intradural and extradural disorders, including: tumours, bone malformations, inflammatory diseases and trauma [1]. Given that, several approaches to those regions have been developed through anterior, antero-lateral and postero-lateral routes [2–4].

This variety of approaches reflects the difficulty to safely reach these regions. Neurosurgical corridors aim to provide the best possible exposure of the surgical field with the minimal manipulation or retraction of anatomical structures and therefore with limited morbidity. Nevertheless, many of these approaches are quite invasive, requiring a variable degree of neurovascular manipulation.

The far-lateral approach (FLA) is an extension of the classical suboccipital approach, consisting in a lateral extension of the craniotomy to reach the condylar fossa along with removal of the posterior arch of C1. Originally described in 1986 by Heros for the management of vertebrobasilar artery lesions [5], its popularity increased two years later with Bernard George series of 14 benign anterior FM tumours successfully resected [6]. It has since became a traditional way to access lesions of the inferior clivus from a posterolateral perspective,

However, the most physiological route to the retro-clival area and the ventral CCJ would in theory be represented by anterior approaches, offering a direct view of deep surgical targets through a corridor that is not crossed by cranial nerves. Since its inception, the trans-nasal approach has been mainly used to treat extradural lesions and to perform CCJ decompression [7–9], although some authors also have reported its use to manage intradural lesions [10]. The recent development of endoscopic endonasal approaches for the treatment of sellar region lesions [11] has led some surgeons to conceive the extended endonasal endoscopicapproach (EEA), which is primarily aimed at reaching pathologies located in suprasellar, parasellar, but also retroclival areas [12–16]. Recent anatomical studies and clinical reports have also demonstrated the possibility of directly approaching any midline structure, from the crista galli to the odontoid process, by different EEAs [17,18]. Finally, the advancement of surgical technique with an improvement of neuro-endoscopic technology led to an evolution of the EEA, including the so-called far-medial endonasal approach (FMEA), with potential to treat lesions located in the inferior clival region (mainly extradural chordomas), as well as in the CCJ.

The FMEA was described by Morera in 2010 [19], consisting in an anterior endoscopic trans-clival approach optimizing surgical exposure via drilling of the lateral inferior clival area, together with a condylar and jugular tubercle partial resection. Endoscopic identification of the supracondylar groove is a key landmark to locate the hypoglossal canal, itself separating the jugular tubercle superiorly and the condylar compartment inferiorly.

The aim of the present study was to perform a morphometric analysis of a) the surgical exposure and b) the manoeuvrability through the operating channels obtained through the FLA and the FMEA (Fig. 1), and to eventually compare our results with those recently published in the neurosurgical literature.

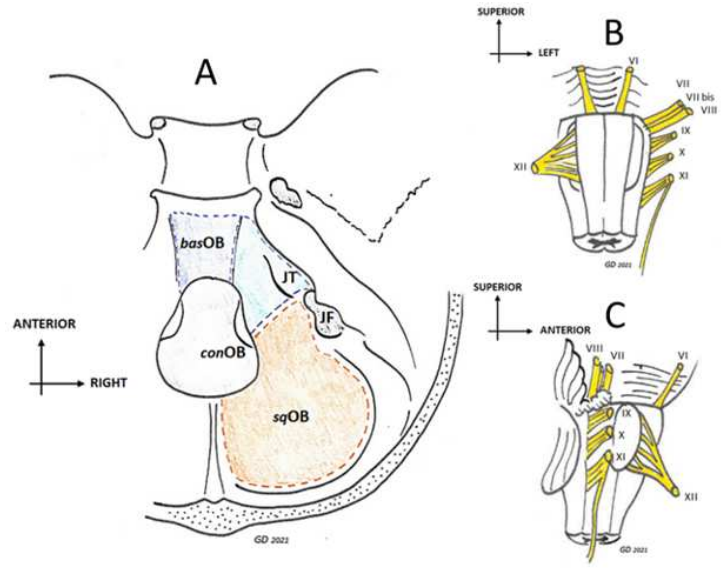

Figure 1. Schematic drawings of main osseous and nervous landmarks of surgical approaches to the foramen magnum. (A) Skull base drawing showing the bone drilling areas around the foramen magnum. The occipital bone is made of three portions, the basilar part (*bas*OB) or clivus anteriorly, the squamous part (*sq*OB) posteriorly and the condylar part (*con*OB) in-between. The jugular foramen (JF) and jugular tubercle (JT) are two important lateral landmarks guiding surgical approaches. The standard endoscopic endonasal approach is represented by the dark blue dotted line, the extended FMEA by the light blue line and the classic FLA by the orange line respectively. (B, C) Schematic drawings of the brainstem exposed through surgical approaches to the foramen magnum: anterior view of the ventromedial brainstem approached via the FMEA (B) and right lateral view of the dorsolateral brainstem approached via the FLA (C).

MATERIAL AND METHODS

Dissections were performed on 10 fixed coloured silicone-injected adult head specimens, without previous brain or skull base abnormalities, at the Skull Base ENT-Neurosurgery Laboratory of the University Hospital of Strasbourg, France. Each specimen underwent a double FLA (for a total of 20 approaches) and a single FMEA (for a total of 10 approaches).

<u>Morphometric Analysis</u>

Before dissection, each specimen underwent a high-resolution computed tomography (CT) scan (1 mm cuts) to allow accurate measurements of deep anatomical structures exposed during dissection along the surgical corridor. Though MRI is the preferred imaging modality in clinical routine when dealing with FM lesions, CT scan was performed here due to its availability in our research laboratory and also due to its high-quality bony definition and analysis, allowing more precise and reproducible evaluation of our parameters of interest.

A post-dissection high-resolution CT scan was also obtained for the purpose of quantitative analysis of the different approaches. The analysis was done using a polygonal surface model to get a morphometric estimation of the area of interest (its surface and volume) on post-dissection CT scan (Fig. 2, 3); those calculations were conducted through the Slicer 3D software (Version 4.10.1, www.slicer.org), which analysed 2 main features:

- extent of surgical exposure (surface and volume of exposure): considered as the maximal 2D/3D area that can be exposed using each approach,
- the freedom of movement (surgical freedom): allowing to reach a specific target area without retracting/damaging important neurovascular structures through the operating channel.

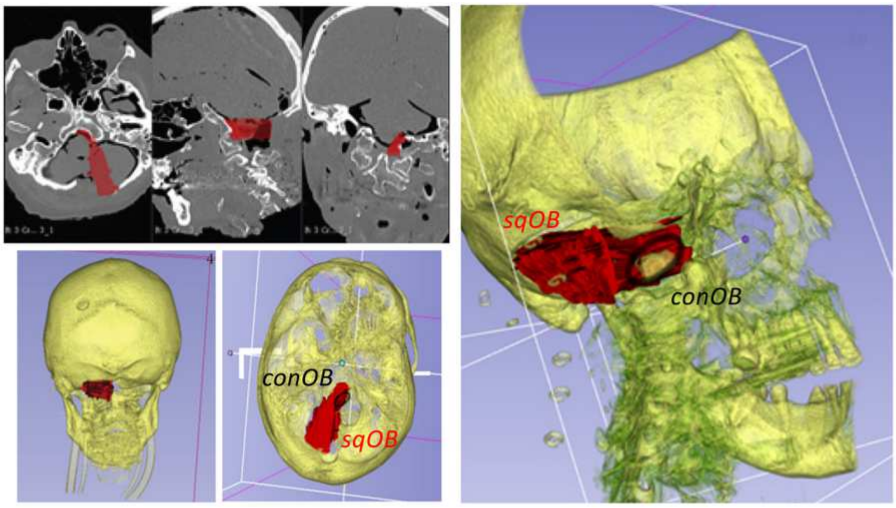

Fig. 2. CT-scan with 3D reconstructions of the surgical volume involved in FLA, accessing the foramen magnum posteriorly through resection of the squamous portion of the occipital bone (*sqOB*) and partial resection of the occipital condyle (*conOB*) highlighted in red.

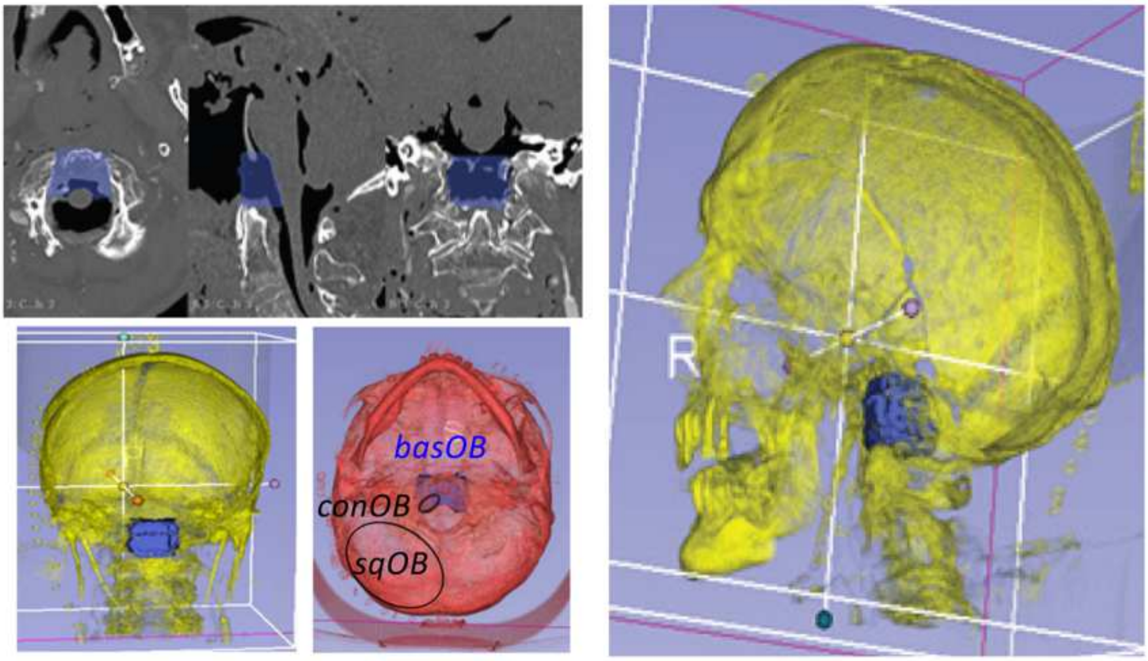

Fig. 3. CT-scan with 3D reconstructions of the surgical volume involving the FMEA, accessing the foramen magnum anteriorly through resection of the basilar portion of the occipital bone (*basOB*) highlighted in dark blue.

Step-by-step description of surgical technique

The FLA was performed bilaterally in all specimens, under microscopic magnification (Zeiss surgical microscope), with the heads fixed in a three-pin Mayfield head holder, in a surgical position (i.e. prone position and slightly rotated 15° to the opposite side). Dissection was performed according to the techniques previously described in the literature, consisting of three critical steps (Fig. 4) :

1°) A “hockey stick” skin incision is performed, extending from the spinous process of C3 to the inion, then curving laterally toward the apex of the mastoid process. Muscles are dissected from the occipital bone and posterior arch of C1, and retracted laterally. At the end of this first step, we identify the suboccipital triangle and the vertebral artery in its V3 segment.

2°) A C1 hemilaminectomy is done, extending from a point just beyond the midline to the groove of the vertebral artery. The vertebral artery is not transposed, to simulate the common usage of FLA in clinical practice. Once the posterior arch of C1 is removed, the posterior atlantooccipital membrane can be detached superiorly from the posterior margin of the FM, allowing then to perform a lateral suboccipital craniotomy. The craniotomy involves the squamous portion of the occipital bone, extending laterally until being a few millimeter away from the neurovascular components of the jugular foramen. Bone resection is in fine limited by veinous structures – namely the sigmoid sinus laterally and the transverse sinus superiorly -. Finally, the exposed occipital condyle is minimally drilled to reproduce a transcondylar variant of the FLA. In order to preserve the stability of the cranio-cervical junction and to ensure the protection of the vertebral artery, condylectomy is limited to its medial third, bordered anteriorly by the hypoglossal canal and inferiorly by the articular facet of the lateral mass of C1.

Fig. 4 Dissection steps of the FLA, from hockey stick incision to C1 hemilaminectomy and occipital craniotomy with partial condylectomy allowing wide dural exposure.

3°) The dura mater is finally opened in the midline, from the height of the dural entry point of the vertebral artery, and curved to the sigmoid sinus margin cranially. The cerebellar hemisphere is then gently retracted until reaching the inferior cranial nerves, vertebral artery and mostly until adequate exposure of the inferior clivus is achieved.

The FMEA is performed with a 4 mm diameter, 18 cm long endoscope with 0° and 30 and sometimes 45° optics, and a TELEPACK X LED image system (Karl Storz GmbH & Co., Tuttlingen, Germany), according to the technique previously described in the literature in the way to expose the FM and inferior clivus along with the condylar region, jugular foramen, jugular tubercle and cranio-cervical junction. The heads were fixed in a Mayfield three-pin headholder and positioned with approximately 15° flexion and 10° rotation to the right, to reproduce the common patient setup in the operating room.

The FMEA is performed via a bilateral transnasal approach, through the following steps:

1°) A bilateral inferior turbinectomy is performed to enlarge the surgical corridor, while taking care of preserving the nasal mucosa flap bilaterally. The mucosal and muscular planes, made by the posterior wall of the nasopharynx, are resected to expose the inferior clivus and the cranial aspect of the craniocervical junction. The level of the jugular foramen and the hypoglossal canal are localized through the identification of the pharyngeal tubercle and the supracondylar groove respectively.

2°) The atlanto-occipital joint capsule is removed to expose the occipital condyle. The clivus is drilled off from the pharyngeal tubercle to the foramen magnum. The superolateral limit of the clivectomy is defined by the lateral pharyngeal tubercle, as going beyond it could result in damaging the internal carotid artery superolaterally or the inferior petrosal sinus and jugular bulb laterally. The ventral aspect of the condyle is drilled up to the cortical bone of the hypoglossal canal, which constitutes the lateral limit of the clival bony removal (Fig. 5).

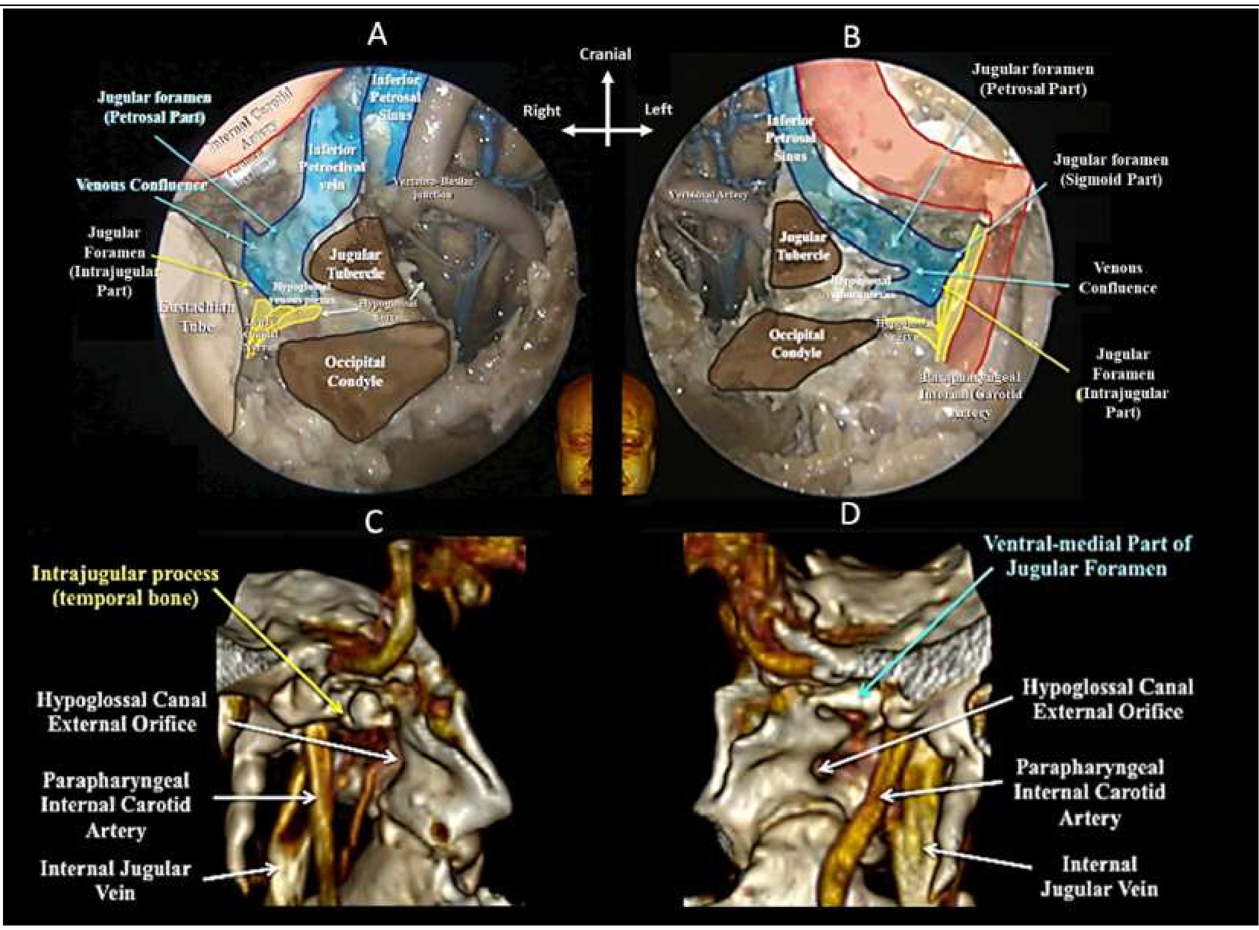

Fig. 5. Endoscopic view of the FM region approached anteriorly after clival resection, showing the ventral brainstem along with the variety of osseous landmarks and neurovascular structures visualized through a narrow surgical corridor on the right (A) and left (B) sides. The clival drilling area is limited by the hypoglossal canal above the occipital condyle and the jugular tubercle viewed bilaterally. Per-procedural findings are correlated with 3D reconstructions of the corresponding CT-scans right (C) and left (D) aspects.

3°) Finally the dura mater is opened in the midline, allowing visualisation of the brainstem, the vertebral, basilar and origin of the posteroinferior cerebellar arteries, along with the cranial nerves IX, X, XI and XII bilaterally. (Fig. 5)

Surgical exposure was quantified during dissections using a paper graduated ruler and was correlated with post-dissection measures based on CT-scan.

<u>Statistical analysis</u>

A paired Student t-tests was used to compare the data for quantitative analysis. In the statistical comparison analysis, a p value < 0.05 was considered significant. All calculations were performed with GraphPad Prism version 6.00 (GraphPad, La Jolla, California, USA)

RESULTS

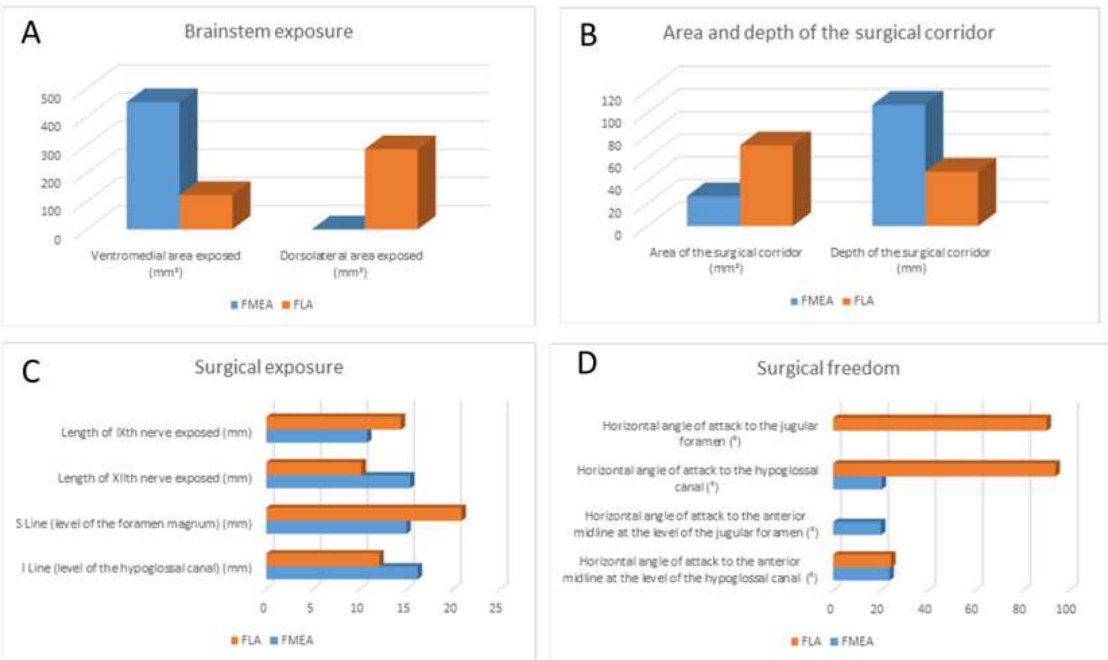

Fig. 6. Main parameters quantified when performing FLA (orange bars) and FMEA (blue bars): (A) Brainstem exposure (B) Area and depth of the surgical corridor provided (C) Surgical exposure of cranial nerves IX and XII, and reference lines respectively defined at the level of the foramen magnum and at the level of the hypoglossal canal. (D) Surgical freedom obtained at the level of interest.

Brainstem exposure

FMEA allowed a significantly wider exposure ($p < 0.01$) of the ventral brainstem, up to 180° of its ventro-medial part (452.4 +/- 14.33 mm^2), compared to the FLA (122.4 +/- 4.58 mm^2) (Fig. 6A). In practice, through the FMEA it was possible to obtain a total exposure of the ventral brainstem, whereas only 25% was exposed with the unilateral FLA.

The widest exposure obtained with the FLA was 407.6 +/- 15.89 mm^2 (40% at the level of the ventro-medial area and 60% at the level of the dorso-lateral area). More specifically, the dorso-lateral area of the brainstem exposed through the FLA was of 285.2 +/- 11.31 mm^2, corresponding to 75% of the entire dorso-lateral face of the brainstem. On the other hand, through the FMEA, it was not possible to expose any aspect of the dorsolateral area of the brainstem, because of the cranial nerves crossing over.

Surgical corridor

The FLA created a surgical corridor up to the ventro-medial area of the posterior fossa in only 70% of the specimens; in the remaining 30% (6/20) the access to the clivus was limited by the presence of a homolateral predominant vertebral artery (Fig. 6B). The mean sectional area of the surgical corridor in the FLA was about 71.4 +/- 3.86 mm^2, whereas the mean sectional area of the FMEA was about 26.4 +/- 3.65 mm^2. The possibility to gently retract the cerebellar hemisphere, together with the wider surgical angle offered by the FLA resulted in a wider surgical corridor than that offered by FMEA. Of note, in 40% of the specimens the spinal root of the XI cranial nerve divided the main surgical corridor created by FLA into two corridors, superior and inferior, each with similar dimensions.

In FLA the depth of the surgical corridor corresponded to the distance between the musculocutaneous flap and the dura mater, its length was on average 48.0 +/- 2.74 mm; on the other hand, in FMEA the depth of the surgical corridor corresponded to the distance between the anterior nasal spine and the dura mater, its average length was 107.2 +/- 3.70 mm.

Surgical exposure

Two key lines were calculated in all specimens: the S Line, or the average distance that could be reached in the axial plane at the level of the foramen magnum, and the I line, or the average distance that could be reached in the axial plane at the level of the hypoglossal canal. The S Line was calculated in the latero-medial sense to the midline for FLA and in the medio-lateral sense to the periphery for FMEA and resulted significantly higher in FLA than in FMEA: 20.9 +/- 1.20 mm versus 15.0 +/- 0.72 mm, $p < 0{,}01$ (Fig. 6C). The I line was calculated in the latero-medial sense for FLA and in the medio-lateral sense for FMEA and resulted significantly higher in FMEA than in FLA: 16,2 +/- 0,84 mm versus 12,1 +/- 0,99 mm, $p < 0{,}01$.

Of note, the average intradural length of the IX cranial nerve exposed by FLA was significantly longer than the exposure provided by FMEA: 14,4 +/- 1,37 mm versus 10.8 +/- 1.30 mm, $p < 0.05$. On the contrary, the average intradural length of the XII cranial nerve exposed by FMEA was significantly longer than that offered by FLA: 15.4 +/- 1.14 mm versus 10.2 +/- 1.03 mm, $p < 0.01$.

Surgical freedom

The extent of surgical exposure and the freedom of movement to the jugular foramen could only be assessed in the corridor created through a FLA, its average value was 90.1° +/- 6.61° (Fig. 6D). In our dissected specimen, the jugular foramen was indeed not reachable at all through a FMEA. On average, the horizontal angle of attack to the hypoglossal canal was significantly higher in FLA than in FMEA: 93.9° +/- 5.51 versus 20.5° +/- 1.05, $p < 0.01$.

The anterior midline at the level of the jugular foramen could not be reached in any anatomical subject through a FLA. Though it was accessible in every subject through FMEA, its angle of attack to the anterior midline was limited (20.2° +/- 1.48). The anterior midline at the level of the hypoglossal canal was accessible in 40% of cases via FLA and 100% of cases via FMEA, with an almost identical angle of attack, ranging between 23.8° and 24.5° in both types of approach.

DISCUSSION

The FM is the largest foramen in the occipital bone of the skull in humans and many other animals. The spinal cord, an extension of the medulla oblongata, passes through the FM as it exits the cranial cavity. Apart from the medulla oblongata, also the vertebral arteries, the anterior and posterior spinal arteries, the tectorial membranes, alar ligaments, and the accessory nerve transit through the FM. This foramen extends anteriorly from the junction of the lower and middle third of the clivus to the upper edge of the C2 body, laterally from the jugular tubercle to the upper aspect of the C2 lamina, and posteriorly from the anterior edge of the occipital bone to the C2 spinous process [17,18].

Dissection Results

Access to the anterior FM and to the CCJ remains one of the most complex neurosurgical procedures because of the proximity to vital neurovascular structures, depth and narrowness of surgical corridors [1]. In the literature, several surgical approaches have been described for this region, each one with its pros and cons [8,20]. In recent years thanks to the progresses in terms of anatomical knowledge of the skull base and the development of endoscopic techniques and the dedicated instrumentation, a new opportunities emerged to exploit the natural endonasal corridor and reach the lower clivus and the CCJ [2,18,21].

Having gathered as a group a 30-year experience with the FLA and a 15-year experience with the EEA [4,16], we designed an anatomical study to compare the extent of surgical exposure and the freedom of movement (manoeuvrability) through both operating channels, FLA and FMEA.

The FLA is very popular worldwide due to its lower rate of complications compared to the extreme-lateral approach, it provides a safe access to the anterior midline, although increasing the risk of vascular complications [3,20,22].

Most results from our anatomical study are in line with previous similar studies [20,22], this is not surprising given the homogeneity of methodology for what regard morphometric analyses (we performed similar types of calculations with the same software). This allowed our data to be comparable to those obtained from previous studies, and increase the generalizability of the conclusions reached so far by other authors.

Our results confirm that the surgical exposure of the ventral surface of the FM and of the inferior clivus is far superior via FMEA; however the manoeuvrability is lower in this latter technique because of the narrow endonasal corridor.

<u>"Open" FLA</u>

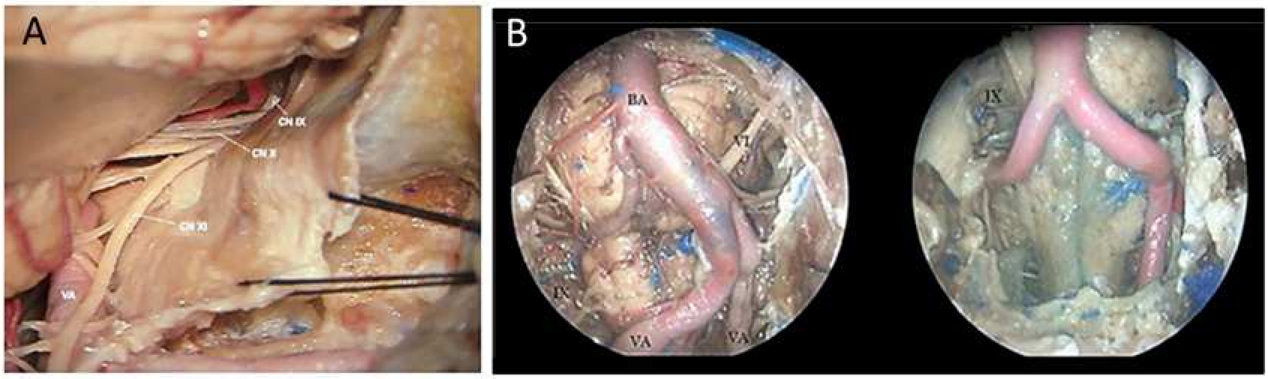

Fig. 7 Dissection views comparing neurovascular structures exposed via the FLA (A) and the FMEA (B) after dural opening. BA: basilar artery; VA: vertebral artery; VI : sixth cranial nerve; IX: ninth cranial nerve;

The FLA is widely used in the treatment of FM lesions, but is also utilized for anterolateral lesions of the inferior clivus, because it allows an easy occipital condyle drilling, with the possibility to release and displace the vertebral artery (VA) and to drill the jugular tuberculum [9,23,24]. In fact the possibility to expose and control the VA in the early stage of the procedure allows to reduce the risk of bleeding during the resection of an inferior clivus lesion, and represents another advantage of the FLA.

In our study, as previously reported, the FLA allowed a good exposure of the inferior clivus as well as of the anterolateral side of the FM and the ventrolateral surface of the brainstem together with the related neurovascular structures, all without the need of traction [20,22,25] (Fig. 7A). This approach also allows a wide exposure of the dorso-lateral area of the posterior cranial fossa [20]. It should be pointed out, however, that the FLA offers a very limited access to the ventromedial brainstem area, in particular to the anterior midline at the cranial level. In fact, in our study it was possible to reach the clivus in only 30% of specimens due to the anatomical obstruction caused by a dominant VA; whereas at the level of the hypoglossal canal, the anterior midline could be reached in only 40% of specimens. Of note, at the level of the jugular foramen, the anterior midline could never be reached. Because of these limitations, the distance reached in a medial direction to the inferior clivus was of 21 mm at the level of the jugular foramen and of 12 mm at the level of the hypoglossal canal.

FMEA

Since its introduction, EEA allowed to overcome several limitations of conventional microsurgical approaches. For instance, it allowed a panoramic and dynamic vision in a narrow surgical corridor with visualisation of numerous landmarks, while guaranteeing excellent image magnification when exploring neurovascular structures (Fig. 7B). With time, neurosurgeons started to use such approach to tackle lesions of the anterior and posterior cranial fossa [17–19,26,27].

In our study, through FMEA the depth of the surgical corridor to the FM had an average of 10.5 cm and was significantly higher to that to the CCJ provided by FLA: because of the narrow surgical corridor, the FMEA is characterized by a lower grade of surgical freedom, compared to the open surgical approaches, in particular for what concern the laterality. Despite these limitations, our results showed that the FMEA allows an excellent exposure and a direct access to the medial part of the anterior FM and to the inferior clivus, with an average distance of 1.5 cm from the midline of the jugular foramen, and of 1.8 cm from the hypoglossal canal. However, the lateral exposure of the lesion is limited by some uncrossable borders such as internal carotid arteries (ICAs), nerve of the pterygoid canal (vidian nerve), jugular veins, hypoglossal nerve and Eustachian tubes [28]. The degree of surgical freedom is also limited by the handling of the endoscope, because of anatomical obstacles such as the nose, the nasal concha and the depth of the endonasal corridor itself. Because of the above described limitations, the FMEA does not allow, in our opinion, a good exposure of lesions localized in the antero-lateral region of the FM and of the inferior clivus, in particular for those whose epicentre is localized at the level of the jugular foramen or at the hypoglossal canal. In fairness, the FMEA should not be considered as a mini-invasive approach because it is really destructive and can lead to important complications, such as the postoperative discomfort related to the turbinectomy, the risk of instability at the level of the CCJ and, most importantly, the risk of meningitis and CSF leak in case of intradural lesions [29]. According to our results, the FMEA is particularly useful for lesions with a small volume and near to the anterior midline (no further than 1.5 cm from the midline).

In order to allow a safe tumour resection through the endoscope, the caudal extension of the lesion should be limited: all tumours that cross the odontoid process are more difficult to treat because of the conflict between the endoscopic instrumentations, the anterior nasal spine and the palatal plate. At last, the extent of the resection over the odontoid process could compromise the stability of the CCJ by damaging the anterior longitudinal ligament [27]. As it has been previously showed by Benet et al., the FMEA could be also considered in a selected group of patients (characterized by good general health, potential healing after a gross total resection of the lesion and tumours with extensions in the ventro-medial and dorso-lateral areas) for combined open FLA in order to achieve a gross total resection of the lesion.

Clinical applications examples

Case vignette 1

A 56-year-old woman presented with a large clival meningioma, centred on the right anterolateral portion of the FM. The vertebral arteries were not encased, the right one being located rather anteriorly and the left one laterally; the brain stem was severely stretched and displaced postero-laterally to the left (Fig. 8A). The Far-Lateral Approach was judged particularly adequate as it exploited the anatomical distortions and the surgical corridor created by the lesion itself (Fig. 8B). Moreover, section of the denticulate ligament allowed gentle mobilization of the upper spinal cord, increasing surgical manoeuvrability. The patient was operated in a prone position, trough the traditional aforementioned steps achieving a complete excision (Fig. 8C).

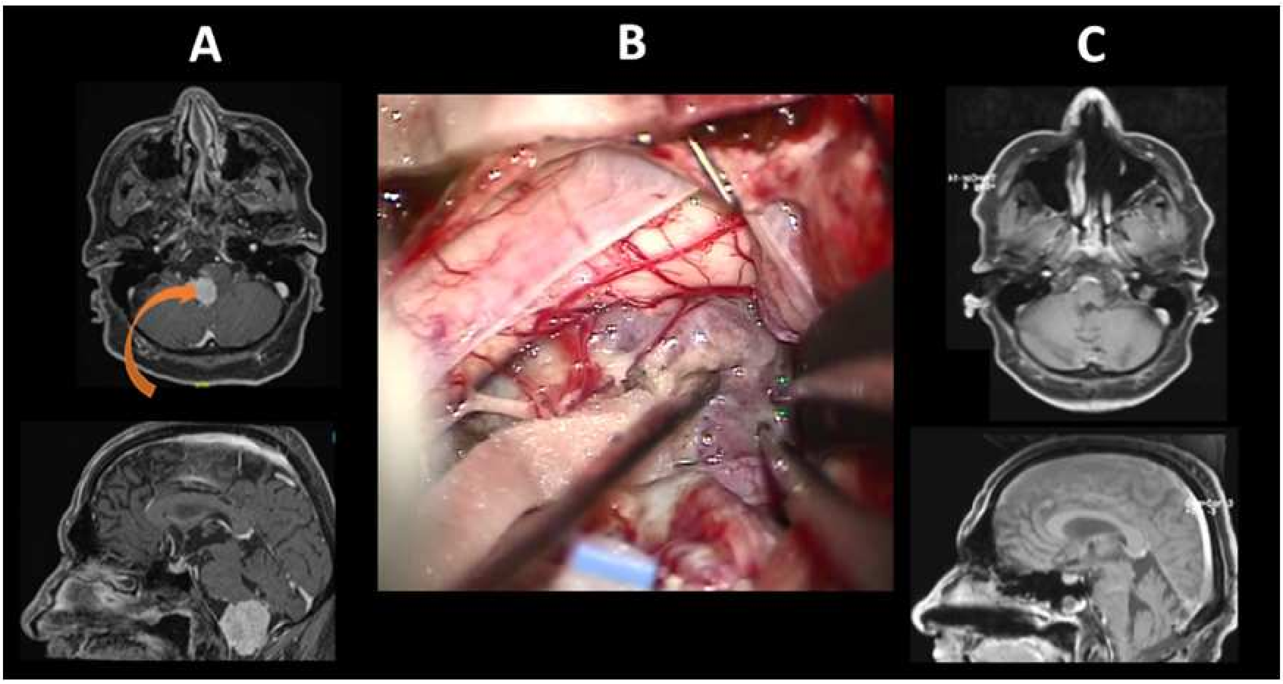

Fig. 8 Case vignette: FLA resection of a clival meningioma, preoperative MRI (A), perioperative view of FLA (B) and postoperative MRI showing complete removal (C).

Case vignette 2

A 47-year old woman presented with a FM meningioma. The epicentre of the lesion was in the ventromedial compartment; it did not extend beyond 1.5 cm from the anterior midline and did not overpass the jugular foramen and the hypoglossal canal laterally (Fig. 9A). The cranial nerves and vertebral artery were located postero-laterally. The caudal extension of the lesion did not exceed the apex of the odontoid. In this case, an Endo-FM approach was chosen (Fig. 9B), allowing adequate exposure so that complete excision could be achieved (Fig. 9C).

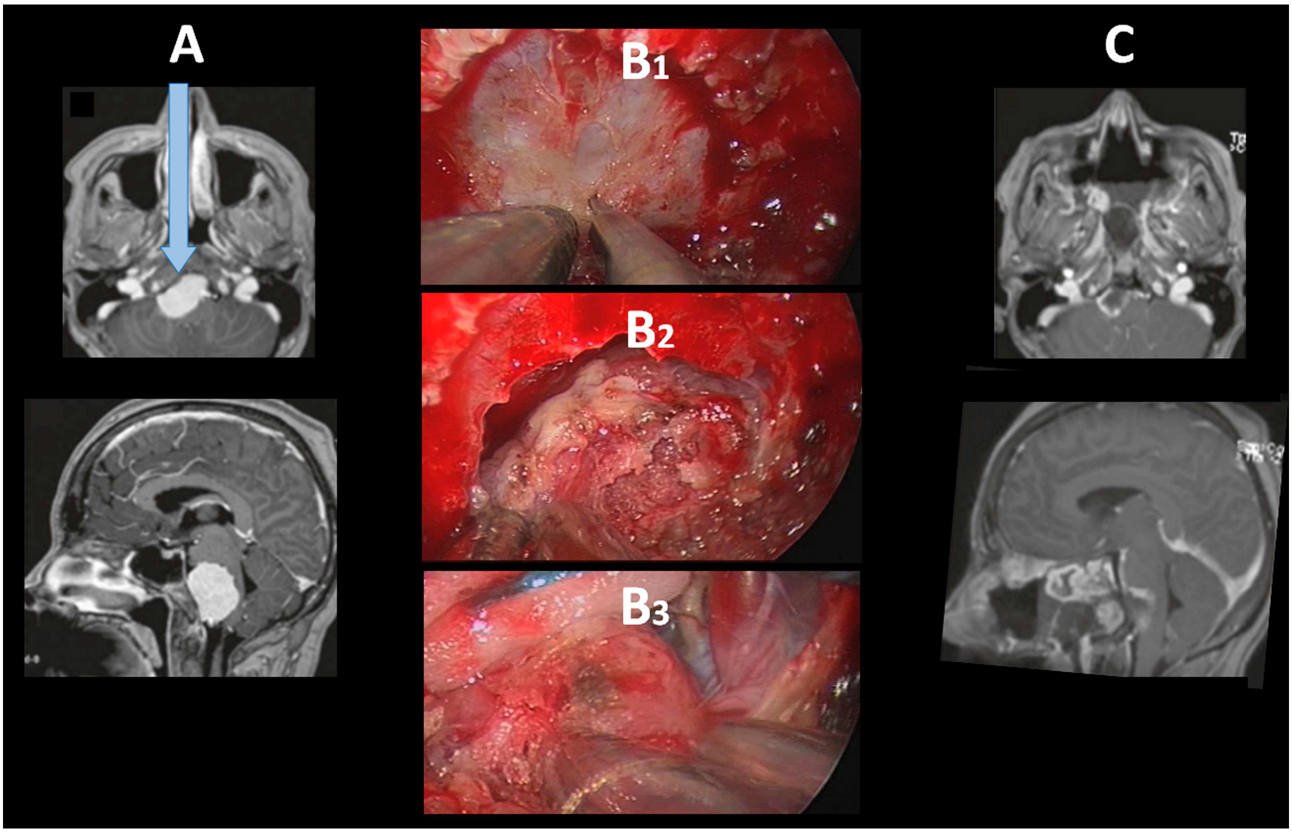

Fig. 9 Case vignette: FMEA resection of a clival meningioma, preoperative MRI (A), peroperative view allowed with FMEA (B) showing dural exposure (B_1) followed by tumour exposure (B_2) and visualization of leptomeninges and neurovascular structures along tumour resection (B_3), postoperative MRI showing complete removal (C).

Study limitations and strengths

Our study is affected by a number of limitations. First of all, the small number of specimens studied: only 10 heads for a total of 20 FLA and 10 FMEA; as a consequence, the morphometric data obtained could have limited significance and should be improved by further studies. Another limitation is represented by the specimens themselves. Because of the fixation, there was a higher level of tissue rigidity, with a lower possibility of traction on neurovascular structures.

At last, it should be specified that the heads used for the dissection were not characterized by pathologies in the anatomical area of interest. Understanding of normal anatomy is necessary to apprehension of disrupted anatomy. But extrapolation of our anatomical data to pathological scenarios are limited, as the normal anatomy here depicted could be variously disrupted by lesions' mass effect, with creation of natural surgical corridors and cleavage planes that need to be assessed on a case-by-case basis.

This anatomical study could therefore benefit from more robust clinical perspectives. We firmly believe that when enhanced with the experience of real-life surgical experience, those anatomical data could lead to the proposition of a clinical algorithm allowing to select the most appropriate surgical approach.

CONCLUSION

Data from this anatomical study align well with other studies in the literature and demonstrate that FMEA and FLA complement each other in the way both provide valuable treatment options for the surgical management of FM and CCJ lesions. A careful pre-surgical planning under the "first do not harm" principle should guide neurosurgeons in opting for an endoscopic or open surgical approach while choosing, on a case-by-case basis, the best technique to obtain the maximal safe resection with minimal risk of iatrogenic complications. Our study suggests that rigorous anatomical knowledge, together with a good surgical dexterity in those working channels, are the key to safely manage such challenging lesions. The future endeavour for skull base surgeons then becomes the identification of patients and lesions characteristics allowing for a comprehensive preoperative evaluation and the selection of the most appropriate surgical approach, this further step should be based on objective evidence from nomograms and should spur into robust operative algorithms.

REFERENCES

1. Samii M, Gerganov VM. Tumors of the occipitocervical junction. In: *Pathology and Surgery around the Vertebral Artery*. Springer Paris; 2011:427-441. doi:10.1007/978-2-287-89787-0_29

2. Komotar R, Zacharia B, McGovern R, Sisti M, Bruce J, D′Ambrosio A. Approaches to anterior and anterolateral foramen magnum lesions: A critical review. *J Craniovert Jun Spine*. 2010;1(2):86. doi:10.4103/0974-8237.77672

3. Leon-Ariza DS, Campero A, Romero Chaparro RJ, Prada DG, Vargas Grau G, Rhoton AL. Key Aspects in Foramen Magnum Meningiomas: From Old Neuroanatomical Conceptions to Current Far Lateral Neurosurgical Intervention. *World Neurosurgery*. 2017;106:477-483. doi:10.1016/j.wneu.2017.07.029

4. Chibbaro S, Cornelius JF, Froelich S, et al. Endoscopic endonasal approach in the management of skull base chordomas—clinical experience on a large series, technique, outcome, and pitfalls. *Neurosurg Rev*. 2014;37(2):217-225. doi:10.1007/s10143-013-0503-9

5. Heros RC. Lateral suboccipital approach for vertebral and vertebrobasilar artery lesions. *Journal of Neurosurgery*. 1986;64(4):559-562. doi:10.3171/jns.1986.64.4.0559

6. George B, Dematons C, Cophignon J. Lateral approach to the anterior portion of the foramen magnum. *Surgical Neurology*. 1988;29(6):484-490. doi:10.1016/0090-3019(88)90145-0

7. Bruneau M, George B. Classification system of foramen magnum meningiomas. *J Craniovert Jun Spine*. 2010;1(1):10. doi:10.4103/0974-8237.65476

8. Doglietto F, Belotti F, Qiu J, et al. Endonasal and Transoral Approaches to the Craniovertebral Junction: A Quantitative Anatomical Study. In: Visocchi M, ed. *New Trends in Craniovertebral Junction Surgery*. Vol 125. Acta Neurochirurgica Supplement. Springer International Publishing; 2019:37-44. doi:10.1007/978-3-319-62515-7_6

9. Matsushima T, Natori Y, Katsuta T, Ikezaki K, Fukui M, Rhoton AL. Microsurgical Anatomy for Lateral Approaches to the Foramen Magnum with Special Reference to Transcondylar Fossa (Supracondylar Transjugular Tubercle) Approach. *Skull Base*. 1998;8(03):119-125. doi:10.1055/s-2008-1058570

10. Talacchi A, Biroli A, Soda C, Masotto B, Bricolo A. Surgical management of ventral and ventrolateral foramen magnum meningiomas: report on a 64-case series and review of the literature. *Neurosurg Rev*. 2012;35(3):359-368. doi:10.1007/s10143-012-0381-6

11. Chibbaro S, Signorelli F, Milani D, et al. Primary Endoscopic Endonasal Management of Giant Pituitary Adenomas: Outcome and Pitfalls from a Large Prospective Multicenter Experience. *Cancers*. 2021;13(14):3603. doi:10.3390/cancers13143603

12. Neligan PC, Mulholland S, Irish J, et al. Flap Selection in Cranial Base Reconstruction: *Plastic and Reconstructive Surgery*. 1996;98(7):1159-1166. doi:10.1097/00006534-199612000-00005

13. Fortes FSG, Carrau RL, Snyderman CH, et al. Transpterygoid Transposition of a Temporoparietal Fascia Flap: A New Method for Skull Base Reconstruction after Endoscopic Expanded Endonasal Approaches. *The Laryngoscope*. 2007;117(6):970-976. doi:10.1097/MLG.0b013e3180471482

14. La Corte E, Aldana PR, Ferroli P, et al. The rhinopalatine line as a reliable predictor of the inferior extent of endonasal odontoidectomies. *FOC*. 2015;38(4):E16. doi:10.3171/2015.1.FOCUS14777

15. Carrabba G, Dehdashti AR, Gentili F. Surgery for clival lesions: open resection versus the expanded endoscopic endonasal approach. *FOC*. 2008;25(6):E7. doi:10.3171/FOC.2008.25.12.E7

16. Chibbaro S, Ganau M, Cebula H, et al. The Endonasal Endoscopic Approach to Pathologies of the Anterior Craniocervical Junction: Analytical Review of Cases Treated at Four European Neurosurgical Centres. In: Visocchi M, ed. *New Trends in Craniovertebral Junction Surgery*. Vol 125. Acta Neurochirurgica Supplement. Springer International Publishing; 2019:187-195. doi:10.1007/978-3-319-62515-7_28

17. Cavallo LM, Cappabianca P, Messina A, et al. The extended endoscopic endonasal approach to the clivus and cranio-vertebral junction: anatomical study. *Childs Nerv Syst*. 2007;23(6):665-671. doi:10.1007/s00381-007-0332-7

18. d'Avella E, Angileri F, de Notaris M, et al. Extended endoscopic endonasal transclival approach to the ventrolateral brainstem and related cisternal spaces: anatomical study. *Neurosurg Rev*. 2014;37(2):253-260. doi:10.1007/s10143-014-0526-x

19. Morera VA, Fernandez-Miranda JC, Prevedello DM, et al. "Far-Medial" Expanded Endonasal Approach to the Inferior Third of the Clivus. *Operative Neurosurgery*. 2010;66(suppl_2):ons211-ons220. doi:10.1227/01.NEU.0000369926.01891.5D

20. Benet A, Prevedello DM, Carrau RL, et al. Comparative Analysis of the Transcranial “Far Lateral” and Endoscopic Endonasal “Far Medial” Approaches: Surgical Anatomy and Clinical Illustration. *World Neurosurgery*. 2014;81(2):385-396. doi:10.1016/j.wneu.2013.01.091

21. Fang CH, Friedman R, Schild SD, et al. Purely endoscopic endonasal surgery of the craniovertebral junction: A systematic review: Endonasal craniovertebral junction surgery. *International Forum of Allergy and Rhinology*. 2015;5(8):754-760. doi:10.1002/alr.21537

22. Wang M, Chae R, Joseph Shehata, et al. Comparative Analysis of the Subtonsillar, Far-Lateral, Extreme-Lateral, and Endoscopic Far-Medial Approaches to the Lower Clivus: An Anatomical Cadaver Study. *World Neurosurgery*. 2019;127:e1083-e1096. doi:10.1016/j.wneu.2019.04.048

23. Di G, Fang X, Hu Q, Zhou W, Jiang X. A Microanatomical Study of the Far Lateral Approach. *World Neurosurgery*. 2019;127:e932-e942. doi:10.1016/j.wneu.2019.04.004

24. Vishteh AG, Crawford NR, Melton MS, Spetzler RF, Sonntag VKH, Dickman CA. Stability of the craniovertebral junction after unilateral occipital condyle resection: a biomechanical study. *Journal of Neurosurgery: Spine*. 1999;90(1):91-98. doi:10.3171/spi.1999.90.1.0091

25. Pai SB, Raghuram G, Keshav GC, Rodrigues E. Far-lateral Transcondylar Approach to Anterior Foramen Magnum Lesions - Our Experience. *Asian J Neurosurg*. 2018;13(3):651-655. doi:10.4103/ajns.AJNS_273_16

26. Singh H, Harrop J, Schiffmacher P, Rosen M, Evans J. Ventral Surgical Approaches to Craniovertebral Junction Chordomas. *Neurosurgery*. 2010;66(suppl_3):A96-A103. doi:10.1227/01.NEU.0000365855.12257.D1

27. Chibbaro S, Cebula H, Aldea S, et al. Endonasal Endoscopic Odontoidectomy in Ventral Diseases of the Craniocervical Junction: Results of a Multicenter Experience. *World Neurosurgery*. 2017;106:382-393. doi:10.1016/j.wneu.2017.06.148

28. Jho HD, Ha HG. Endoscopic endonasal skull base surgery: Part 3--The clivus and posterior fossa. *Minim Invasive Neurosurg*. 2004;47(1):16-23. doi:10.1055/s-2004-818347

29. Kassam AB, Prevedello DM, Carrau RL, et al. Endoscopic endonasal skull base surgery: analysis of complications in the authors’ initial 800 patients: A review. *JNS*. 2011;114(6):1544-1568. doi:10.3171/2010.10.JNS09406