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Review Article

An investigation of craniocervical stability post-condylectomy

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ABSTRACT

Background: Occipital condylectomy is often necessary to gain surgical access to various neurological pathologies. As the lateral limit of the craniovertebral junction (CVJ), partial condylectomy can lead to iatrogenic craniocervical instability. What was once considered an inoperable location is now the target of various complex neurosurgical procedures such as tumor resection and aneurysm clipping.

Methods: In this study, we will review the anatomical structure of the CVJ and provide the first comprehensive assessment of studies investigating craniovertebral stability following condylectomy with the transcondylar surgical approaches. Furthermore, we discuss future considerations that must be evaluated to optimize the chances of preserving craniocervical stability postcondylectomy.

Results: The current findings postulate upward of 75% of the occipital condyle can be resected without significantly affecting mobility of the CVJ. The current findings have only examined overall dimensions and have not established a significant correlation into how the shape of the occipital condyles can affect mobility. Occipitocervical fusion should only be considered after 50% condyle resection. In terms of indicators of anatomical stability, components of range of motion (ROM) such as the neutral zone (NZ) and the elastic zone (EZ) have been discussed as potential measures of craniocervical mobility. These components differ by the sense that the NZ has little ligament tension, whereas the EZ does represent ROM where ligaments experience tension. NZ is a more sensitive indicator of instability when measuring for instability postcondylectomy.

Conclusion: Various transcondylar approaches have been developed to access this region including extreme-lateral and far-lateral condylectomy, with hopes of preserving as much of the condyle as possible and maintaining postoperative craniocervical stability.

Keywords: Biomechanics, Condylectomy, Craniocervical stability, Craniovertebral junction

INTRODUCTION

The craniovertebral junction (CVJ), separating the base of the skull from the subaxial cervical spine, has unique and complex bone structure and neurovascular architecture.[19,38] This structure houses vital neural, vascular, and lymphatic structures while allowing for special motion of cranial bones including flexion, extension, and axial rotations.[24,38] Osseous and ligamentous supports are responsible for maintaining stability of this junction while allowing for its unique range of motion (ROM).[38] CVJ stability is necessary to maintain adequate flow of cerebrospinal fluid, establish the appropriate "gaze angle," avoid dysphagia and dyspnea, and, most importantly, to prevent ventral brainstem compression by establishing an appropriate clival-axial angle.[12] CVJ instability can lead to complications such as vertebral artery compression, nerve compression, and obstructive hydrocephalus.[5] CVJ abnormalities can be congenital, developmental, secondary to an acquired disease process, or result from trauma or surgical procedures such as condylectomy.[5]

Despite the potential risk of iatrogenic CVJ instability, partial occipital condylectomy, or resection of a portion of the occipital condyle, is used in surgical procedures for the treatment of spasmodic torticollis,[10] vertebral and vertebrobasilar artery lesions,[13,36] and resection of adjacent tumors using far-lateral approaches (FLAs).[28,29] In this review, we will provide the first complete assessment of concerns for craniocervical instability after condylectomy or partial condylectomy.

DEFINING SURGICAL ANATOMY

Occipital condylectomy involves resection of the occipital condyle. The occipital condyles are two masses comprising the lateral limit of either side of the CVJ and the foramen magnum, while the medial tubercles of the condyles serve as an attachment point for the alar ligament.[25] The majority of condyles as assessed in 202 skulls by Naderi *et al*. were found to be ovular shaped (>50% as reported), however were also found to be shaped as "S-like," eight-like, triangle-like, ring-like, two-portioned, or deformed as well.[25] These masses articulate with the superior facets of C1 and range in length between 16.7 and 30.6 mm, in width between 6.5 and 15.8 mm, and in height between 5.8 and 18.2 mm as determined by anatomical imaging and measurement through Vernier caliper.[4,11,18,25,26] The dimensions of the occipital condyles have not been found to correlate with skull circumference or volume nor do they correlate with the size of the foramen magnum.[11,25] Both condyles are tunneled by the hypoglossal canal, allowing passage of the hypoglossal nerve through the skull to innervate the extrinsic and intrinsic muscles of the tongue.[25] The intracranial orifice of the hypoglossal canal is located medial to the occipital condyle while the extracranial orifice is laterally to the condyle. The placement of the orifices of the canal serves as landmarks for the FLA in condylectomy.[25,39]

Partial condylectomy is performed to access either intra- or extra-dural pathology positioned anterior or anterolateral to the cervicomedullary region or to treat cranial nerve compression.[28,37] In the pediatric population, partial condylectomy has been successfully utilized to treat spasmodic torticollis due to compression of the hypoglossal nerve.[10] In the adult population, partial condylectomy is mainly indicated to access aneurysms of the vertebral artery, vertebrobasilar junction, proximal artery, or posterior inferior cerebellar artery.[13,23,33,36] Further, partial condylectomy is indicated in accessing tumors of the foramen magnum and the clivus, as it has been found that the superomedial portion of the condyle can obstruct visualization of the clivus in particular.[17,29,37]

TRIALS AND OUTCOMES

Several studies have assessed the stability of the craniocervical region through various condylectomy approaches. While there has yet to be a predisposed algorithm for determining craniocervical stability following a condylectomy, several trials involving cadaveric specimens have found indications of CVJ stability based on kinematic and biomechanical analysis. In a study by Vishteh *et al*., the authors sought to determine the biomechanical stability of the occipitoatlantal occiput (Oc-C1) and atlantoaxial (C1-2) motion segments following a unilateral gradient condylectomy.[37] The authors performed several nondestructive biomechanical tests after the progressive unilateral condylectomy was performed using frameless stereotactic guidance.[37] The results showed that resection of 50% or more of the occipital condyle produced significantly enhanced hypermobility at Oc-C1 [Table 1].[7,14,17,28,37] After a 75% recession, the biomechanics of both the occipitoatlantal occiput and the atlantoaxial segments had drastically changed further.[37] In a further trial by Perez-Orribo *et al*., the authors sought to evaluate the stability of the craniocervical junction after anterior unilateral condylectomy through an endoscopic-endonasal approach.[28] This approach involves allowing the surgeon to navigate the front of the brain and top of the spine by operating through the nose using a thin tube to thread the inner nasal and inner cranial space. The study involved seven human cadavers who underwent nondestructive biomechanical flexibility maneuvers.[28] Results demonstrated that at C0-C1 mobility during flexion, extension, and axial rotation increased significantly postcondylectomy, with ROM increasing after 75% condyle resection.[28] Significance at C1-C2 was less apparent. This study ultimately indicated that variation in approaches can lead to an altered expression of the degree of condyle recession. Moreover, in a study by Kshettry *et al*., the CVJ was also evaluated only after a unilateral joint-sparing condylectomy with a far-lateral approach.[17] This approach required partial resection of the occipital condyle and differs from other studies through the incorporation of the robotic spine system.[17] The study performed *in vitro* flexibility tests using the KR16 robotic system on seven fresh cadaveric spines following unilateral join-sparing condylectomy.[17] This system applied a constant

Table 1: Summary of studies analyzing craniocervical stability after various condylectomy approaches.

Author	Major finding
Vishteh *et al.*,[37] 1999	Recession of 50% or more of the condyle produces significant hypermobility at Oc-C1 following a unilateral gradient condylectomy.
Perez-Orribo *et al.*,[28] 2013	ROM increased significantly after 75% condyle recession with the endoscopic endonasal approach.
Jian *et al.*,[14] 2015	OCF appears to increase stability of the CVJ after intramedullary tumor resection.
Kshettry *et al.*,[17] 2016	50% condyle recession did not significantly change ROM following a joint-sparing condylectomy.
Eli *et al.*,[7] 2019	Bilateral constructs provide greater stiffness than unilateral after a complete unilateral condylectomy.

ROM: Range of motion, OCF: Occipitocervical fusion, CVJ: Craniovertebral junction

40 Newton force for head weight simulation followed by three loading and unloading cycles for continuous movement to simulate flexion-extension, lateral bending, and axial rotation. The results were analyzed and compared findings to an intact state. The findings showed that only values at 100% condylectomy were statistically significant, while coupled motions were only statistically significant at 75% and 100% condyle recession.[17] This indicates that different cardinal motions at various condyle recessions provide different clinical outcomes. Furthermore, in a study by Eli *et al.*, posterior fixation constructs were evaluated on eight human cadaveric specimens to assess the progression of instability following a radical unilateral condylectomy.[7] Unilateral and bilateral fixation techniques were compared to determine the approach that provides greater biomechanical strength.[7] The results showed that the bilateral fixation constructs provided statistically greater stiffness at only certain planes of motions. The bilateral Oc-C2 construct was stiffer than the unilateral construct in axial rotation and lateral bending, with no difference in flexion extension.[7] The authors finally concluded that the bilateral construct provides superior stiffness compared to the unilateral construct. Finally, in a chart review study by Jiang *et al.*, the stability of the craniocervical junction was assessed following the occipitocervical fusion (OCF) after the resection of spinal extramedullary tumors in the CVJ.[14] The authors determined that a limited condylectomy, laminectomy, or facetectomy for recession of spinal cord tumors have a strong link to upper cervical instability.[14] The results included nine patients, with all patients improving after an OCF according to the Frankel grade classification. Therefore, the authors concluded that OCF following a tumor recession can potentially be a useful surgical procedure for preserving CVJ stability and preventing kyphosis of the upper cervical spine.[14] Further studies involving various pathologies and approaches are summarized with [Table 2].[1-3,8,9,15,16,20-22,27,29,31,32,34,35,39]

OPINIONS

The aftermath of the study from Vishteh *et al.* found that performing a fusion postcondylectomy of the occipitoatlantal motion segments should be considered only if half or more of the occipital condyle is resected.[37] However, the study by Perez-Orribo *et al.* quantified this indication as >75% while preforming the condylectomy with the endoscopic endonasal approach.[28] In the study by Kshettry *et al.*, the authors expressed that prior researchers concluded that OC fusion should only be considered after 50% condyle resection.[17] Therefore, they were weary to avoid iatrogenic stability, and so they conducted an OC joint-sparing procedure and hypothesized that this approach will add more stability compared to that of the previous studies. The authors suggested that using the joint-sparing technique can remove up to 75% of the condyle without resulting in significant biomechanical instability. Through this greater degree of condyle recession, their conclusions differ from that of prior studies. In summary, these three studies suggest that depending on the condylectomy approach, the degrees of recession that accomplishes craniocervical stability can be expressed differently. These findings also present the basis of a potential predictive model of determining what degree of recession is needed to achieve stability based on the approach conducted. In terms of indicators of anatomical stability, components of ROM such as the neutral zone (NZ) and the elastic zone (EZ) have been discussed as potential measures of craniocervical mobility.[37] These components differ by the sense that the NZ has little ligament tension, whereas the EZ does represent ROM where ligaments experience tension.[37] Researchers have determined that the NZ is a more sensitive indicator of instability when measuring for instability postcondylectomy.[37] However, the EZ has also been discussed as a potential reliable measure as results show that both the EZ and NZ show superior inter specimen variability than traditional ROM results.[37] Therefore, further studies validating these findings are warranted. In terms of the methodology of studies assessing craniocervical stability after a condylectomy, authors have suggested different limitations. These limitations include that cadaveric studies only test for acute instability and cannot access the repeated cyclical loading and unloading that contribute to chronic instability. In addition, the fact that resection percentages do not represent the true volumetric percentage resection of the condyle is also discussed as a limiting factor to these studies.[17] Moreover, in the study by Eli

Table 2: Studies assessing condylar resection and extent of resection.

Author and year	**Total patients in study**	**Patients undergoing condylar resection**	**Pathology**	**Vertebral artery encasement by lesion (% cases)**	**Surgical approach**	**Extent of condylar resection**	**Instability (%)**
Sekhar *et al*.,[32] 1990	5	5	Foramen Magnum Meningioma	–	EL	One-third or half	0
Kratimenos and Crockard,[15] 1993	8	8	Foramen Magnum Meningioma	–	FL	One-third	0
Sekhar *et al*.,[31] 1994	9	9	Foramen Magnum Meningioma		EL	One-third or half	0
Bertalanffy *et al*.,[2] 1996	19	19	Foramen Magnum Meningioma	–	FL, SO TC	One-third	0
Samii *et al*.,[30] 1996	38	6	Foramen Magnum Meningioma	40%	PM, LSO	One-third	0
George *et al*.,[8] 1997	40	40	Foramen Magnum Meningioma	38%	FL	Partial	0
Pirotte *et al*.,[29] 1998	6	6	Foramen Magnum Meningioma	–	FL	One-third or half	0
Arnautovic *et al*.,[1] 2000	18	18	Foramen Magnum Meningioma	–	TC	One-third or half	0
Goel *et al*.,[9] 2001	17	2	Foramen Magnum Meningioma	59%	SO	One-third or one-fourth	0
Sanabria *et al*.,[22] 2002	7	2	Foramen Magnum Meningioma		TO, SO, TC	One-third or half	0
Margalit *et al*.,[21] 2005	42	28	Meningioma (18), chordoma (12), glomus tumor (3), schwannoma (3), adenoid cystic carcinoma (1), chondrosarcoma (1), epidermoid cyst (1), metastatic thyroid carcinoma (1), neuroenteric cyst (1), pituitary adenoma (1)		Lat	12 complete (all underwent fusion), 16 partial (one underwent fusion)	1
Shin *et al*.,[34] 2006	46	28	Meningioma (16), chordoma (17), Schwann cell tumor (2), glomus tumor (2), metastasis (3), synovial carcinoma (1), chondrosarcoma (1), non-Hodgkin lymphoma (1), recurrent ACTH-secreting Carc (1), mucoepidermoid carcinoma (1), hemangioblastoma (1)		FL	8<30%, 150%, 15>70%, and 4 bilateral 50%	0

(Contd...)

Table 2: *(Continued).*

Author and year	Total patients in study	Patients undergoing condylar resection	Pathology	Vertebral artery encasement by lesion (% cases)	Surgical approach	Extent of condylar resection	Instability (%)
Kryzanski *et al.*,[16] 2014	13	13	10 meningioma, 1 brainstem GBM, 1 PICA aneurysm, 1 odontoid pannus	0%	FL	One-third	0
Pai *et al.*,[27] 2018	8	8	3 epidermoid, 2 meningioma, 2 vertebral artery aneurysm, 1 clival chordoma		FL	One-third	0
Magill *et al.*,[20] 2019	28	28	Meningioma	36%	FL (78.6%, n=22), SO (21.4%, n=6)	One-third	0
Bilgin *et al.*,[3] 2019	11	11	Meningioma		SO (7), FL (4)	One-third	0
Srinivas *et al.*,[35] 2019	20	14	Meningioma	55%	FL	One-third	0
Total	335	245					

et al., despite the authors finding that bilateral constructs provide greater biomechanical strength, it was determined that the implementation of these constructs should only be considered through a case-by-case assessment.[7] The unilateral construct was found to decrease abnormal motions at the expense of being less stiff, therefore, its usage may be appropriate for procedures such as a temporary internal stabilization.[7]

As previously mentioned, many of these studies are limited by having to mimic spinal loading and cardinal motions on cadavers, having small sample sizes, and comparing different approaches to one another. This makes the assessment of CVJ instability challenging for spine and skull base surgeons alike. In addition, there has yet to be a consensus on the ideal treatment of craniocervical stability [Table 3].[6] Nevertheless, the findings of these cadaveric studies can formulate a criteria that may be used to assess craniocervical instability, while also creating a predictive model in determining what degree of condyle recession can be performed to preserve the stability of the CVJ junction.

FUTURE CONSIDERATIONS

In light of advances in approach to condylectomy, it is imperative future research continues to establish the extent of resection in condylectomy on craniovertebral hypermobility. The current findings postulate upward of 75% of the occipital condyle can be resected without significantly affecting mobility of the CVJ. However, there is still a lack of research exploring how the shape of the resected condyle may affect stability, as the current findings have only examined overall dimensions and not established a significant correlation into how the shape of the occipital condyles can affect mobility.

Table 3: Opinions regarding craniocervical instability based on resection studies.

Author	Opinion
Vishteh *et al.*,[37] 1999 Perez-Orribo *et al.*,[28] 2013 Kshettry *et al.*,[17] 2016	• The degree of condyle resection in maintaining craniocervical stability can be dependent on the condylectomy approach.
Vishteh *et al.*,[37] 1999 Kshettry *et al.*,[17] 2016	• The elastic zone and neutral zone are both accurate assessors of segmental instability. • Cadaveric models have limited testing for craniocervical instability. • Resection percentages may not represent the true volumetric percentage resection of the condyle. • There is a need for comparison trials that compare the same condylectomy approach rather than dissimilar approaches.
Eli *et al.*,[7] 2019	• Unilateral and bilateral constructs can have clinical value in providing biomechanical strength after a condylectomy.
Choi *et al.*,[6] 2013	• There is yet to be a consensus on the ideal treatment for craniocervical stability.

Further, it will be helpful to examine long-term changes in craniovertebral stability following condylectomy as the majority of tests examining ROM utilized cadaveric samples in the acute setting to establish a relative ROM, however, this may not be the most accurate representation of a patient population that is capable of recovery and physical therapy following a condylectomy procedure.

CONCLUSION

Condylectomy will continue to be performed to expose the surgical window necessary for various neurosurgical procedures. When condylectomy is performed, surgical approach must be considered as similar magnitude of condylar resection may lead to varying degrees of craniocervical stability depending on the approach used. Furthermore, each individual patient's pre- and post-operative soft-tissue stability must be taken into consideration when estimating the degree of condylar resection that will allow for preserved postoperative stability. When CVJ stability is iatrogenically compromised, occipitocervical fusion may be a useful means of restoring stability. Future studies comparing the various condylectomy approaches and the degree to which condylar resection may be performed while simultaneously maintain postoperative craniocervical stability are necessary to establish more definitive surgical recommendations.

Declaration of patient consent

Patient's consent not required as there are no patients in this study.

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Conflicts of interest

There are no conflicts of interest.

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