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Original Article

Craniovertebral junction 360°: A combined microscopic and endoscopic anatomical study

ABSTRACT

Objectives: Craniovertebral junction (CVJ) can be approached from various corridors depending on the location and extent of disease. A three-dimensional understanding of anatomy of CVJ is paramount for safe surgery in this region. Aim of this cadaveric study is to elucidate combined microscopic and endoscopic anatomy of critical neurovascular structures in this area in relation to bony and muscular landmarks.

Materials and Methods: Eight fresh-frozen cadaveric heads injected with color silicon were used for this study. A stepwise dissection was done from anterior, posterior, and lateral sides with reference to bony and muscular landmarks. Anterior approach was done endonasal endoscopically. Posterior and lateral approaches were done with a microscope. In two specimens, both anterior and posterior approaches were done to delineate the course of vertebral artery and lower cranial nerves from ventral and dorsal aspects.

Results: CVJ can be accessed through three corridors, namely, anterior, posterior, and lateral. Access to clivus, foreman magnum, occipital cervical joint, odontoid, and atlantoaxial joint was studied anteriorly with an endoscope. Superior and inferior clival lines, supracondylar groove, hypoglossal canal, arch of atlas and body of axis, and occipitocervical joint act as useful bony landmarks whereas longus capitis and rectus capitis anterior are related muscles to this approach. In posterior approach, spinous process of axis, arch of atlas, C2 ganglion, and transverse process of atlas and axis are bony landmarks. Rectus capitis posterior major, superior oblique, inferior oblique, and rectus capitis lateralis (RCLa) are muscles related to this approach. Occipital condyles, transverse process of atlas, and jugular tubercle are main bony landmarks in lateral corridor whereas RCLa and posterior belly of digastric muscle are the main muscular landmarks.

Conclusion: With advances in endoscopic and microscopic techniques, access to lesions and bony anomalies around CVJ is becoming easier and straightforward. A combination of microscopic and endoscopic techniques is more useful to understand this anatomy and may aid in the development of future combined approaches.

Key words: Craniovertebral junction; endoscopic endonasal; rectus capitis lateralis; vertebral artery.

Introduction

Craniovertebral junction (CVJ) is osteoligamentous membranous complex formed around the transition zone of neuraxis between brain and spinal cord. Layers of muscles, ligaments, and membranes support bony complex of occiput, atlas, and axis from all around which helps in adding mobility as well as stability to this critical area. Major neurovascular structures are intimately related to this area of transition where they transverse membranous and bony orifices. CVJ can be affected by congenital, developmental, degenerative,

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traumatic, and neoplastic pathologies. To manage these pathologies, various approaches have been described in literature.[1-9] With recent advances in endoscopic technology, there is renewed interest in direct anterior approach to ventrally located pathologies.[4,10-12] There are many recent cadaveric and surgical studies validating the feasibility of endoscopic approaches.[11-17] However, all these studies describe this anatomy in isolation either endoscopic or microscopic. Being a complex area circumventing 360° with multiple joints, a three-dimensional (3D) understanding of this anatomy is crucial for safe surgeries in this region. In the present anatomical study, we have described the relation of critical neurovascular structures such as vertebral artery (VA) and lower cranial nerves in relation to various bony and muscular landmarks from anterior, posterior, and lateral corridors.

Materials and Methods

Eight cadaveric specimens were prepared for dissection at the neuroanatomical laboratory of the Neurosurgical Department at the University of Pittsburgh School of Medicine. The common carotid arteries, VAs, and internal jugular veins (IJV) were isolated, cannulated with flexible tubing, and dyed with red or blue water-soluble pigments using previously described methods.[18] Cadaver heads in which the vessels were injected with colored silicone were dissected using ×2.5 to ×10 magnification of a surgical microscope (Carl Zeiss AG, Oberkochen, Germany), and 4 mm, 0° and 45° angle, 18 cm Hopkins endoscopes (Karl Storz GmbH and Co. KG, Tuttlingen, Germany), attached to a xenon light source (Xenon Nova 175, 20131520; Karl Storz GmbH and Co. KG, Tuttlingen, Germany), a high-definition camera (model 22220150; Karl Storz GmbH and Co. KG, Tuttlingen, Germany), an electric drill (Stryker GmbH and Co. KG, USA), and standard microsurgical instruments. Images were acquired using a Canon T4i DSLR camera (Canon Corp., Tokyo, Japan).

Results

The anatomic approaches in this study were divided into three corridors: Anterior, posterior, and lateral. Anterior dissection was predominantly carried out by endoscope whereas posterior and lateral corridors were mainly studied by microscopic approach.

Anterior corridor

Craniovertebral junction

Anterior approach to ventral CVJ and brainstem is a direct approach without traversing critical neurovascular structures. Anterior access is a direct approach to clivus, foramen magnum, occipitocervical joint (OC1), anterior arch of atlas, and odontoid process of axis [Figure 1]. Anterior corridor was studied by endonasal endoscopic technique. It was divided into four stages: nasopharyngeal, muscular, osteoligamentous, and intradural. Standard endoscopic endonasal approaches to CVJ require creating a more wide surgical corridor. Removing middle turbinate from one side and lateralizing on the other side can create this. Access to foramen magnum and CVJ requires low trajectory compared to sellar approaches [Figure 2]. Posterior nasal septum, inferior sphenoid wall, and vomer are removed to reach rhinopharyngeal part of clivus. Bone over clivus and carotid protuberance is drilled and removed depending on the level of exposure [Figure 2a]. Lateral limit of exposure is carotid protuberance, foramen lacerum, vidian canal, and eustachian tube (ET) from upward below [Figure 2a]. Nasopharyngeal mucosa is removed, widely exposing the underlying basipharyngeal fascia and median raphe covering prevertebral muscles [Figure 2b and c]. Two muscles cover this area anterior to foramen magnum and extend from clivus downward: Longus capitis and rectus capitis anterior (RCpA). More medial is longus capitis which extends as four tendinous slips from anterior tubercles of transverse processes of III, IV, V, and VI cervical vertebrae and ascend upward to get attached to clivus between the superior and inferior clival lines [Figure 2d]. Longus capitis is removed and has multiple bellies [Figure 2e]. Atlanto-occipital membrane (AOM) is a broad, dense fibrous structure that extends from the anterior edge of the foramen magnum to the superior edge of the anterior arch of the atlas [Figure 2f]. Median raphe is a thick band of connective tissue, which is attached to pharyngeal tubercle in the midline at clivus and continues below as anterior longitudinal ligament [Figure 2f]. RCpA is another short muscle immediately behind longus capitis arising from the anterior surface of the lateral mass and root of transverse process of atlas, passing obliquely upward to be inserted between inferior clival line and foramen magnum in supracondylar groove [Figure 2g and h]. These muscles create two well-defined lines of attachment on the ventral surface of the lower clivus, namely superior clival line (for the longus capitis) and the inferior clival line (for the RCpA) [Figures 1c and 2h].[12] This is comparable to the attachment of the neck muscles on the dorsal surface of the occipital squama, where they create the superior (for the splenius capitis and sternocleidomastoid) and inferior (for the semispinalis) nuchal or occipital lines [Figure 1a and b].[12] Importantly, the inferior clival line or supracondylar groove provides a reliable landmark for estimating the position of the hypoglossal canal and its external orifice, which are situated just posterior and lateral to the groove, respectively [Figures 1h and 2h].[12,16] AOM and anterior median raphe are removed to expose foramen magnum, OC1 joint, and anterior

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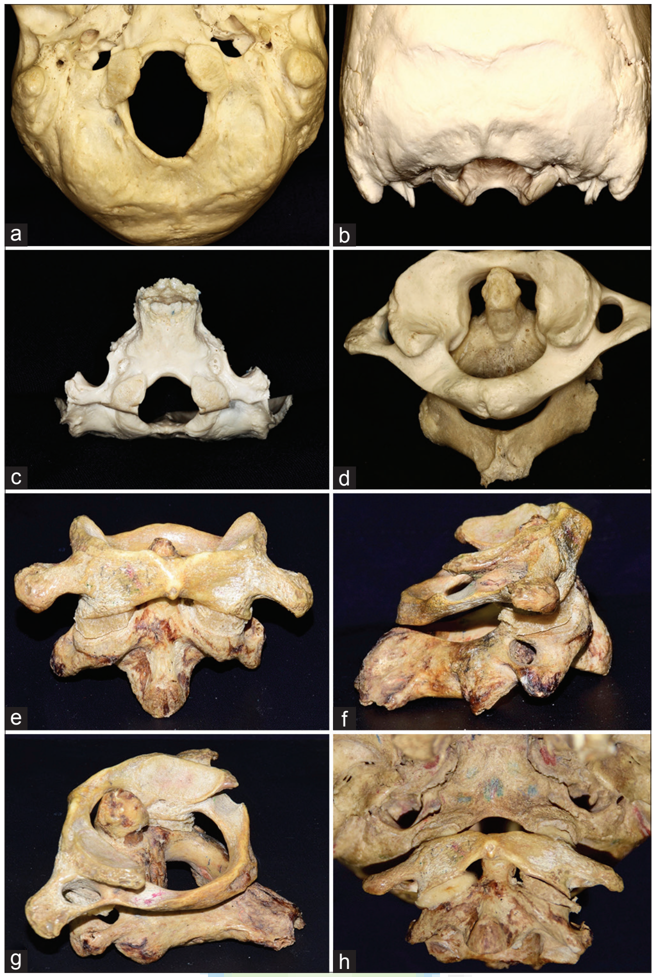

Figure 1: Osseous anatomy of craniovertebral junction. (a) Inferior view of the occipital condyles, foramen magnum, and clivus. The occipital condyles are ovoid structures located along the lateral margin of the anterior half of the foramen magnum. Their articular surfaces are convex, face downward and laterally, and articulate with the superior facet of atlas. The condylar fossa behind occipital condyle is frequently the site of a canal called condylar canal. The jugular process of the occipital bone extends laterally from the posterior half of the occipital condyle to form the posterior margin of the jugular foramen. The stylomastoid foramen is situated lateral to the jugular foramen. The styloid process is located anterior and slightly medial to the stylomastoid foramen. (b) Posterior, external view of foramen magnum and occipital bone. The convex external surface of the squamosal part of occipital bone has several prominences. The largest prominence, the external occipital protuberance, is situated at the central part of the external surface. The superior nuchal line radiates laterally from the protuberance. A vertical ridge, the external occipital crest, descends from the external occipital protuberance to the midpoint of the posterior margin of the foramen magnum. The inferior nuchal lines run laterally on both sides from the midpoint of the crest. Mastoids are visible laterally with grooves from muscle attachments. Styloid processes can be seen directed medially and anteriorly. Occipital condyles can be seen directed downward and laterally. (c) Anterior view of ventral occipital bone. The basilar part of the occipital bone, which is also referred to as the clivus, is a thick quadrangular plate of bone that extends forward and upward to join the sphenoid bone just below the dorsum sella. On the inferior surface of the basilar part, a small elevation, the pharyngeal tubercle, gives attachment to the fibrous raphe of the pharynx. The clivus is the place of attachment of longus capitis and the rectus capitis anterior. These muscles create well-defined lines of attachment on the ventral surface of the clival bone, superior clival line (for the longus capitis), and inferior clival line (for the rectus capitis anterior). Note that the inferior clival line is located at the same level of the external orifice of the hypoglossal canal. Occipital condyles can be seen here as oval, convex downward, face downward and laterally, and have their long axes directed forward and medially. (d) Superior oblique view of atlas and axis vertebra. Atlas is the first cervical vertebra with two lateral masses formed by superior and inferior articular facets, which are connected in front by a short anterior arch and behind by a longer curved posterior arch. The upper surface of each lateral mass has an oval concave facet that faces upward and medially and articulates with the occipital condyle. The medial aspect of each lateral mass has a small tubercle for the attachment of the transverse ligament of the atlas. The transverse process projects from the lateral masses. (e) Anterior view of atlas and axis vertebra. The anterior arch of atlas has a well-defined tubercle in midline for attachment of longus coli and anterior longitudinal ligament. Axis has a body, which is distinguished by odontoid process. The odontoid and body are flanked by a pair of large oval facets that extend laterally from the body onto the adjoining parts of the pedicles and articulate with the inferior facets of the atlas. The superior facets of axis are anterior to the inferior facets. (f) Lateral view of atlas and axis vertebra. Transverse foramen of axis faces superolaterally, thus permitting the lateral deviation of the vertebral artery as it passes up to the more widely separated transverse foramina in the atlas. The inferior articular facets are situated at the junction of the pedicles and lamina and face downward and forward. (g) Superolateral oblique view showing position of dens in relation to superior articular facets of atlas. (h) Anterior view of ventral aspect of clivus, foramen magnum, atlas, and axis. The clivus is separated on each side from the petrous part of the temporal bone by the petroclival fissure that extends from foramen lacerum to jugular foramen. The atlanto-occipital joints are seen here in the anterior aspect of foramen magnum. Tip of odontoid process lies roughly at the level of atlanto-occipital joints

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Figure 2: Stepwise extended endonasal endoscopic approach to foramen magnum and craniovertebral junction. (a) Sphenoid stage of dissection has been completed. Right side infratemporal fossa has been dissected showing path of eustachian tube and branches of mandibular nerve in depth. On the left side, posterior wall of maxillary sinus in front of infratemporal fossa is still visible. (b) View of mucosa of rhino pharynx with eustachian tubes as lateral limits of this exposure. (c) Nasopharyngeal mucosa has been removed exposing basipharyngeal fascia overlying longus capitis muscle and median raphe attached to pharyngeal tubercle in midline. (d) Longus capitis muscle can be seen after the removal of fascia. It is attached lateral to pharyngeal tubercle along superior clival line. (e) Longus capitis muscle has multiple bellies and it is attached in layers to clivus as can be seen after partial removal from the right side. (f) On both sides, longus capitis is removed exposing median raphe part of anterior longitudinal ligament attached to pharyngeal tubercle and laterally forming thick, broad membrane called anterior atlanto-occipital membrane. (g) Both longus capitis and anterior atlanto-occipital membrane have been removed exposing anterior longitudinal ligament in midline and atlanto-occipital joint. Rectus capitis anterior muscle can be seen laterally attaching along clivus from inferior clival line to foramen magnum. (h) Anterior longitudinal ligament and rectus capitis anterior muscle are also removed here exposing foramen magnum and arch of C1 with both atlanto-occipital joints. Gap between C1 arch and foramen magnum is filled with dense connective tissue, which also encloses apical and alar ligaments attached to the dens of C2. Pharyngeal tubercle can be seen here. (i) Another specimen showing foramen magnum after the removal of anterior longitudinal ligament and anterior atlanto-occipital membrane. Supracondylar groove can be identified laterally with rectus capitis anterior (j) clivus after the removal of muscles with superior and inferior clival lines. Inferior clival line corresponds to supracondylar groove laterally. Anterior arch of C1 partially removed, thus exposing odontoid process. (k) Alar ligaments, which are thick, fibrous bands that attach to the posterolateral roughened surface of the odontoid and ascend obliquely lateral to attach the alar tubercles located on the medial side of occipital condyles. Odontoidectomy begins with drilling of central core as seen here. (l) Once dens is removed, transverse ligament can be seen as extending between transverse tubercles on the medial side of C1 lateral masses. Vertical part of cruciform ligament can be seen extending from transverse ligament to foramen magnum. (m) In few specimens, another transverse band of ligament may be present just above the transverse ligament attached to the medial side of occipital condyles and it is called transverse occipital ligament. Transverse ligament is broad in middle and tapered laterally. (n) Intradural exposure of vertebrobasilar complex with cranial nerves. Internal carotid artery can be seen on both sides from carotid canal up to intradural segment. Cervicomedullary junction can be seen which is demarcated by ventral rootlets of C1 nerve. AOM, atlanto-occipital membrane; ET, eustachian tube; FL, foramen lacerum; ICA, internal carotid artery; Inf cli line, inferior clival line; OC1, occipitocervical joint; postwall maxilla, posterior wall of maxilla; RCpA, rectus capitis anterior; SuCG, supracondylar groove; Sup cli line, superior clival line; Trans lig, transverse ligament; Trans occi lig, transverse occipital ligament

arch of atlas [Figure 2h]. Space between foramen magnum and anterior arch of atlas is filled with dens connective tissue and contains apical ligament and alar ligaments [Figure 2i]. Anterior arch of atlas is removed partially to expose odontoid process with attached ligaments [Figure 2j]. The atlas has two lateral masses connected by anteriorly convex, anterior arch having a midline anterior tubercle and by a posterior surface that articulates with the anterior surface of the odontoid process [Figure 1d and e]. The alar ligaments are thick fibrous bands that arise from the posterolateral roughened surface of the odontoid and ascend obliquely, laterally, and superiorly toward the alar tubercle on the medial side of the occipital condyles [Figure 2k]. The apical ligament of the dens has a broad cartilaginous base that

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arises on the apex of the dens and extends to the anterior border of foramen magnum [Figure 2h]. Posterior surface of dens also has a posterior facet that articulates with the cartilaginous facet on the anterior surface of the cruciform ligament.[19] The anterior cortical surface and core of the dens are drilled, leaving only a thin shell of bone, which can be removed with rongeurs [Figure 2k]. It is not always possible to remove the base of the dens with this approach. Removal of dens exposes thick, white, strong band called transverse ligament, which arches posterior to dens and holds it in position [Figure 2l]. It extends from tubercles on the medial side of the lateral masses of atlas. This ligament is usually broad in middle and taper laterally [Figure 2m]. Transverse ligament is the horizontal part of cruciform ligament which has two upper and lower vertical bands. The upper vertical band of the cruciform ligament arises from the median part of the superior edge of the transverse band and ascends between the tectorial membrane and the apical ligament to insert on the intracranial surface of the clivus. The lower vertical band descends from the lower margin of the transverse ligament and inserts on the posterior surface of the body of the axis [Figure 2l].[17,19] Approximately, 8%–20% of CVJs another transverse band of ligament maybe present just above the transverse ligament attached to the medial side of occipital condyles and it is called transverse occipital ligament [Figure 2m].[17,19] This can sometimes be confused with transverse ligament. The tectorial membrane, a broad fibrous band that spans the area between the medial edges of the occipital condyles, is a rostral extension of the posterior longitudinal ligament that attaches to the axis inferiorly and the clivus superiorly. It is separated from dura by epidural venous plexus. Once dura is opened, the junction of spinal canal with medulla is exposed, which is defined as being at the level of origin of C1 ventral roots [Figure 2n]. The initial intradural segment of VA is also exposed along with its relation to XII nerve rootlets as they arise from preolivary sulcus of medulla. Both VA join to form basilar artery close to pontomedullary junction and can be visualized.

Clivus and foramen magnum

Clivus is thick central portion of bone formed by synchondrosis of basisphenoid and occipital bone and extend from dorsum sella to foramen magnum [Figure 1c and h]. On sides, it is separated from petrous part of temporal bone by petroclival fissure that extend from foramen lacerum to jugular foramen [Figure 1h].

Clivus is divided into three parts: Superior, middle, and inferior. The superior portion is located above the level of the sellar floor; the middle portion extends from the sellar level to the level of sphenoid floor; and the inferior portion from the sphenoid floor to the foramen magnum.[20] Grossly, the petroclival fissure that extends from the foramen lacerum to the jugular foramen borders the clivus laterally.[20] According to the level of clivus, various areas of posterior fossa can be accessed. ET, foramen lacerum, and paraclival internal carotid artery (ICA) limit lateral extent of exposure in this approach from below upward [Figure 3a]. Basilar venous plexus extends variably between the layers of dura and can be a source of bleeding during drilling of clivus. Dura covering clivus is supplied by dorsal clival artery, which is the branch of meningohypophyseal trunk arising from cavernous ICA [Figure 3b]. This artery also gives branch to interdural segment of VI nerve and forms arterial network with branch from opposite side. This artery can be the source of blood supply to meningiomas and other extradural lesions arising in this area. One needs to be careful about trajectory of VI nerve in the upper clivus which takes acute course to enter cavernous sinus; this segment lies medial to paraclival ICA and it is prone to injury while approaching lesions around petrous apex [Figure 3b]. More lateral exposure can be obtained in the middle inferior clivus by removing bone posteromedial to paraclival ICA and inferior to laceral ICA [Figure 3b]. The flocculus and the choroid plexus protruding from the foramen of Luschka behind the rootlets of the IX and X nerves and the VII, VIII nerve complex arising from the brainstem anterosuperior to the foramen of Luschka may be seen in the transnasal exposure [Figure 3c].[16,17] Transclival exposure gives a direct access to anterior brainstem extending from midbrain to cervicomedullary junction [Figure 3c-e]. Upper clivus dura can be opened to expose the upper pons, basilar artery, VI, V, and III nerves, superior cerebellar and posterior cerebral arteries, and the basilar apex [Figure 3c and d]. The lateral limits of this exposure are the paraclival ICAs and the inferior petrosal sinuses.[15] Drilling the bone around the carotid artery allows the artery to be retracted to expose cranial nerves VII and VIII, the medial surface of the Mackle's cave, and the anteromedial part of the cavernous sinus. Opening the lower clival dura exposes the VAs and their dural entry, proximal segments of the posterior inferior cerebellar arteries (PICAs), median anterior medullary vein, cranial nerves IX-XII, olives, and medullary pyramids [Figure 3d-f].[15-17] Access to jugular fossa is blocked in front by parapharyngeal ICA and can be accessed in case where medially placed lesion displaces the ICA laterally [Figure 3f].

Posterior corridor

Posterior corridor is a direct gateway to dorsal brainstem, cerebellum, foramen magnum, OC1, and atlantoaxial joint. Posterior corridor was studied microscopically and then it was compared with endoscopic anterior corridor to get a 3D view of critical neurovascular anatomy. This corridor was

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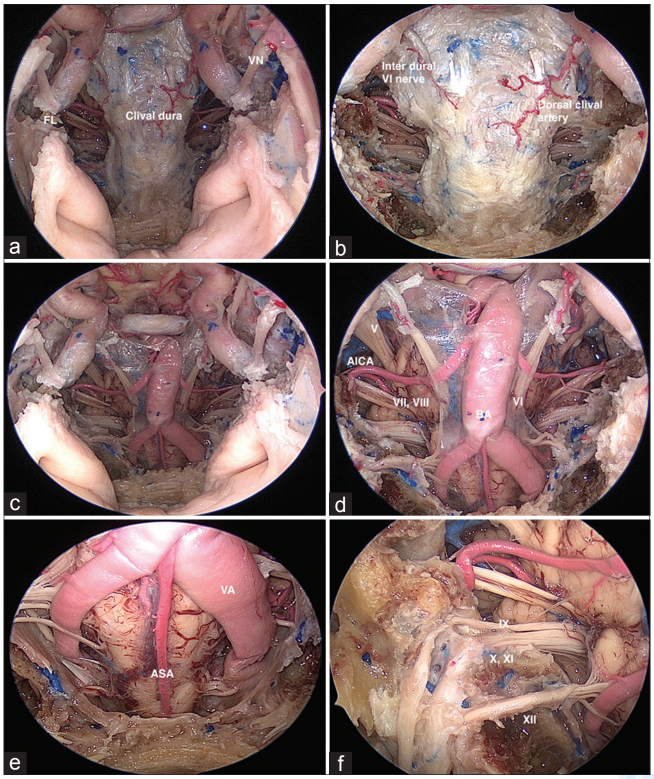

Figure 3: Intradural exposure of clivus and foramen magnum area. (a) Nasal, sphenoid, and clival stages of dissection have been completed. Bone from posterior clinoid to foramen magnum and anterior arch of C1 and dens has been removed exposing clival dura and transverse ligament. Petrous apex has also been drilled exposing the laceral segment of internal carotid artery. Some parts of lateral dura have been opened exposing cranial nerves. Paraclival internal carotid artery is seen on both sides. Vidian nerve is visible on both sides extending from inferolateral aspect of laceral segment of internal carotid artery to sphenopalatine ganglion. Both side eustachian tubes are visible in the inferior part of exposure. (b) Clival dura showing VI nerve passing into cavernous sinus on both sides. On the left side, dorsal clival artery branch of cavernous internal carotid artery can be seen extending along clival dura and giving blood supply to VI nerve. (c) Clival dura is opened leaving behind the layer of arachnoid. Vertebrobasilar junction is visible with the origin of anterior spinal artery. Anterior inferior cerebellar artery is seen arising from basilar artery and passing toward internal acoustic meatus. Cranial nerves from V to XII can be seen arising from brainstem. (d) Close-up view of the origin of cranial nerves. Both VI nerves have medial origin from pontomedullary junction with more angular inclining course. V nerve has more lateral origin and course. VII and VIII nerves can be seen passing into internal acoustic meatus with the loop of anterior inferior cerebellar artery. (e) Close-up view of cervicomedullary junction showing intradural entry of vertebral artery and origin of anterior spinal artery. Rootlets of XII nerve can be seen arising in relation to vertebral artery. Ventral rootlets of the first cervical nerve can be seen arising from the upper cervical cord just in front of dentate ligament. (f) Dissection of jugular foramen and hypoglossal canal. In the upper part, internal acoustic meatus is visible with anterior inferior cerebellar artery. Jugular foramen is opened and venous injection is removed showing IX nerve passing superiorly in a separate subcanal. X and XI cranial nerves can be seen traveling together just below IX nerve. XII nerve can be seen extending from brainstem through hypoglossal canal. AICA, anterior inferior cerebellar artery; ASA, anterior spinal artery; BA, basilar artery; FL, foramen lacerum; VA, vertebral artery; VN, vidian nerve

studied in three stages: Muscular, extradural, and intradural. Key landmarks and important relationships of muscles and vascular structures were identified in relation to bony landmarks.

Muscular stage

To get a wide view of all the deep structures, large skin flap was removed extending from both sides of the neck up to the vertex [Figure 4a]. Muscles of posterior compartment of neck can be divided into three layers, namely, superficial, intermediate, and deep.[2,3,21,22] Superficial layer is mainly formed by trapezius and sternocleidomastoid, taking origin along superior nuchal line running lateral from external occipital protuberance [Figure 1b]. Intermediate layer is formed by semispinalis capitis medially and splenius capitis laterally [Figure 4b]. Semispinalis capitis is broad, fleshy muscle arising from multiple tendons from the tips of the transverse processes of the upper six or seven thoracic and the VII cervical vertebrae, from the articular processes of the three cervical vertebrae above this (C4–C6), and it is inserted between the superior and inferior nuchal lines of the occipital bone [Figure 4b and c]. Splenius capitis is broad, flat muscle present deep to sternocleidomastoid and inserted along mastoid process of the temporal bone and into the rough surface on the occipital bone just below the lateral third of the superior nuchal line. The muscles of deep layer occupying occipito-atlantal space create suboccipital triangle [Figure 4c and d]. The suboccipital triangle is limited by three muscles; above and medially by the rectus capitis posterior major; above and laterally by the superior oblique; and below and laterally by the inferior oblique. A layer of dense fibrofatty tissue covers the triangle deep to these muscles. The floor of triangle is formed by the posterior AOM and the posterior arch of the atlas [Figure 4d]. The structures in the triangle are the VA with its muscular and meningeal branches and the C1 nerve, both of which lie in a groove on the upper surface of the lateral part of the posterior arch of the atlas. This groove can be converted into arch or tunnel depending on the ossification of arch of atlas [Figure 4d and e]. There is rich venous plexus around VA, which can have variable communications with other venous spaces and venous sinuses around jugular foramen, foramen magnum, and sigmoid sinus.[21,22] The atlantoaxial region has inferior oblique muscle superiorly and semispinalis and splenius cervicalis inferiorly and medially, respectively [Figure 4d]. Fibrofatty tissue and rich venous plexus around the vertical segment of VA again fill this area. Another major landmark in this area is thick C2 ganglion, which is intimately related to atlantoaxial joint [Figure 4f and g].[22] The dorsal ramus of C2 gives rise to the greater occipital nerve, which passes through the semispinalis capitis to reach the posterior scalp.

Extradural stage

The muscles forming the margins of the suboccipital triangle are removed to expose the VA ascending through the transverse process of atlas and behind the OC1 joint and the

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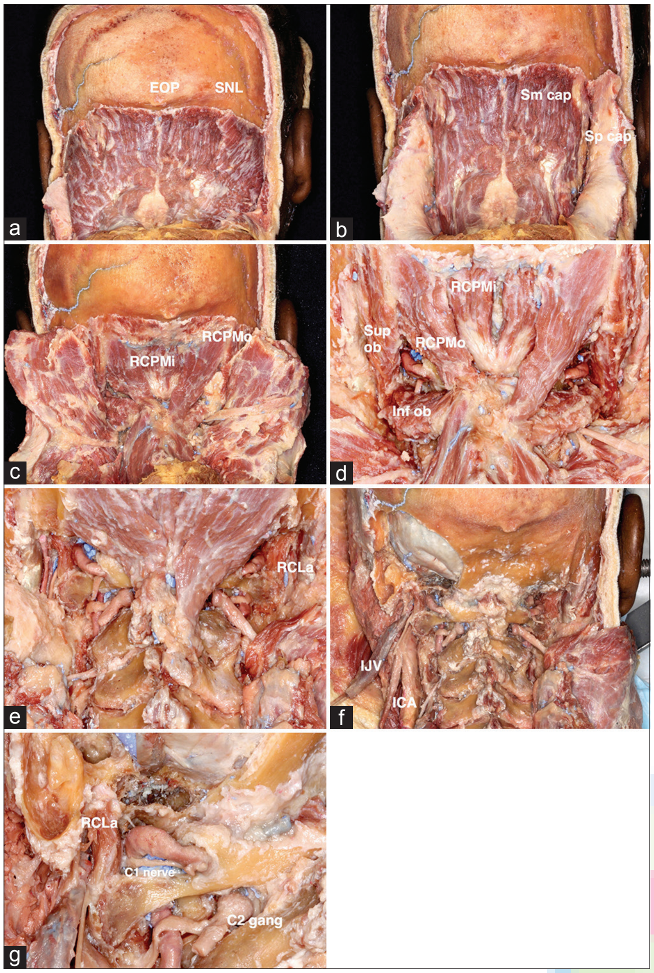

Figure 4: Stepwise dissection of posterior approach to craniovertebral junction, foramen magnum, and jugular foramen. (a) Skin subcutaneous tissue and trapezius have been removed to show splenius capitis laterally and semispinalis capitis medially. Superior nuchal line can be seen extending laterally from the external occipital protuberance. (b) Splenius capitis is reflected laterally exposing the second layer of neck muscle, i.e., semispinalis capitis. (c) Semispinalis capitis is reflected from its occipital attachment exposing the third layer of deep muscles of neck. Rectus capitis posterior major and minor are seen with some parts of superior oblique and inferior oblique. (d) Suboccipital triangle is seen here formed by rectus capitis posterior major, superior oblique, and inferior oblique. Connective tissue and venous plexus are cleared exposing vertebral artery on both sides. (e) Semispinalis cervicis, superior oblique, and inferior oblique are removed showing C2 ganglion in relation to vertebral artery before it enters transverse foramina of atlas. Rectus capitis lateralis is now visible extending from the upper surface of transverse process of atlas to the jugular process of occipital bone. (f) Overview of dissection after retrosigmoid craniectomy to visualize intracranial course of vertebral artery and cranial nerves. Carotid sheath has been opened on the left side to expose internal jugular vein, internal carotid artery, and lower cranial nerves. (g) Close-up view of vertebral artery and rectus capitis lateralis muscle. C2 ganglion can be seen lying over atlantoaxial joint. Dorsal rami of C1 nerve can be seen traveling below vertebral artery and above the arch of atlas. EOP, external occipital protuberance; ICA, internal carotid artery; IJV, internal jugular vein; Inf ob, inferior oblique; RCLa, rectus capitis lateralis; RCPMi, rectus capitis posterior minor; RCPMo, rectus capitis posterior major; SNL, superior nuchal line; Sm cap, semispinalis capitis; Sp cap, splenius capitis; Sup ob, superior oblique; VA, vertebral artery

surrounding venous plexus. Rectus capitis lateralis (RCLa) can be seen as a short, flat muscle, arises from the upper surface of the transverse process of the atlas, and it is inserted into the under surface of the jugular process of the occipital bone. This muscle acts as a useful landmark in approaches to jugular foramen in far lateral approaches and in extended anterior approaches too [Figure 4e and g].[2,3]

The VA after coming out of transverse foramen of the atlas deviates laterally to reach the transverse foramen of the atlas, which is situated further lateral than the transverse foramen of the axis. VA above the transverse process of atlas takes a sharp medial bend to travel across groove on the upper surface of atlas before it penetrates dura. This bend is also intimately related to the medial side of RCLa muscle [Figure 4e-g]. After passing medially above the lateral part of the posterior arch of the atlas, the artery enters the vertebral canal by passing below the lower, arched border of the posterior AOM; this transforms into osseofibrous ring on the upper groove of atlas which may ossify into a complete or incomplete bony canal surrounding the artery.[23]

With this exposure, retrosigmoid craniectomy was done without mobilizing VA. The occipital condyles project downward along the lateral edges of the anterior half of the foramen magnum. They face downward and laterally to articulate with the superior facets of the atlas, which face upward and medially. Superficial layer of cortical bone covering the occipital condyle is removed to expose soft cancellous bone. Further drilling of the cancellous bone in and above the posterior third of the condyle exposes the second layer of hard, cortical bone that surrounds the hypoglossal canal. After exposing the hypoglossal canal above the occipital condyle, the bone of the jugular tubercle situated above the hypoglossal canal can be removed extradurally to gain additional exposure [Figure 5a and b].[2,3]

Intradural stage

Bone was removed widely extending from external occipital protuberance and superior nuchal line to foramen magnum. Posterior arch of atlas was removed along with posterior elements from the rest of cervical vertebra. Jugular tubercle was removed on one side to give a comparative view against the other side. After this, dura is opened over cerebellum and cervical spine. This gives a panoramic view of cerebellum, cervicomedullary junction, and cervical cord from dorsal aspect [Figure 5]. Cerebellum can be gently lifted with retractor to get an unobstructed view of intracranial course of VII–XII cranial nerves. VII, VIII nerve complex is seen entering internal acoustic meatus [Figure 5a and b]. Just

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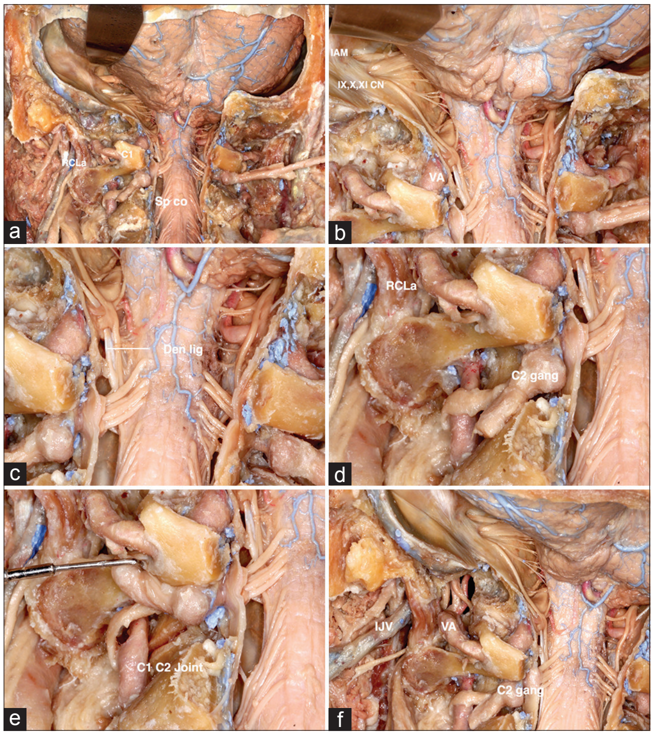

Figure 5: Intradural dissection of craniovertebral junction and jugular foramen. (a) Overview of dissection after the removal of occipital bone, spinous process, and lamina of cervical vertebrae. Jugular tubercle is removed on the left side to compare with exposure on the right side. Dura has been opened and excised from both cerebellum and cervical spine. The left side cerebellum is gently retracted exposing VII, VIII nerve complex entering internal acoustic meatus and IX, X, XI nerves entering jugular foramen. (b) Close-up view showing lower cranial nerves entering jugular foramen. Spinal part of XI nerve can be seen passing upward to jugular foramen. Denticulate ligament can be seen arising from cervical spine and getting attached to dura matter as shiny white structure. VA artery after entering dura passes forward to medulla where it is related to fascicles of XII nerve. Vertebral artery is enclosed in bony ring formed superior to the arch of atlas on the left side. (c) C2 ganglion can be seen in relation to atlantoaxial joint. (d) Unilateral view showing relation of C2 nerve, vertebral artery, and rectus capitis lateralis muscle. (e) C2 nerve is lifted to expose atlantoaxial joint. (f) Dissection done after the removal of jugular tubercle and some parts of supracondylar bone. Internal jugular vein is slightly displaced to expose IX, X, XI, and XII cranial nerves. Lateral dissection done to expose the extradural course of lower cranial nerves in relation to occipital condyle sigmoid sinus, vertebral artery, and rectus capitis lateralis muscle. C2 gang, C2 ganglion; Den lig, dentate ligament; IAM, internal acoustic meatus; IJV, internal jugular vein; RCLa, rectus capitis lateralis; Sp co, spinal cord; VA, vertebral artery

below and posterior to it, one can see IX, X, and XI nerves coursing toward jugular foramen. Dorsal rootlets of cervical spine are seen traveling intradurally [Figure 5a]. Muscles over mastoid are reflected to follow IJV, ICA, and extracranial part of the lower cranial nerves into the neck. VA is seen piercing the dura where it is encased in a fibrous tunnel that binds the posterior spinal artery, dentate ligament, first cervical nerve, and the spinal accessory nerve to it [Figure 5c].[2,3,23] At the CVJ, the dentate ligament is located between the VA and ventral roots of C1 anteriorly and the branches of the posterior spinal artery and spinal accessory nerve posteriorly, and it is often incorporated into the dural cuff around the VA [Figure 5b and c]. The most rostral attachment of the dentate ligament is located at the level of the foramen magnum above where the VA pierces the dura and behind the XI nerve, although the dentate ligament is located anterior to the XI nerve at lower levels [Figure 5b and c]. The rootlets forming the spinal portion of the XI nerve, which arise from the cervical portion of the spinal cord midway between the dorsal and ventral rootlets as far caudally as C5, unite to form a trunk that ascends through the foramen magnum between the dentate ligament and the dorsal roots and enter the posterior fossa behind the VA [Figure 5c-e].[3] Jugular process, which forms the posterior margin of the jugular foramen, can be removed to expose the transition between the sigmoid sinus, jugular bulb, and IJV. Here, IJV can be reflected to show course of IX, X, and XI cranial nerves just after coming out of jugular foramen. XII nerve joins these nerves immediately after coming out of hypoglossal canal. These nerves are here anteromedial to RCLa muscle and anterolateral to occipito-atlantal joint [Figure 5f].

Occipital condyle, supracondylar bone with hypoglossal canal, and jugular tubercle were taken out anteriorly by endonasal approach as described earlier. This gives better orientation of lower cranial nerves in relation to VA [Figure 6a-d]. Dural cuff of jugular foramen and hypoglossal canal was removed carefully while preserving cranial nerves [Figure 6e-g]. The rootlets of the XII nerve originate ventral to the inferior olive and join in hypoglossal canal before exiting the hypoglossal canal [Figure 6b and c]. It exits the hypoglossal canal and joins IX, X, and XI nerves below the jugular foramen in the interval between the ICA and IJV [Figure 6b].[2] IX nerve can be seen passing anteriorly in a separate subcanal in jugular foramen, whereas X and XI nerves pass together in separate subcanal of jugular foramen [Figure 6e and f]. After the IX nerve exits the jugular foramen, it turns forward, crossing the lateral surface of the ICA deep to the styloid process. At the level where X and XI nerves exit the jugular foramen, they are located behind the IX nerve on the posteromedial wall of the IJV [Figure 6d and e]. As the X nerve passes lateral to the outer orifice of the hypoglossal canal, the XII nerve joins it medially [Figure 6c and e]. The accessory nerve departs the vagal ganglion after it exits the jugular foramen and descends obliquely laterally between the ICA and IJV and then backward across the lateral surface of the vein to reach its muscles [Figure 6f and g].[24]

Lateral corridor

Lateral corridor was mainly studied with a microscope. A wide skin flap was reflected exposing muscles attached

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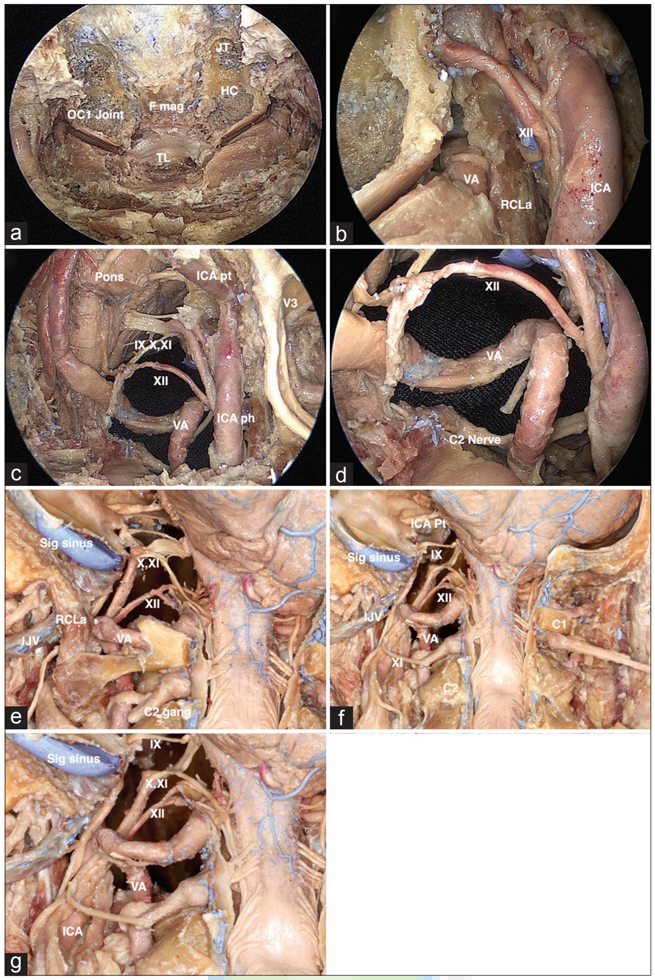

Figure 6: Comparison of endoscopic and microscopic views with three-dimensional relationships of neurovascular structures at craniovertebral junction. (a) Endoscopic view of foramen magnum and occipitocervical joint. Transverse ligament can be seen after the removal of dens in midline. Supracondylar groove is drilled exposing hypoglossal canal and jugular tubercle. (b) Close-up view of OC1 joint. Vertebral artery can be seen posteromedial to rectus capitis lateralis muscle and lower cranial nerves can be seen anterolateral to this muscle and joining internal carotid artery. (c) Bone extending from clivus, occipital condyle, lateral mass of atlas, and anterior and posterior arch of atlas has been removed. Dura has also been removed, and jugular foramen is fully dissected. IX, X, and XI cranial nerves can be seen arising from lateral medullary sulcus and entering jugular fossa where it is joined by the spinal part of IX cranial nerve. Cranial nerve XII can be seen arising as multiple rootlets, which join to form two fascicles, which in turn join to form single trunk in hypoglossal canal from where it comes out to join other lower cranial nerves. Vertebral artery can be seen entering dura and joining other side artery to form basilar artery at pontomedullary sulcus. Pharyngeal internal carotid artery is seen followed by petrous portion before coming into foramen lacerum. Lateral to internal carotid artery, mandibular branch of V cranial nerve is visible. (d) Close-up view of vertebral artery in relation to XII nerve above and C2 nerve below. C1 nerve can be seen traveling on the underside of vertebral artery. (e) Microscopic view after the removal of jugular tubercle, occipital condyle, and jugular foramen is fully dissected. IX, X, and XI nerves can be seen coming out of jugular foramen after being joined by the spinal portion of XI nerve. XII nerve can be seen coming out separately through hypoglossal canal where two fascicles join to form a single nerve. After coming out, it joins other cranial nerves in relation to internal carotid artery and internal jugular vein. This part of lower cranial nerves is anterior to rectus capitis lateralis muscle as can be seen here. (f) Full microscopic view of lower cranial nerves and vertebral artery after the removal of lateral mass of atlas and anterior and posterior arch along with rectus capitis lateralis muscle. Internal jugular vein is reflected laterally out of view. Now, IX nerve can be seen coming out of jugular foramen through separate subcanal. After coming out, it joins internal carotid artery for a short distance before passing anteriorly to supply pharyngeal sensory and muscular branches. X nerve is the thickest of lower cranial nerves and travel posterior to internal carotid artery and anterior to internal jugular vein. XI nerve is directed more posteriorly and comes out to supply sternocleidomastoid and trapezius muscles. XII nerve travels along internal carotid artery and forms ansa cervicalis and then goes medially and forward to supply the muscles of tongue. Vertebral artery can be seen in relation to these nerves and C2 nerve. VII, VIII nerve complex can be seen entering internal acoustic meatus just anterosuperior to jugular foramen. Petrous internal carotid artery is also visible in the depth. (g) Close-up view of the same dissection. C2 gang, C2 ganglion; F mag, foramen magnum; HC, hypoglossal canal; ICA, internal carotid artery; ICA ph, pharyngeal segment of internal carotid artery; ICA pt, petrous segment of internal carotid artery; IJV, internal jugular vein; JT, jugular tubercle; OC1 joint, occipitocervical joint; RCLa, rectus capitis lateralis; Sig sinus, sigmoid sinus; TL, transverse ligament; VA, vertebral artery

to mastoid process of temporal bone and superior nuchal line of occipital bone [Figure 7a]. Most superficial layers of muscles are formed by the sternocleidomastoid and splenius capitis muscles laterally and the trapezius and the semispinalis capitis muscles medially [Figure 7a]. The occipital artery may pass superficial or deep into the longissimus capitis [Figure 7b].[2] Reflecting the longissimus capitis downward exposes the semispinalis capitis and

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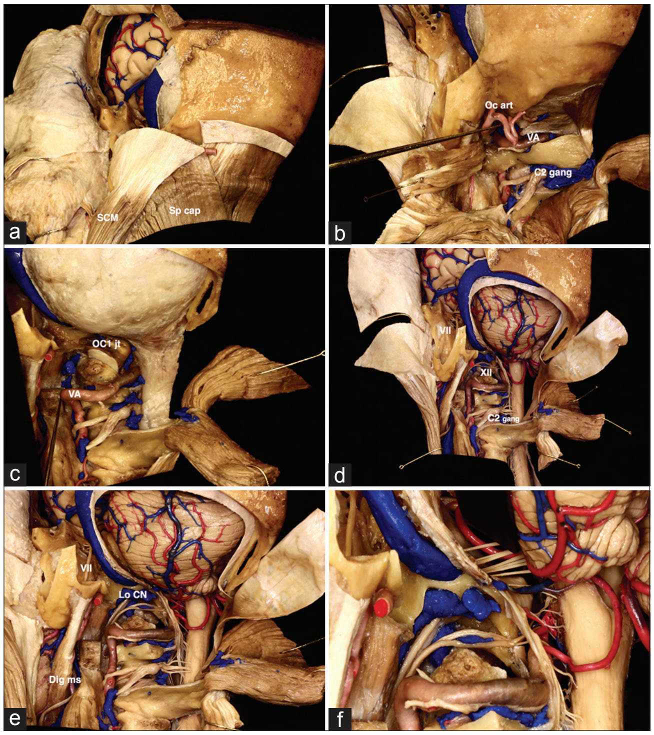

Figure 7: Stepwise microscopic approach to craniovertebral junction by far-lateral approach. (a) Skin and subcutaneous tissue reflected exposing muscles attached to mastoid process and occipital bone. Sternocleidomastoid is seen moving forward and splenius capitis moving backward. (b) Superficial and deep muscles removed exposing transverse process of C1, C2 ganglion and vertebral artery. (c) Suboccipital craniectomy is done with the removal of foramen magnum and posterior elements of C1 and C2 vertebra. Occipitocervical joint and C1 C2 joints are exposed. Vertebral artery can be seen passing vertically than turning horizontally to enter intradurally. (d) Dura is opened in front of sigmoid sinus, cerebellum, and cervical spine. Supracondylar bone is drilled with jugular tubercle. Mastoidectomy has been done preserving the tip, and vertical mastoid segment of facial nerve is visible with the origin of chorda tympani nerve. Hypoglossal nerve is seen traveling along hypoglossal canal. Course of vertebral artery is visible from C3 vertebra onward. (e) Close-up view of dissection showing atlantoaxial joint in relation to C2 ganglion. Vertebral artery can be seen traveling across the arch of C1 to enter intracranially. (f) Cerebellum is retracted exposing intracranial path of lower cranial nerves. C2 gang, C2 ganglion; Dig ms, digastric muscle; Lo CN, lower cranial nerves; OC1 Jt, occipitocervical joint; Oc art, occipital artery; SCM, sternocleidomastoid; Sp cap, splenius capitis; VA, vertebral artery

the superior and inferior oblique muscles as well as the transverse process of the atlas. Reflecting these muscles from their attachment exposes suboccipital triangle. Muscles of suboccipital triangles are removed to expose squama of occipital bone, lamina of atlas, and transverse process of atlas with vertical and horizontal segment of VA from axis to its dural entrance [Figure 7b]. This also exposes C2 ganglion along with atlantoaxial joint. A suboccipital craniectomy was done along with the removal of bone over foramen magnum, posterior arch of atlas and transverse foramen of atlas, and axis vertebrae [Figure 7c]. This exposes VA along its course in relation to OC1 and atlantoaxial joints. The OC1 joint and the posterior condylar emissary vein are exposed along with C2 ganglion. Dura is removed over the cerebellum and spinal cord to show intracranial structures. The cancellous bone within the occipital condyle has been drilled away while preserving the cortical and articular surfaces to expose the XII nerve in the hypoglossal canal [Figure 7d]. Digastric muscle can be seen passing forward from digastric groove in lateral part of exposure. Mastoid cavity was drilled exposing VII nerve with chorda tympani, semicircular canals, and middle ear ossicles. Drilling in supracondylar area was extended to involve jugular tubercle to get access to area in front of the brainstem.[2] If a more lateral exposure is needed, or the jugular foramen is to be opened from posteriorly, the jugular process of the occipital bone can be removed after detaching the RCLa muscle from its lower surface [Figure 7e]. Removing the jugular process will expose the transition between the sigmoid sinus, jugular bulb, and IJV. Retracting cerebellar hemisphere at this stage gives a view of anterolateral brainstem with lower cranial nerves [Figure 7f]. The intradural segment of the VA, after emerging from the fibrous dural tunnel, ascends in front of the rootlets of the hypoglossal nerve to reach the front of the medulla oblongata where it unites near the junction of pons and medulla with its mate to form the basilar artery.[2,3,24]

Discussion

CVJ is a collective term that refers to occipital bone, atlas, and axis, with its supporting ligaments and membranes that provide stability and mobility to this critical area of transition between brain and spinal cord. This unique anatomical configuration of CVJ allows its functional mobility and at the same time provides protection to critical neurovascular structures through a wide range of motion in various directions. A thorough understanding of 3D anatomy and relations of various neurovascular structures is paramount for surgical management of these pathologies.

There is renewed interest in anterior approaches with recent advances in endoscopic technology. Traditionally, transoral approach has been the most direct approach without any undue neurovascular manipulation to extradural lesions in clival and ventral CVJ. Sometimes, it has been used for intradural lesion too.[5] However, transoral approaches are associated with high patient morbidity and complication rates[4,13,17] whereas transnasal endoscopic approach offers added advantage of less morbidity of oropharynx and better visuality.[4,13] In recent times, its feasibility is validated by various cadaveric and clinical studies.[10-14] Complication rates are quite low, and the problem of cerebrospinal fluid leak has largely been overcome with the advent of vascularized pedicle flaps.[25]

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Endoscopic approach can provide access to the entire skull base extending from anterior cranial fossa to the body of C2 in midline.[20] Lateral exposure is limited here by ET, medial pterygoid plates, and paraclival ICAs. However, with some drilling and removal of bone, more lateral areas can be accessed.[12,16] Muscles of ventral CVJ are thin and have avascular plane in midline that can be used to retract them laterally or remove them as U-shaped flap for later reconstruction.[13] Anterior tubercle of C1 is a useful midline landmark that can be confirmed with image guidance. OC1 joints act as lateral limit of this exposure. Although no biomechanical studies have been performed addressing the stability of the OC1 joint after ventromedial condyle resection, statistically significant hypermobility is produced at the OC1 joint after more than 50% of the dorsomedial condyle is resected.[26] Transverse ligament is thick, white transverse band that can be identified easily after the removal of odontoid. It can sometimes be confused with transverse occipital ligament that can be present in up to 8%–40% of cases.[16,18] Transverse ligament extends between lateral masses of C1 whereas transverse occipital ligament extends between occipital condyles.

For endonasal endoscopic approach to foramen magnum, inferior clival, and petroclival fissure, superior limit is paraclival and laceral segment of ICA and inferior limit is occipital condyles. Hence, a standard endoscopic endonasal approach to the inferior third of the clivus has a trapezoid shape, determined by the narrower space between the condyles inferiorly. Drilling occipital condyle on one or both sides can extend this operative corridor. Far medial extension of transclival approach with its two modifications, namely transcondylar and transjugular approach offers visualization of dural entry point of VA and cisternal part of lower cranial nerves.[12,16] The hypoglossal canal is situated posterior to the level of the supracondylar groove, with its outer orifice located lateral to the level of the supracondylar groove.[16] Hence, superior and inferior clival lines, pharyngeal tubercle, OC1 joint, C1 tubercle, supracondylar groove, hypoglossal canal, and jugular tubercle are some of the useful bony landmarks to be identified in this dissection.

Limitation of these approaches is mainly narrow corridor with restricted movements due to nasal anatomy. They have largely been overcome with advancement in instrumentation and removal of nasal septum and turbinates. However, ET, configuration of pharyngeal ICA, and occipital condyles are other anatomical limitations, which need to be considered while approaching pathologies located more inferiorly and laterally.[17] Amount of condyle resection and damage to alar ligaments can lead to cranio-cervical instability requiring posterior fixation.[16] Tortuous or medially displaced pharyngeal ICAs can make this approach impossible and it needs to be considered before operation, especially in elderly patients. Another limitation of this approach is inferior extent of pathology. Lesions extending below C2 vertebra are difficult to access by this approach. Another absolute contraindication for transnasal endoscopic approach is medially or ventrally located critical neurovascular structure requiring their handling before entering the lesion.[16] For accessing lateral pathologies or lesion behind occipital condyles, a lateral or posterior corridor is preferred over anterior corridor.

Posterior approaches to CVJ are more traditional approach to deal with pathologies related to dorsal brainstem cerebellum and spinal cord, jugular foramen, foramen magnum, OC1 joint, and atlantoaxial joint. For any type of joint manipulation, fixation, or instrumentation, posterior approach is preferred over direct approach.[7,8,22,27] VA is the major vascular structure encountered in this corridor. VA adopts a serpentine course in relation to CVJ region.[22] This artery has multiple loops and has an intimate relationship with atlas and axis. Venous plexus and thick connective tissue cover the entire course in this region, making its identification difficult during surgery.[21,22] However, some useful landmarks can help in early identification and safety of this major vessel. Suboccipital triangle is a useful landmark to identify and locate horizontal segment of VA as it travels across groove on the upper surface of the posterior arch of atlas.[2,3,21,22] Another major landmark in this area is thick C2 ganglion, which is intimately related to atlantoaxial joint.[22] Many times, for better exposure of atlantoaxial joint or instrumentation in this region, C2 ganglion can be sacrificed. VA after coming out of transverse process of C1 takes a sharp medial bend to travel across groove on the upper surface of C1 before it penetrates dura. This bend is also intimately related to the medial side of RCLa muscle.[2,3,23] We found RCLa muscle to be of critical importance and important landmark in various corridors around CVJ. This muscle acts as a useful landmark in approaches to jugular foramen, far lateral approaches, and extended anterior approaches too [Figure 4e and g]. RCLa muscle provides a landmark for estimating the position of the jugular foramen and the facial nerve, which exits the stylomastoid foramen just lateral to the jugular foramen.[24] IJV with lower cranial nerves are anterior to this muscle and VA is posteromedial to it. Occipital condyles are another useful extradural landmark for extended posterior or far lateral approaches. The bone of the jugular tubercle situated above the hypoglossal canal can be removed extradurally to gain additional exposure.[2]

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The basic far-lateral approach without drilling of the occipital condyle may be all that is required to reach some lesions located along the anterolateral margin of the foramen magnum. However, it also provides a route through which the transcondylar, supracondylar, and paracondylar approaches and several modifications of these approaches can be completed.[2] A more extensive removal of the articular surfaces and condyles can be done to gain access to extradural lesions situated along the anterior and lateral margins of the foramen magnum. In the transtubercular variant of the supracondylar approach, the prominence of the jugular tubercle that blocks access to the area in front of the IX, X, and XI cranial nerves is removed extradurally to increase visualization of the area in front of the brainstem and to expose the origin of a PICA that arises from the distal part of the VA near the midline. Muscles that are especially significant in this exposures are the three muscles forming the suboccipital triangle and the levator scapulae, RCLa, and the posterior belly of the digastric.[2]

In obliterating and coagulating the venous plexus around the VA, there is a risk that some of the branches of the VA, which arise in an extradural location or even a hypoplastic VA, might be occluded or divided. The posterior spinal artery, and uncommonly the PICA, may arise extradurally in the region of the portion of the vertebral venous plexus.[21] Another key aspect of this approach is the condyle drilling, which requires an understanding of the relationship of the hypoglossal canal to the occipital condyle. In drilling the upper posterior portion of the condyle, the posterior condylar vein may be a source of bleeding, which could be mistaken for bleeding from the venous plexus in the hypoglossal canal. The extradural removal of the jugular tubercle should be performed with caution because of the risk of injuring the IX, X, and XI cranial nerves that hug and often course in a shallow groove at the site where they cross the tubercle.

An excellent landmark for identifying the jugular process is the RCLa muscle, which extends upward just behind the jugular bulb. The muscle is located medial to the site where the occipital artery enters the retro-mastoid area by passing between the RCLa and posterior belly of the digastric. The posterior belly of the digastric muscle, which attaches along the digastric groove just posterior to the stylomastoid foramen, provides a useful landmark for identifying the VII nerve. A limited or more extensive mastoidectomy may be completed, depending on the length of the mastoid segment of the facial nerve to be exposed and the extent to which the bone on the lateral aspect of the jugular bulb must be removed. Hence, RCLa, posterior belly of digastric muscle, occipital condyle, jugular process, hypoglossal canal, and jugular tubercle are useful bony and muscular landmarks to be identified in this dissection of lateral corridor.

Conclusion

This cadaver study has been done to better elucidate 3D anatomy of CVJ and relation of critical neurovascular structures to specific bony and muscular landmarks. A combined view of microscopic and endoscopic relation of CVJ anatomy is more useful and easy to understand. With advances in endoscopic and microscopic techniques, access to lesions and bony anomalies around CVJ is becoming easier and straightforward. This anatomical knowledge and dissection in cadaver lab will assist future neurosurgeons in developing combined approaches and facilitating safe surgery in this difficult to access region of human body.

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Conflicts of interest
There are no conflicts of interest.

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