Relevant Anatomy of the Craniovertebral Junction

1

Elena d'Avella, Luigi Maria Cavallo, Matteo De Notaris, Jose Pineda, Alberto Di Somma, Paolo Cappabianca, and Alberto Prats-Galino

1.1 Introduction

Craniovertebral junction (CVJ) refers to the complex transition from the skull to the spine. Its bony structure consists of the occipital bone, atlas (C1), and axis (C2) (Fig 1.1) [1–3]. The occipital bone surrounds the foramen magnum and has three parts: a squamosal part located behind the foramen magnum, a clival portion located anterior to the foramen magnum, and a condylar part that connects the squamosal and clival parts. The atlas, the first cervical vertebra, is ring shaped and consists of two thick lateral masses situated at the anterolateral parts of the ring connected with short anterior and longer posterior arches. The upper facet of each lateral mass articulates with the occipital condyle that protrudes from the condylar part of the occipital bone (atlanto-occipital joints). The inferior facet of each lateral mass articulates with the superior articular facet of the axis. The axis, the second cervical vertebra, is distinguished by the odontoid process (dens), which projects upward from the body. On the front of the dens is an articular facet that forms a joint with the facet on the back of the anterior arch of the atlas. The body is connected to the lateral mass by short and strong pedicles. Articular facets of the axis extend lateral

E. d'Avella (✉) · L. M. Cavallo · P. Cappabianca
Division of Neurosurgery, Department of Neurosciences and Reproductive and Odontostomatological Sciences, Università di Napoli "Federico II", Naples, Italy

M. De Notaris
Neurosurgery Operative Unit, Department of Neurosciences, "G.Rummo" Hospital, Benevento, Italy

J. Pineda · A. Prats-Galino
Laboratory of Surgical NeuroAnatomy (LSNA), Human Anatomy and Embriology Unit, Faculty of Medicine, Universidad de Barcelona, Barcelona, Spain

A. Di Somma
Institut Clínic de Neurociències (ICN), Department of Neurological Surgery Hospital Clínic de Barcelona, Universidad de Barcelona, Barcelona, Spain

E. Tessitore et al. (eds.), *Surgery of the Cranio-Vertebral Junction*,
https://doi.org/10.1007/978-3-030-18700-2_1

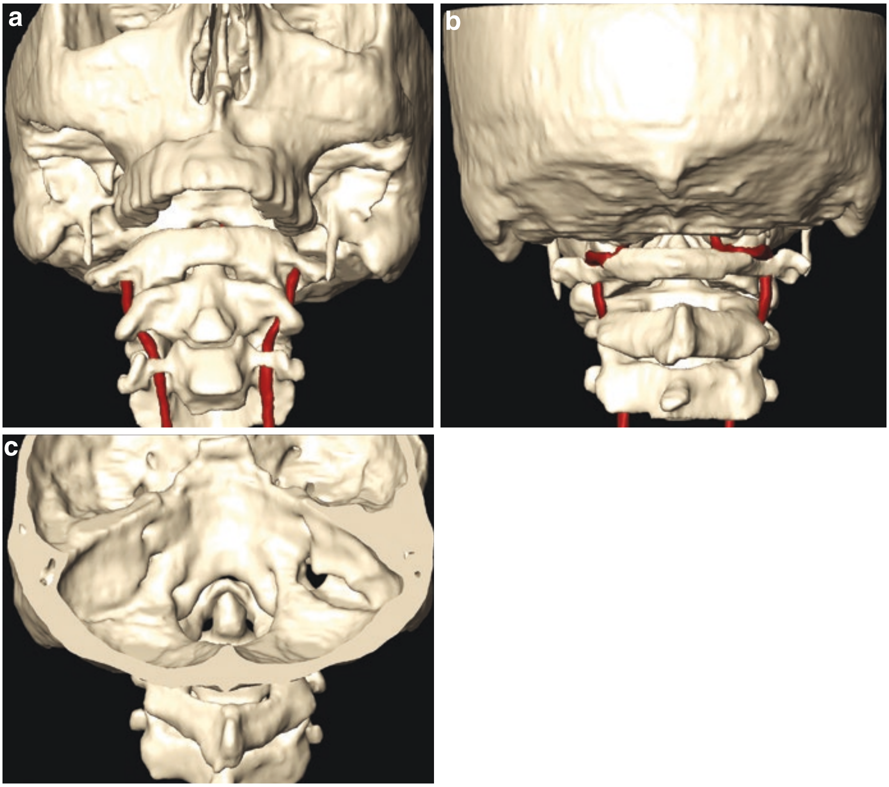


Fig. 1.1 3D anatomical model of the craniovertebral junction (CVJ). Its bony structure consisting in the occipital bone, atlas and axis is shown as seen from an anterior (**a**), posterior (**b**), and superior-posterior intracranial perspective (**c**). The extracranial course of the vertebral artery, which is the major vessel related to the CVJ, is represented

from the body and articulate superiorly with the inferior facets of the atlas [1–5]. Muscles, ligaments, and membranes that provide stability and mobility to the craniovertebral junction support the bony structure of this critical region [2, 5].

Major neurovascular structures are intimately related to the CVJ where they transverse membranous and bony orifices. These include the lower cranial and upper spinal nerves, the caudal brainstem and rostral spinal cord, the vertebral artery and its branches, and the venous drainages through the jugular vein and the vertebral plexus [1, 3, 6, 7]. Anatomy of the vertebral artery will be further detailed in a dedicated chapter.

A thorough understanding of three-dimensional (3D) CVJ anatomy and relations with surrounding neurovascular structures is paramount for the surgical management of pathologies in this region. The aim of this chapter is to describe the relevant anatomy of the CVJ as seen from a posteromedial, posterolateral, anterolateral and anteromedial perspectives. Anatomical dissection through the anteromedial corridor was carried out by an endoscopic endonasal access whereas posterior and lateral corridors were studied by microscopic vision.

Merging together anatomical information coming from endoscopic and microsurgical investigations with the reconstruction of 3D computed models might provide a 360° full and clear understanding of this complex area, more readily applicable to the operative setting.

1.2 Posteromedial Perspective of the CVJ (Fig. 1.2)

1.2.1 Bony Structures

The posteromedial perspective of the CVJ is focused on the squamosal part of the occipital bone bordering the foramen magnum and on the posterior arch of C1 and C2 (Fig. 1.3).

The posterior surface of the squamosal part of the occipital bone in its medial portion has some relevant protuberances on which muscles of the neck attach: the external occipital protuberance (EOP), situated at the central part of the external surface; the superior nuchal line (SNL) and the inferior nuchal lines (INL) that radiate laterally from the protuberance; the posterior border of foramen magnum (FM); and the midline occipital crest, a vertical ridge that descends from the EOP to the midpoint of the posterior margin of the foramen magnum. The area below and between the superior and inferior nuchal lines is rough and irregular and serves as the site of attachment of numerous muscles. There is great variability in the position of the superior nuchal line, and therefore, it does not reflect the internal position of

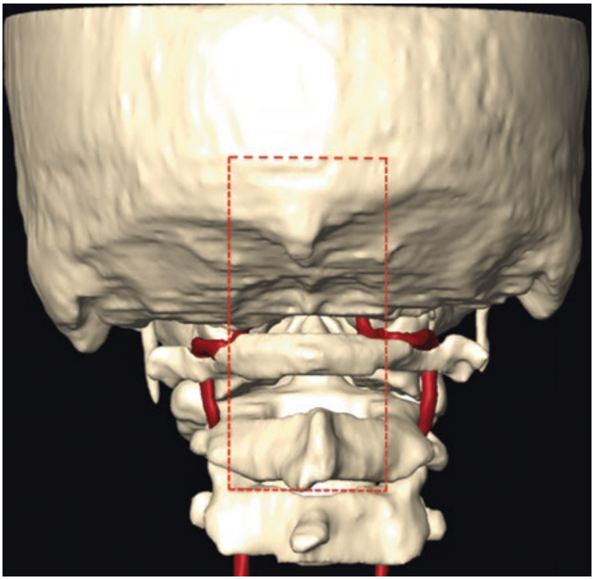


Fig. 1.2 3D anatomical model of the CVJ as seen from a posterior view. The area corresponding to the posteromedial perspective is highlighted with red dotted lines

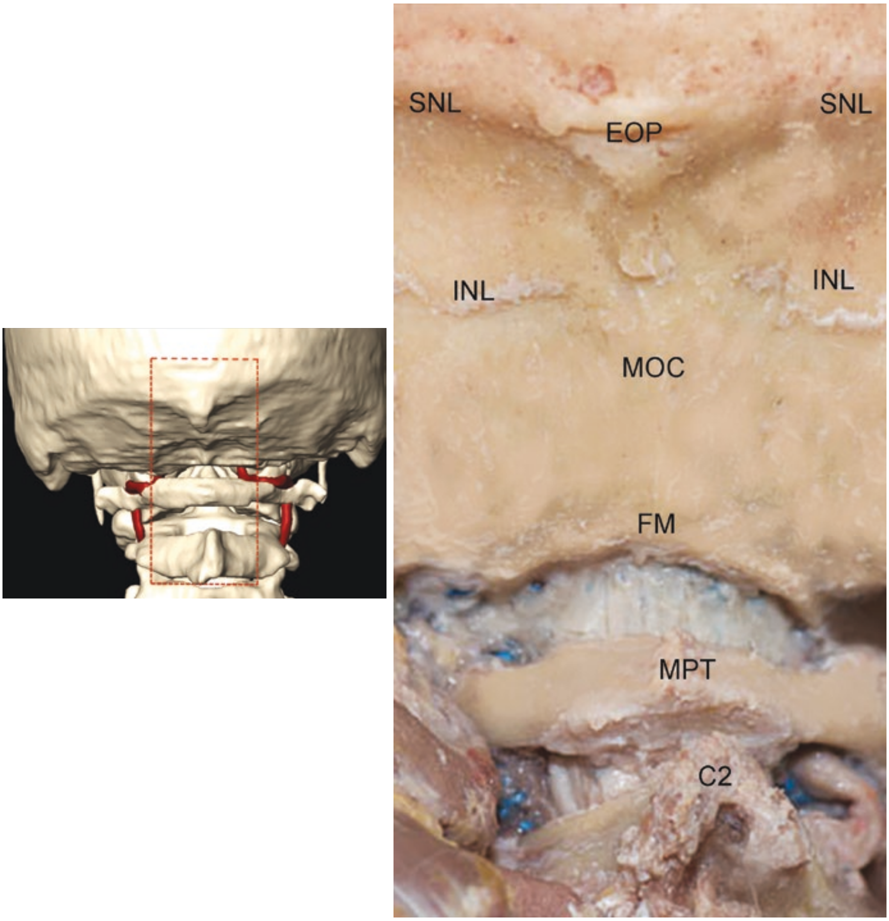


Fig. 1.3 The posteromedial perspective of the CVJ is focused on the squamosal part of the occipital bone bordering the foramen magnum and on the posterior arch of C1 and C2. On the left side of the image, the 3D model is for anatomical reference for the area of interest. The posterior surface of the squamosal part of the occipital bone in its medial portion has some relevant protuberances on which muscles of the neck attach: the external occipital protuberance; the superior nuchal line and the inferior nuchal lines; the posterior border of foramen magnum; the midline occipital crest. The area below and between the superior and inferior nuchal lines is rough and irregular and serves as the site of attachment of numerous muscles. On the posterior arch of the atlas is the median posterior tubercle, which substitutes the spinous process of any other vertebra. The posterior arch of the axis distinguishes by harboring the thickest lamina than on any other cervical vertebrae and a large spinous process serving as an attachment point of important suboccipital triangle muscles and the nuchal ligament. *C2* spinous process of the axis; *EOP* external occipital protuberance; *FM* posterior border of foramen magnum; *INL* inferior nuchal line; *MOC* midline occipital crest; *MPT* median posterior tubercle of the atlas; *SNL* superior nuchal line

transverse sinus accurately. The relation of confluence of the sagittal sinus with the transverse sinus (torcular Herophili) to EOP is more consistent [2, 4, 8].

On the posterior arch of the atlas is the median posterior tubercle, which substitutes the spinous process of any other vertebra. The posterior arch of the axis distinguishes by harboring the thickest lamina than on any other cervical vertebrae and a large spinous process serving as an attachment point of important suboccipital triangle muscles and the nuchal ligament [1, 5].

1.2.2 Muscular Relationships (Fig. 1.4)

The trapezius is the most superficial muscle that is encountered when exploring the CVJ through a posteromedial corridor. It extends from the medial half of the SNL, the EOP, and the spinous processes of the cervical and thoracic vertebrae and converges on the shoulder to attach to the scapula and the lateral third of the clavicle. In a deeper layer, the splenius capitis is exposed in its medial half running to the spinous processes of the lower cervical and upper thoracic vertebrae. Deep to the splenius capitis, the semispinalis capitis begins medially at the midline occipital crest in the area between the superior and inferior nuchal lines and attaches below to the upper thoracic and lower cervical vertebrae (Fig. 1.5) [4, 8, 9]. In the next layer, along the posteromedial corridor, the rectus capitis posterior minor can be seen extending from the medial part and below the inferior nuchal line to the tubercle of the posterior arch of the atlas (Fig. 1.6) [6, 10].

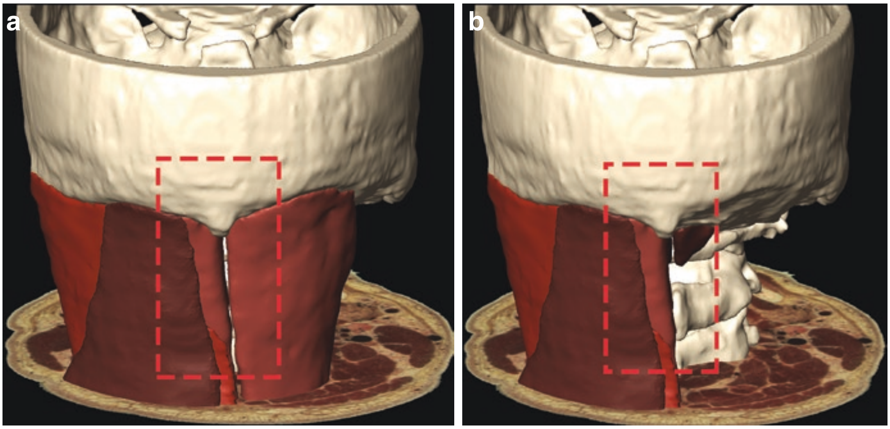


Fig. 1.4 3D model of the muscular layers visible through a posteromedial perspective to the CVJ. The anatomical area of interest is limited by the red dotted lines. The superficial layer (**a**) is represented by the trapezius muscle (dark brown), splenius capitis muscle (dark orange), and semispinalis capitis (light brown). On the right half of the picture, trapezius and splenius capitis muscles have been removed, revealing the semispinalis capitis muscle. The deep muscular layer (**b**) is represented by rectus capitis posterior minor muscles (dark brown), exposed after the removal of the superficial layer muscles on the left side of the picture

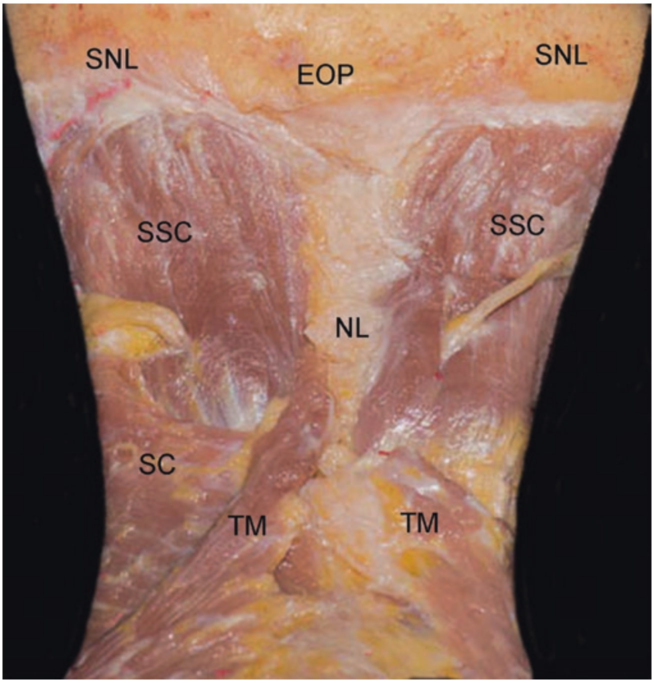


Fig. 1.5 Posteromedial perspective of the CVJ: muscular relationships. Trapezius is the most superficial muscle. It extends from the medial half of the superior nuchal line, the external occipital protuberance, and the spinous processes of the cervical and thoracic vertebrae and converges on the shoulder to attach to the scapula and the lateral third of the clavicle. Here, it has been partially resected in its rostral part to expose in a deeper layer the splenius capitis in its medial half, running to the spinous processes of the lower cervical and upper thoracic vertebrae. On the right side of the picture the splenius capitis has been resected. Deep to the splenius capitis, the semispinalis capitis begins medially at the midline occipital crest in the area between the superior and inferior nuchal lines and attaches below to the upper thoracic and lower cervical vertebrae. In the midline, the nuchal ligament forms a septation dividing the posterior neck muscles on the left and right sides. Moreover, some of these muscles attach medially to this structure. The nuchal ligament extends from the spinous process of the cervical vertebrae to the external occipital protuberance. *EOP* external occipital protuberance; *NL* nuchal ligament; *SC* splenius capitis; *SNL* superior nuchal line; *SSC* semispinalis capitis; *TM* trapezius muscle

In the midline, the nuchal ligament forms a septation dividing the posterior neck muscles on left and right sides. Moreover, some of these muscles attach medially to this structure. The nuchal ligament extends from the spinous process of the cervical vertebrae to the EOP [11].

1.2.3 Extradural Structures

The posterior border of the foramen magnum and the upper border of the posterior arch of the atlas are connected by the posterior atlanto-occipital membrane (PAOM)

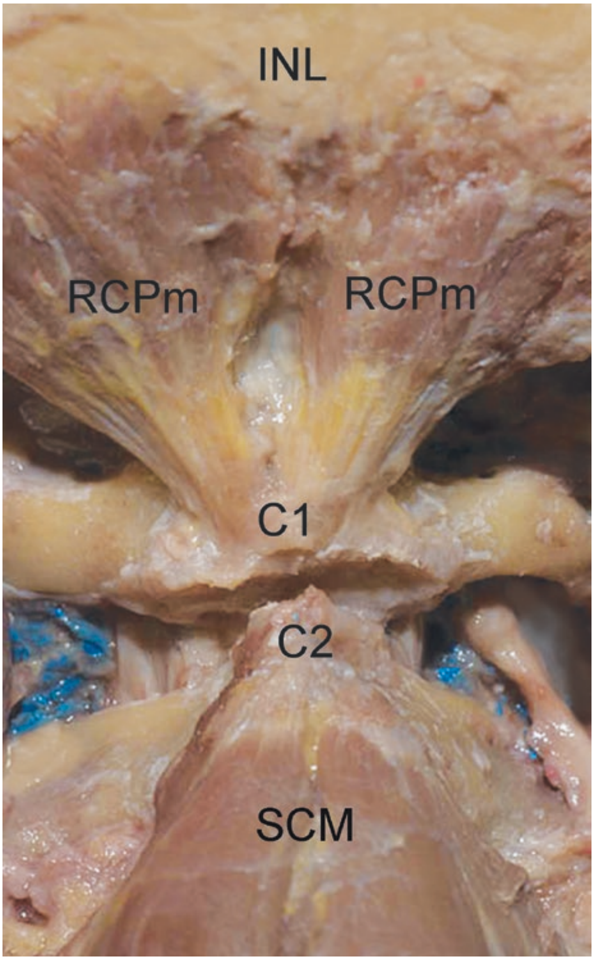


Fig. 1.6 Posteromedial perspective of the CVJ: muscular relationships. The deepest layer of muscle consists of the rectus capitis posterior minor muscles. The muscles extend from the medial part and below the inferior nuchal line to the tubercle on the posterior arch of the atlas. *C1* median posterior tubercle of the atlas; *C2* spinous process of the axis; *INL* inferior nuchal line; *RCPm* rectus capitis posterior minor muscle; *SCM* semispinalis cervicis muscle

that runs adjacent to the rectus capitis posterior minor posteriorly and the dura mater anteriorly. Connection or interdigitation of the PAOM with both the rectus capitis posterior minor muscles and the spinal dura mater can be observed. The PAOM is continuous inferiorly with a thin membrane named the posterior atlanto-axial membrane, which is attached above to the lower border of the posterior arch of the atlas and below to the upper edges of the laminae of the axis, in series with the ligamentum flavum [4, 12]. The posterior opening of the FM is wider posteriorly than anteriorly and transmits the medulla (Fig. 1.7).

The venous channels in the dura mater surrounding the foramen magnum in its posteromedial aspect are the marginal sinus and the occipital sinus. The marginal sinus is located between the layers of the dura in the rim of the foramen magnum. It communicates posteriorly with the occipital sinus. The occipital sinus courses in the cerebellar falx [9, 13].

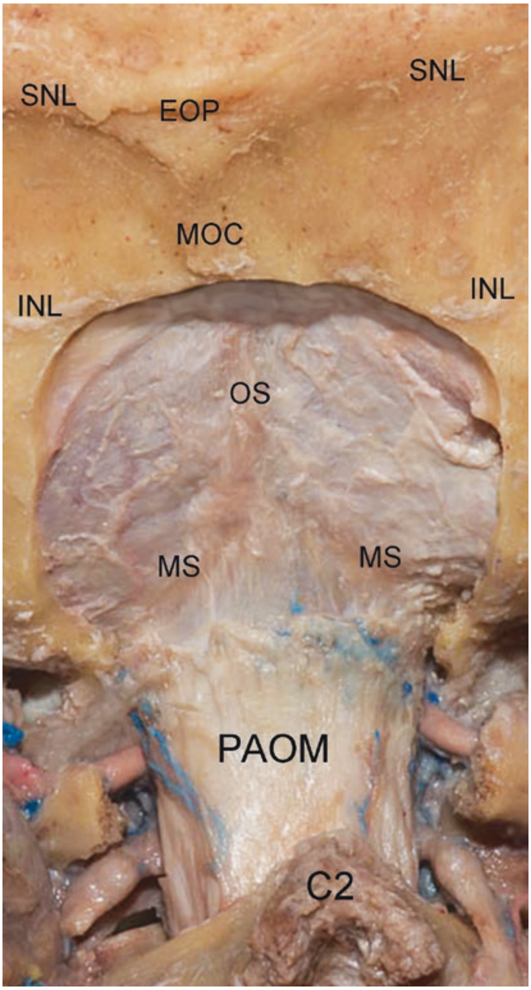


Fig. 1.7 Posteromedial perspective of the CVJ. The middle portion of the squamosal part of the occipital bone and the posterior arch of the atlas have been removed. The posterior border of the foramen magnum has been opened. The posterior border of the foramen magnum and the upper border of the posterior arch of the atlas are connected by the posterior atlanto-occipital membrane that runs adjacent to the rectus capitis posterior minor posteriorly and the dura mater anteriorly. The venous channels in the dura mater surrounding the foramen magnum in its posteromedial aspect are the marginal sinus and the occipital sinus. The marginal sinus is located between the layers of the dura in the rim of the foramen magnum. It communicates posteriorly with the occipital sinus. The occipital sinus courses in the cerebellar falx. *C2* spinous process of the axis; *EOP* external occipital protuberance; *INL* inferior nuchal line; *MOC* middle occipital crest; *MS* marginal sinus; *OS* occipital sinus; *PAOM* posterior atlanto-occipital membrane; *SNL* superior nuchal line

1.2.4 **Intradural Anatomy** (Fig. 1.8)

Through a posteromedial perspective, the medulla can be exposed, occupying the foramen magnum. The medulla blends indistinguishably into the spinal cord at a level arbitrarily set to be at the upper limit of the dorsal and ventral rootlets forming the first cervical nerve. Posteromedially, the spinal cord is divided by the posteromedian sulcus into symmetrical halves. Each half is occupied by the posterior funiculus. At the upper cervical level, the surface of the posterior funiculus is divided by another shallow longitudinal furrow, the posterior intermediate sulcus, into the fasciculus gracilis medially and the fasciculus cuneatus laterally. Superiorly, the posterior surface of the medulla is composed in the midline of the inferior half of the fourth ventricle and laterally by the inferior cerebellar peduncles. Inferiorly the posterior surface is composed of the gracile fasciculus and tubercle medially, and the cuneate fasciculus and tubercle laterally [2, 8, 14].

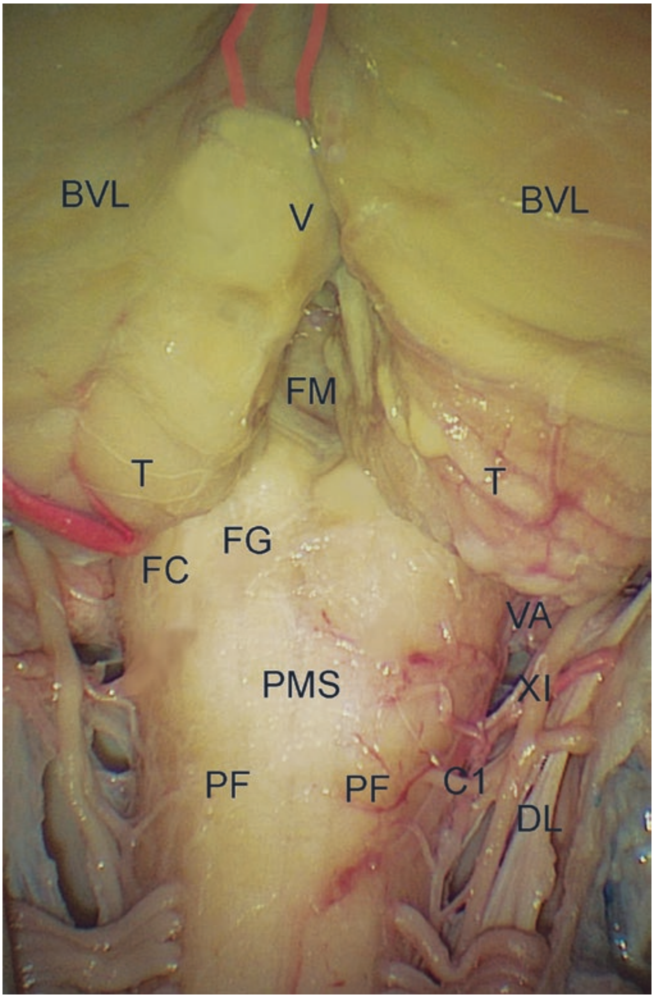


Fig. 1.8 Posteromedial intradural perspective of the CVJ. The medulla is exposed where it blends indistinguishably into the spinal cord at a level arbitrarily set to be at the upper limit of the dorsal and ventral rootlets forming the first cervical nerve. The spinal cord is divided by the posteromedian sulcus into symmetrical halves. Each half is occupied by the posterior funiculus. At the upper cervical level, the surface of the posterior funiculus is divided by another shallow longitudinal furrow, the posterior intermediate sulcus, into the fasciculus gracilis medially and the fasciculus cuneatus laterally. The posteromedial aspect of the cerebellum related to the foramen magnum consists in the lower part of the hemispheres (formed by the tonsils and the biventral lobules) and the lower part of the vermis (formed by the nodule, uvula, and pyramid). Between the tonsils, the foramen of Magendie communicates with the fourth ventricle. The vertebral artery in its third segment (V3) pierces the posterior atlanto-occipital membrane, then dura mater, to enter the posterior fossa. As the artery pierces the dura, it is encased in a fibrous tunnel that binds the posterior spinal artery, dentate ligament, first cervical nerve, and the spinal accessory nerve to the vertebral artery. The C1 nerve root passes through the dura mater on the lower surface of the vertebral artery. The accessory nerve is the only cranial nerve that passes through the foramen magnum, between the dentate ligament and the dorsal spinal roots. *BVL* biventral lobule of the cerebellar hemisphere; *C1* dorsal root of the first cervical nerve; *DL* dentate ligament; *FC* fasciculus cuneatus; *FG* fasciculus gracilis; *FM* foramen of Magendie; *PF* posterior funiculus; *PMS* posteromedial sulcus; *T* tonsil; *V* vermis; *VA* vertebral artery; *XI* accessory nerve

The posteromedial aspect of the cerebellum related to the foramen magnum consists in the lower part of the hemispheres (formed by the tonsils and the biventral lobules) and the lower part of the vermis (formed by the nodule, uvula, and pyramid). The cerebellar surface above the posterior part of the foramen magnum has a deep vertical depression, the posterior cerebellar incisura, which contains the falx cerebelli and extends inferiorly toward the foramen magnum. The vermis is folded into and forms the cortical surface within this incisura. The vermian surface within the incisura is composed of the pyramid in its upper half and of the uvula that projects downward between the tonsils. Inferiorly, the posterior cerebellar incisura is continuous with the vallecula cerebelli, an opening between the tonsils that extends upward through the foramen of Magendie into the fourth ventricle. Each tonsil is an ovoid structure that is attached along its superolateral border to the remainder of the cerebellum. The superior pole faces the inferior half of the roof of the fourth ventricle. The anterior surface of each tonsil faces and is separated from the posterior surface of the medulla by the cerebello-medullary fissure. This fissure extends superiorly to the level of the roof of the fourth ventricle and the lateral recesses of the fourth ventricle. The dorsal wall of the fissure is formed by the uvula in the midline and the tonsils and biventral lobules laterally. The ventral wall is formed by the inferior medullary velum and tela choroidea. The inferior medullary velum is a thin sheet of neural tissue that blends into the ventricular surface of the nodule medially and stretches laterally across the superior pole of the tonsil. The tela choroidea, from which the choroid plexus projects, forms the lowest part of the roof of the fourth ventricle [4, 5, 14, 15].

The vertebral artery in its third segment (V3) pierces the PAOM, then dura mater, to enter the posterior fossa. As the artery pierces the dura, 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. The C1 nerve root passes through the dura mater on the lower surface of the vertebral artery. The posterior spinal artery arises from the posteromedial surface of V3 initial just outside or inside the dura mater. In the subarachnoid space, it courses medially between the accessory nerve and the dentate ligament. At the lower medulla, it divides into an ascending branch that supplies the gracile and cuneate tubercles, the rootlets of the accessory nerve, and the choroid plexus near the foramen of Magendie, and a descending branch that supplies the superficial part of the dorsal half of the cervical spinal cord. It anastomoses with the posterior branches of the radicular arteries that enter the vertebral foramen at lower levels. The descending branch gives rise to collateral branches, which course medially across the posterior surface of the spinal cord and join to form an artery that course in the posterior midline [2, 16, 17].

The posterior meningeal artery arises from the posterosuperior surface of the vertebral artery. Its origin may be intra- or extradural and supplies the dura mater of the posterior and posterolateral part of the posterior cranial fossa [4, 17].

The median posterior spinal vein, which courses along the posteromedian spinal sulcus, is continuous above with the main vein on the posterior surface of the medulla and the median posterior medullary vein, which courses along the posteromedian medullary sulcus. The transverse medullary and transverse spinal veins cross the medulla and spinal cord at various levels, interconnecting the major longitudinal channels [3, 5, 14].

The accessory nerve is the only cranial nerve that passes through the foramen magnum between the dentate ligament and the dorsal spinal roots. The main caudal trunk from the spinal cord is exposed through a posteromedial perspective. There are frequently communications between the C1 nerve root and the spinal accessory nerve [18, 19].

The dentate ligament is a white fibrous sheet that is attached to the spinal cord medially and to the dura mater laterally. Its rostral attachment is at the level of the foramen magnum where the vertebral artery pierces the dura. The ligament courses behind the accessory nerve at that level [4, 14].

1.3 Posterolateral Perspective of the CVJ (Fig. 1.9)

1.3.1 Bony Structures

The posterolateral perspective of the CVJ is directed at the condylar part of the occipital bone and lateral masses of atlas and axis (Fig. 1.10).

On the posterolateral external surface of the squamosal part of the occipital bone that extends from the EOP to the mastoid process of the temporal bone, an important bony landmark is the asterion. The asterion is located at the junction of the lambdoid, occipito-mastoid, and parieto-mastoid sutures and is commonly related to the lower half of the junction of the transverse and sigmoid sinuses. The superior and inferior nucal lines cross the posterolateral external surface of the occipital bone radiating laterally from the EOP and serves as the site of attachment of numerous muscles [2, 6].

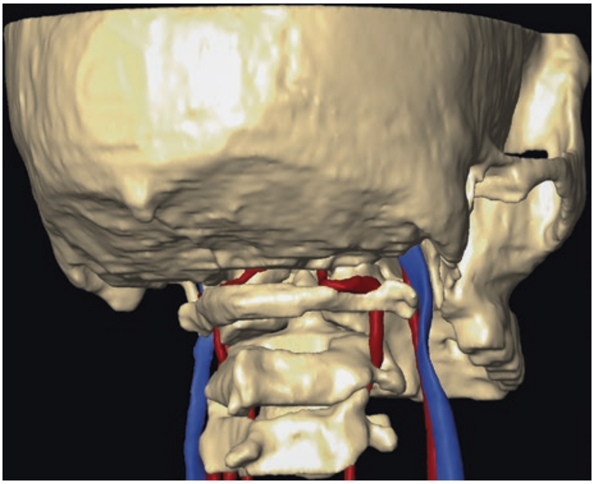


Fig. 1.9 3D anatomical model of the CVJ as seen from a posterolateral perspective. Bony relationships with the main arterovenous structures are shown, i.e., with the vertebral artery, internal jugular vein, and internal carotid artery

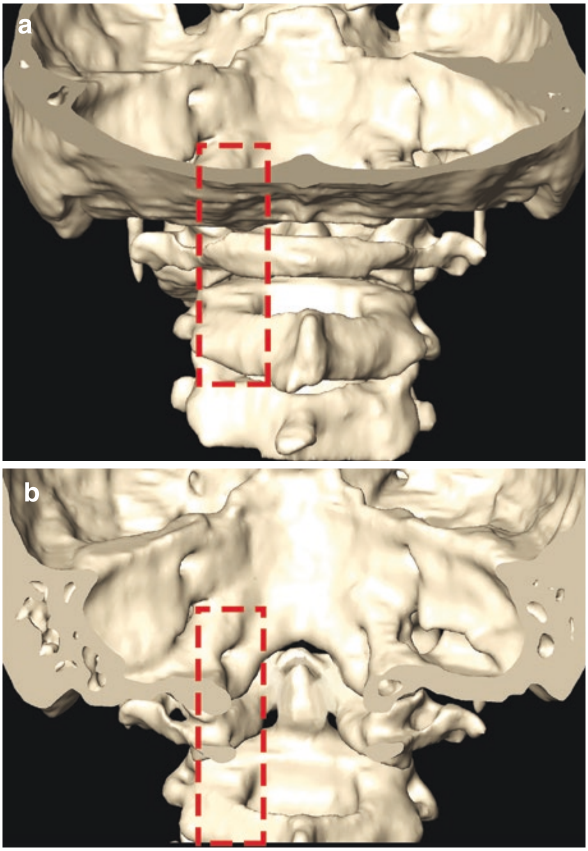


Fig. 1.10 3D anatomical model showing the CVJ bony structures focused by a posterolateral perspective on the extracranial surface (**a**) and on the intracranial surface after removal of the squamous part of the occipital bone and posterior arch of C1. (**b**) The condylar part of the occipital bone and lateral masses of atlas and axis are enclosed in a red dotted rectangular area

The condylar part of the occipital bone includes the occipital condyles and the condylar fossa, and it is situated at the sides of the foramen magnum. The occipital condyles protrude from the external surface of this part. They project downward along the lateral edges of the anterior half of the foramen magnum. The articular surfaces, which are ovoid with the long axis in the anteroposterior direction, are located on the lower-lateral margin of the condyles. They face downward and laterally to articulate with the superior facets of the atlas, which face upward and medially. The condylar fossa is a depression on the external surface of the occipital bone behind the condyle [20, 21].

Lateral masses are the most voluminous bony parts of atlas forming four facet joints. The upper surface of each lateral mass has an oval concave facet that faces upward and medially and articulates with the occipital condyle that faces downward and laterally. The inferior surface of each lateral mass has a circular, flat, or slightly concave facet that faces downward, medially, and slightly backward, and it articulates with the superior articular facet of the axis. The lateral mass of the atlas on its upper-outer surface has a groove in which the V3 segment of the vertebral artery courses. The groove may be partly or fully converted into a foramen by a bridge of bone that arches backward from the posterior edge of the superior articular facet of the atlas to its posterior arch. The medial aspect of each lateral mass has a small tubercle for the attachment of the transverse ligament of the atlas [1, 5, 22, 23].

Each lateral mass of the axis consists of a pair of large oval facets that extend laterally from the vertebral body onto the adjoining parts of the pedicles and articulate with the inferior facets of the atlas superiorly and the superior facet of the third cervical vertebra inferiorly. The superior facets do not form an articular pillar with the inferior facets but are anterior to the latter [5, 20, 23].

1.3.2 Muscular Relationships

The most superficial layer of muscles of the CVJ that is encountered through a posterolateral perspective is formed by the sternocleidomastoid that passes obliquely downward across the side of the neck from the lateral half of the superior nuchal line and mastoid process to the upper part of the sternum and the adjacent part of the clavicle. The splenius capitis in its lateral half is partially covered by the sternocleidomastoid. It extends from the lateral third of the superior nuchal line medially to the spinous processes of the lower cervical and upper thoracic vertebrae. Deep to the splenius capitis and sternocleidomastoid are the semispinalis capitis beginning medially at the midline occipital crest and extending laterally to the occipitomastoid junction in the area between the superior and inferior nuchal lines and the longissimus capitis muscle, which attaches above to the posterior margin of the mastoid process. Both of these muscles attach below to the upper thoracic and lower cervical vertebrae (Fig. 1.11) [4, 22, 24].

The occipital artery is also exposed together with the superficial and deep muscles in this region. It courses medially related to the longissimus capitis and semispinalis capitis just below the superior nuchal line to ascend in the superficial fascia of the posterior scalp. The great occipital nerve ascends with the occipital artery and supplies the scalp as far forward as the vertex and occasionally the back of the ear. It ascends obliquely between the inferior oblique and the semispinalis capitis muscles and pierces the latter and the trapezius muscle near their attachments to the occipital bone [17, 25].

In the next layer, the muscles bounding the suboccipital triangle are covered by the semispinalis capitis medially and by the splenius capitis laterally (Figs. 1.12 and 1.13). The superior oblique muscle extends from the area lateral to the semispinalis capitis between the superior and inferior nuchal lines to the transverse process of the atlas. The inferior oblique muscle extends from the spinous process of the axis to the transverse process of the atlas. The rectus capitis posterior major extends from and below the lateral part of the inferior nuchal line to the spine of the axis. The triangle deep to these muscles is covered by a layer of dense fibro-fatty tissue. The structures in the triangle are the V3 segment of the vertebral artery on the posterior arch of the atlas and the first cervical nerve [10, 17, 22, 25].

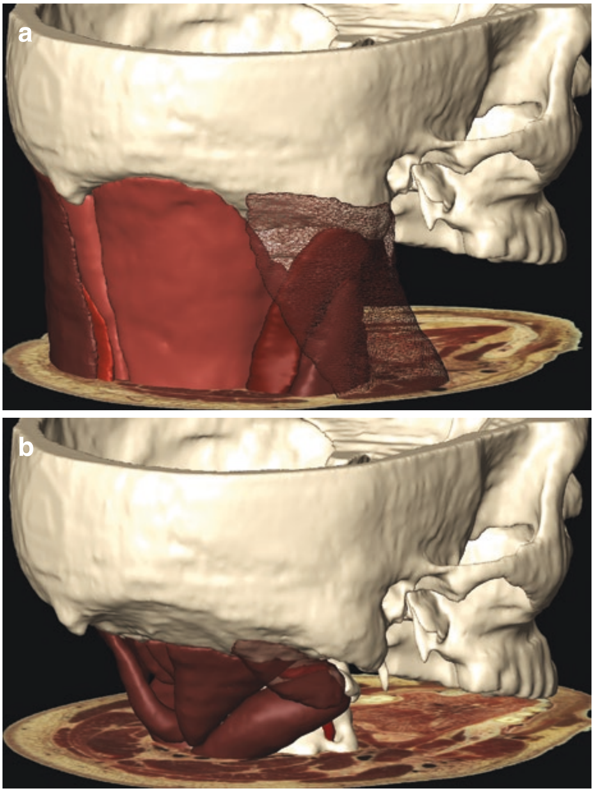


Fig. 1.11 Muscular structures visualized through a posterolateral perspective of the CVJ are represented in a 3D anatomical model. The superficial layer (**a**) with the transparent sternocleidomastoid and the muscles bounding the suboccipital triangle (**b**) are reconstructed

1.3.3 Extradural Structures

Through a posterolateral perspective, the segment of the vertebral artery extending from the transverse foramen of C2 to its entrance to the dura is exposed (V3). The artery, after ascending through the transverse process of the atlas, is located on the medial side of the rectus capitis lateralis muscle. From here it turns medially behind the lateral mass of the atlas and the atlanto-occipital joint and is pressed into the groove on the upper surface of the posterior arch of the atlas, where it courses in the floor of the suboccipital triangle. The triangle is not always easy to identify because of the thick fascia, which covers the deepest layer of the posterior neck muscles. This fascia and the underlying fat and the rich paravertebral venous plexus obscure the anatomical relationship of these muscles (Figs. 1.14 and 1.15) [17, 23].

At the level of the intervertebral foramen dorsal and ventral cervical nerves, roots unite to form the spinal nerve. At the same level, the neurons of the dorsal roots collect to form ganglia. The ganglion associated at the first cervical dorsal root may be absent. The C1, C2, and C3 nerves, distal to the ganglion, divide into dorsal and ventral rami. The dorsal rami divide into medial and lateral branches that supply the skin and muscles of the posterior region of the neck. The C1 nerve, termed the suboccipital nerve, leaves the vertebral canal between the occipital

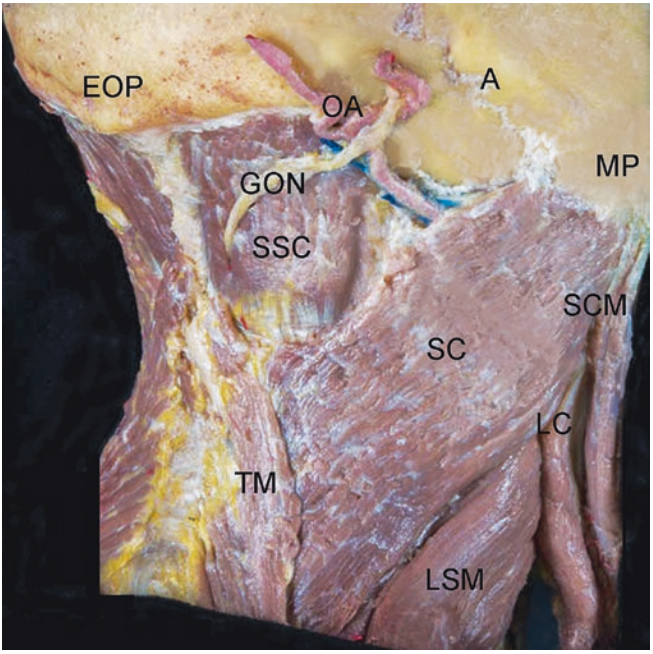


Fig. 1.12 The posterolateral perspective of the CVJ: muscular relationships. The most superficial layer of muscles is formed by the sternocleidomastoid that passes obliquely downward across the side of the neck from the lateral half of the superior nuchal line and mastoid process to the upper part of the sternum and the adjacent part of the clavicle. The splenius capitis in its lateral half is partially covered by the sternocleidomastoid. It extends from the lateral third of the superior nuchal line medially to the spinous processes of the lower cervical and upper thoracic vertebrae. Deep to the splenius capitis and sternocleidomastoid are the semispinalis capitis beginning medially at the midline occipital crest and extending laterally to the occipito-mastoid junction in the area between the superior and inferior nuchal lines, and the longissimus capitis muscle, which attaches above to the posterior margin of the mastoid process. Both of these muscles attach below to the upper thoracic and lower cervical vertebrae. The occipital artery is also exposed together with the superficial and deep muscles in this region. It courses medially related to the longissimus capitis and semispinalis capitis just below the superior nuchal line to ascend in the superficial fascia of the posterior scalp. The great occipital nerve ascends with the occipital artery and supplies the scalp as far forward as the vertex and occasionally the back of the ear. It ascends obliquely between the inferior oblique and the semisplenius capitis muscles and pierces the latter and the trapezius muscle near their attachments to the occipital bone. *A* asterion; *EOP* external occipital protuberance; *GON* great occipital nerve; *LC* longissimus capitis muscle; *LSM* levator scapulae muscle; *MP* mastoid process; *OA* occipital artery; *SC* splenius capitis; *SCM* sternocleidomastoid muscle, partially removed; *SSC* semispinalis capitis; *TM* trapezius muscle

bone and atlas and has a dorsal ramus that is larger than the ventral ramus. The dorsal ramus courses between the posterior arch of the atlas and the vertebral artery to reach the suboccipital triangle, where it sends branches to the rectus capitis posterior major and minor, superior and inferior oblique, and the semispinalis capitis, and occasionally has a cutaneous branch that accompanies the occipital artery to the scalp. The C1 ventral ramus courses between the posterior arch of the

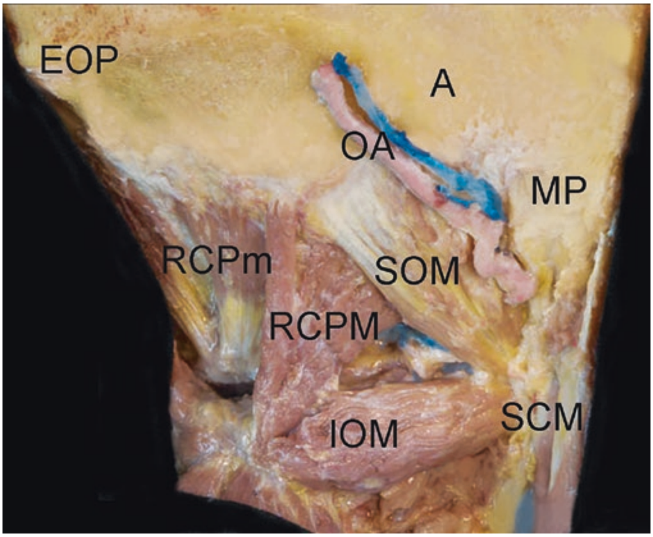


Fig. 1.13 The posterolateral perspective of the CVJ: muscular relationships. The muscles bounding the suboccipital triangle are exposed. The superior oblique muscle extends between the superior and inferior nuchal lines to the transverse process of the atlas. The inferior oblique muscle extends from the spinous process of the axis to the transverse process of the atlas. The rectus capitis posterior major extends from and below the lateral part of the inferior nuchal line to the spine of the axis. The triangle deep to these muscles is covered by a layer of dense fibrofatty tissue. The structures in the triangle are the V3 segment of the vertebral artery on the posterior arch of the atlas and the first cervical nerve. *A* asterion; *EOP* external occipital protuberance; *IOM* inferior oblique muscle; *MP* mastoid process; *OA* occipital artery; *RCPM* rectus capitis posterior major muscle; *RCPm* rectus capitis posterior minor muscle; *SCM* sternocleidomastoid muscle; *SOM* superior oblique muscle

atlas and the vertebral artery and passes forward, lateral to the lateral mass of the atlas and medial to the vertebral artery, and supplies the rectus capitis lateralis. The C2 nerve emerges between the posterior arch of the atlas and the lamina of the axis where the spinal ganglion is located extradurally, medial to the inferior facet of C1 and the vertebral artery. Distal to the ganglion, the nerve divides into a larger dorsal and a smaller ventral ramus. After passing below and supplying the inferior oblique muscle, the dorsal ramus divides into a large medial and a small lateral branch. The medial branch forms the greater occipital nerve. The lateral branch sends filaments that innervate the splenius, longissimus, and semisplenius capitis and is often joined by the corresponding branch from the C3 nerve. The C2 ventral ramus courses between the vertebral arches and transverse processes of the atlas and axis and behind the vertebral artery. Two branches of the C2 and C3 ventral rami, the lesser occipital and greater auricular nerves, curve around the posterior border and ascend on the sternocleidomastoid muscle to supply the skin behind the ear [1, 2, 6, 24].

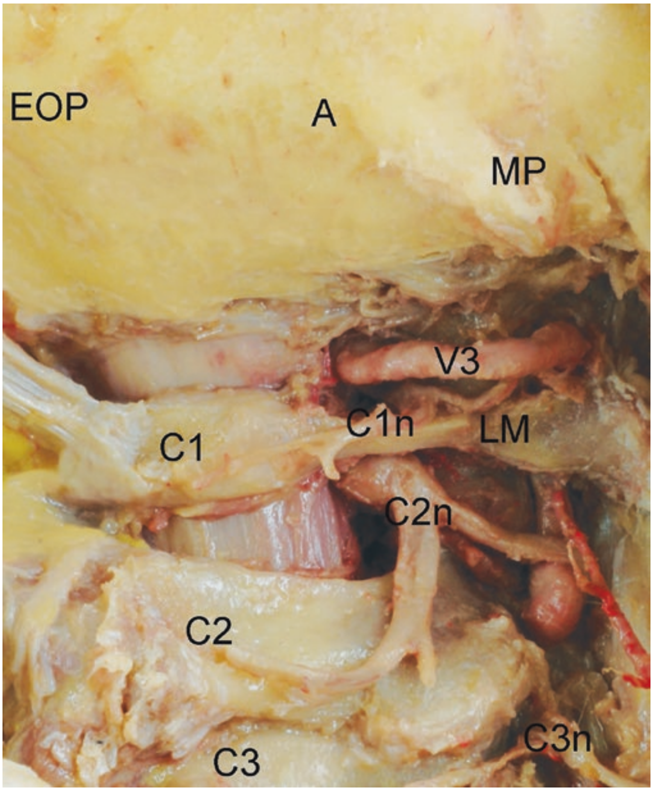


Fig. 1.14 The posterolateral perspective of the CVJ is directed at the external surface of the squamosal part of the occipital bone that extends from the EOP to the mastoid process of the temporal bone. On this surface, an important bony landmark is the asterion, located at the junction of the lambdoid, occipito-mastoid, and parieto-mastoid sutures. The asterion is commonly related to the lower half of the junction of the transverse and sigmoid sinuses. The lateral mass of the atlas on its upper-outer surface has a groove in which the V3 segment of the vertebral artery courses. The groove may be partly or fully converted into a foramen by a bridge of bone that arches backward from the posterior edge of the superior articular facet of the atlas to its posterior arch. *A* asterion; *C1* atlas; *C1n* suboccipital nerve; *C2* axis; *C2n* second cervical nerve; *C3* third cervical vertebra; *C3n* third cervical nerve; *EOP* external occipital protuberance; *LM* lateral mass of the atlas; *MP* mastoid process; *V3* third segment of the vertebral artery

The condylar foramen is present in the condylar fossa posterior to the occipital condyle. It transmits the posterior condylar vein, which is an important emissary vein of the cranium. This vein connects the vertebral venous plexus with the sigmoid-jugular complex. The condylar foramen is one of the largest emissary foramina of the skull and the posterior condylar vein, which traverses it, forms an important alternative source of venous drainage when the venous flow into the sigmoid sinus-jugular complex is impeded [22, 23, 25].

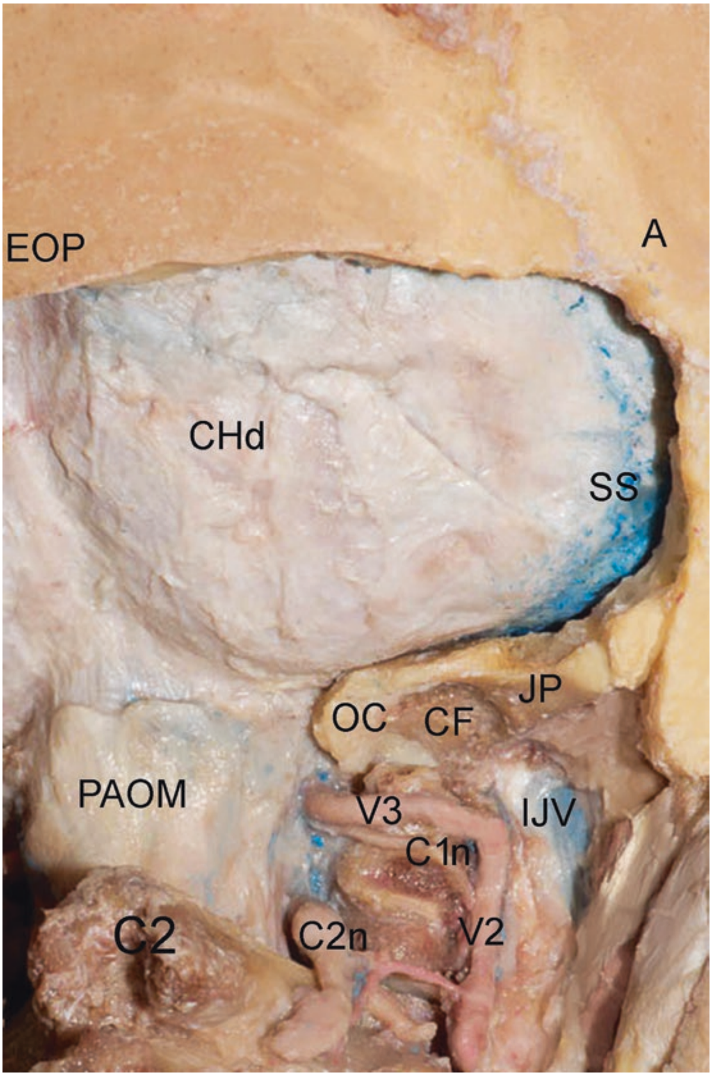
The hypoglossal canal (HC), which transmits the hypoglossal nerve, is situated above the condyle and is directed forward and laterally from the posterior cranial fossa. The canal is surrounded superiorly by the jugular tubercle, supero-laterally by the jugular foramen, laterally by the sigmoid sinus, and inferiorly by the occipital condyle. The intracranial end of the HC is located approximately 5 mm above the junction of the posterior and middle third of the occipital condyle and appropriately 5 mm below the jugular tubercle. The extracranial end is located immediately above the junction of the anterior and middle third of the occipital condyle and medial to the jugular foramen. The HC is surrounded by cortical bone. It consists of the hypoglossal nerve, a meningeal branch of the ascending pharyngeal artery, and the venous plexus of the hypoglossal canal, which communicates the basilar venous plexus with the marginal sinus that encircles the foramen magnum. The hypoglossal nerve enters the canal as two groups of roots that merge just before exiting the canal (Fig. 1.16) [6, 26, 27].

The sigmoid sinus borders the posterior cranial fossa laterally and descends along the sigmoid groove. It exits the cranium through the sigmoid part of the jugular foramen and descends anterolateral to the occipital condyle and anterior to the transverse process of the atlas [8, 13, 23].

Fig. 1.15 Posterolateral perspective of the CVJ. The squamosal part of occipital bone in its posterolateral aspect, from the external occipital protuberance to the asterion and mastoid process, has been removed. The posterior border of the foramen magnum has been opened and the posterior arch of C1 removed. The dura mater covering the cerebellar hemisphere in the posterior cranial fossa is exposed. The sigmoid sinus borders the posterior cranial fossa laterally and descends along the sigmoid groove. It exits the cranium through the sigmoid part of the jugular foramen and descends anterolateral to the occipital condyle and anterior to the transverse process of the atlas. The condylar part of the occipital bone is situated at the sides of the foramen magnum and includes the occipital condyles and the condylar fossa. The condylar fossa is a depression on the external surface of the occipital bone behind the condyle. The occipital condyles, which articulate with the atlas, protrude from the external surface of this part. The articular surfaces are located on the lower-lateral margin of the condyles. They face downward and laterally to articulate with the superior facets of the atlas, which face upward and medially. Lateral masses are the most voluminous bony parts of atlas forming four facet joints. The upper surface of each lateral mass articulates with the occipital condyle. The inferior surface articulates with the superior articular facet of the axis. At the level of the intervertebral foramen dorsal and ventral cervical nerves roots unite to form the spinal nerve. At the same level, the neurons of the dorsal roots collect to form ganglia. The ganglion associated at the first cervical dorsal root may be absent. The C1 nerve, termed the suboccipital nerve, leaves the vertebral canal between the occipital bone and atlas and has a dorsal ramus that is larger than the ventral ramus. The C2 nerve emerges between the posterior arch of the atlas and the lamina of the axis where the spinal ganglion is located extradurally, medial to the inferior facet of C1 and the vertebral artery. Distal to the ganglion, the nerve divides into a larger dorsal and a smaller ventral ramus. *A* asterion; *C1n* suboccipital nerve; *C2* spinous process of the axis; *C2n* second cervical nerve; *CF* condylar fossa; *CHd* dura mater covering the cerebellar hemisphere; *EOP* external occipital protuberance; *IJV* internal jugular vein; *JP* jugular process; *OC* occipital condyle; *PAOM* posterior atlanto-occipital membrane; *SS* sigmoid sinus; *V2* second segment of the vertebral artery; *V3* third segment of the vertebral artery

1.3.4 Intradural Structures

The posterolateral perspective at the CVJ allows for intradural exposure of the cerebello-medullary cistern and posterior spinal cistern. The cerebello-medullary cistern extends from the dorsal margin of the inferior olive around the dorsolateral medulla to the biventral lobule of the cerebellum. The glossopharyngeal (IX) and vagal nerves (X) and the medullary portion of the accessory nerve (XI) arise within and course through this cistern to reach the jugular foramen (Fig. 1.17). The intradural segment of the vertebral artery (V4) can be divided into a lateral medullary



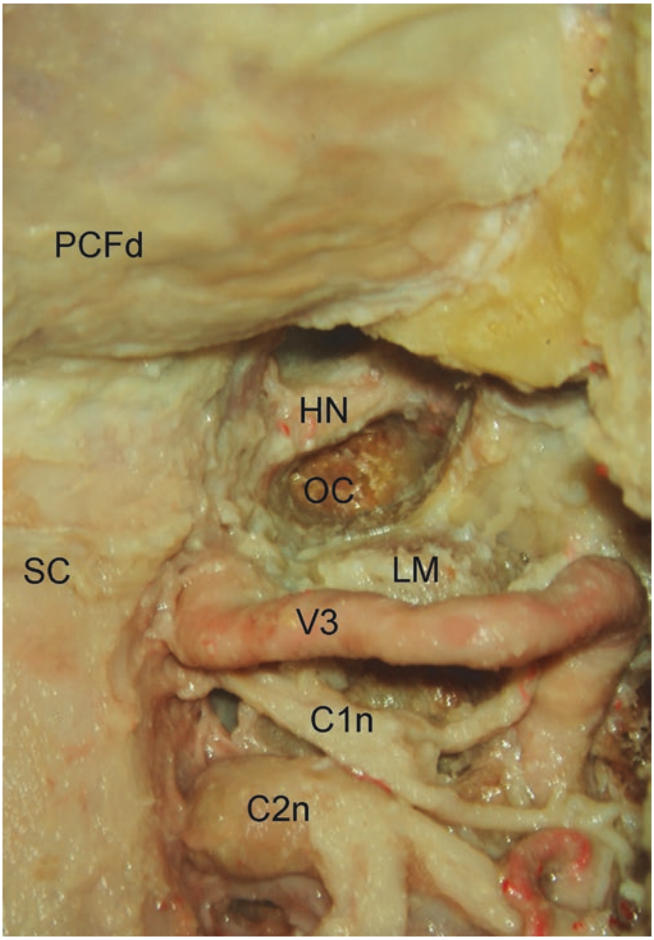


Fig. 1.16 Posterolateral perspective of the CVJ. The hypoglossal nerve is exposed after the opening of the hypoglossal canal. The hypoglossal canal is situated above the condyle and is directed forward and laterally from the posterior cranial fossa. The canal is surrounded superiorly by the jugular tubercle, supero-laterally by the jugular foramen, laterally by the sigmoid sinus, and inferiorly by the occipital condyle. The intracranial end of the hypoglossal canal is located approximately 5 mm above the junction of the posterior and middle third of the occipital condyle and appropriately 5 mm below the jugular tubercle. The extracranial end of the hypoglossal canal is located immediately above the junction of the anterior and middle third of the occipital condyle and medial to the jugular foramen. The hypoglossal canal is surrounded by the cortical bone. *C1n* first cervical nerve; *C2n* second cervical nerve; *HN* hypoglossal nerve; *LM* lateral mass of the atlas; *OC* occipital condyle; *PCFd* dura of the posterior cranial fossa; *SC* spinal cord; *V3* third segment of the vertebral artery

segment and an anterior medullary segment. The V4 lateral medullary segment begins at the dural foramen and passes anterior and superior along the lateral medullary surface to terminate at the pre-olivary sulcus. The posterior inferior cerebellar artery (PICA) enters this cistern after originating from the fourth segment (V4) of

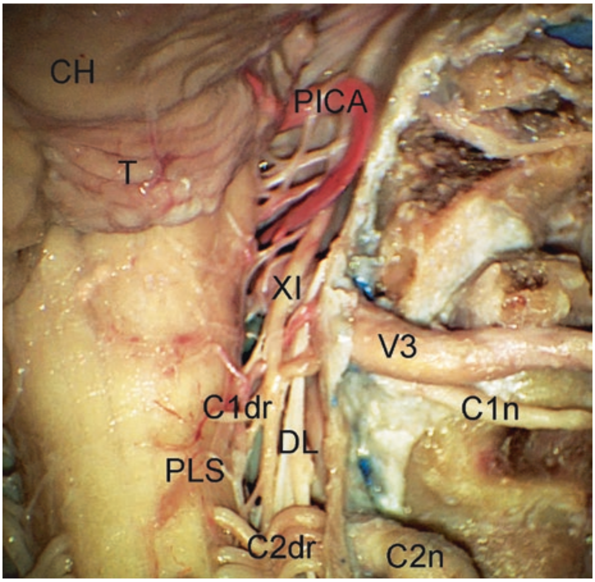


Fig. 1.17 Posterolateral intradural perspective of the CVJ. At the level of the spinal cord, the posterior lateral sulcus is situated along the line where the dorsal roots enter the spinal cord. Each dorsal root is composed of a series of six to eight rootlets. The dorsal roots of the first two cervical nerves pass posterior to the dentate ligament and accessory nerve. *CH* cerebellar hemisphere; *C1dr* dorsal root of the first cervical nerve; *C1n* first cervical nerve; *C2dr* dorsal roots of the second cervical nerve; *C2n* second cervical nerve; *DL* dentate ligament; *PICA* posterior inferior cerebellar artery; *PLS* posterior lateral sulcus; *T* tonsil; *V3* third segment of the vertebral artery; *XI* accessory nerve

the vertebral artery intradurally. In the cerebello-medullary cistern, the PICA passes dorsally between the rootlets of the IX, X, and XI cranial nerves and pursues a posterior course around the medulla (Fig. 1.18) [19, 20, 28, 29].

The lateral surface of the medulla is formed predominantly by the inferior olives. The glossopharyngeal, vagus, and accessory nerves arise from the medulla as a line of rootlets situated along the posterior edge of the inferior olive in the post-olivary sulcus. The only location where the glossopharyngeal nerve may consistently be distinguished from the vagal nerve is just proximal to a dural septum, which separates these nerves as they penetrate the dura to enter the jugular foramen. The hypoglossal nerve arises as a line of rootlets that exit the brainstem along the anterior margin of the lower olive in the pre-olivary sulcus, a groove between the olive and medullary pyramid. The rootlets of the XII pass behind the vertebral artery to reach the hypoglossal canal. The vertebral artery may stretch the hypoglossal rootlets posteriorly over its dorsal surface. The accessory nerve in the cranial fossa is composed of one main trunk from the spinal cord and three to six small rootlets that emerge from the medulla. The nerve joins the vagus nerve entering the jugular foramen (Fig. 1.19) [6, 14].

At the level of the spinal cord, the posterior lateral sulcus is situated along the line where the dorsal roots enter the spinal cord. Each dorsal root is composed of a

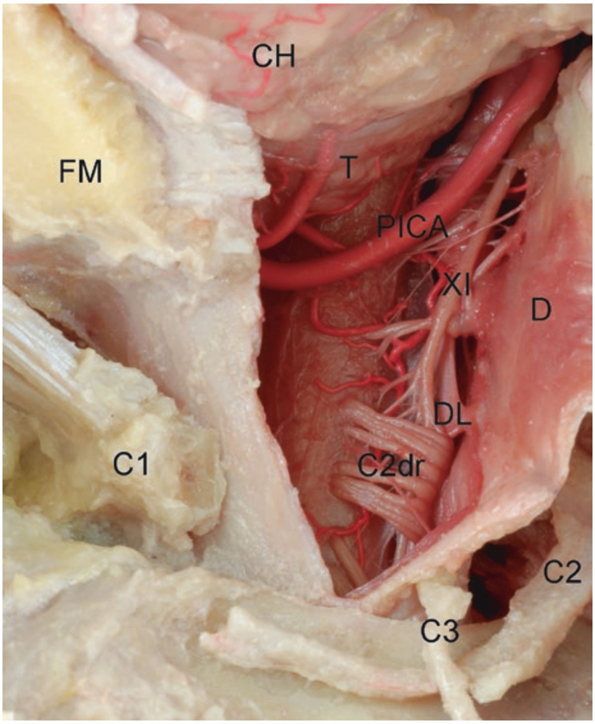


Fig. 1.18 Posterolateral intradural perspective of the CVJ. The posterior inferior cerebellar artery enters the cerebello-medullary cistern after originating from the fourth segment of the vertebral artery. In the cerebello-medullary cistern, the posterior inferior cerebellar artery passes dorsally between the rootlets of the IX, X, and XI cranial nerves and pursues a posterior course around the medulla. *CH* cerebellar hemisphere; *C1* atlas partially removed; *C2* second cervical nerve; *C2dr* dorsal roots of the second cervical nerve; *C3* third cervical nerve; *D* dura mater opened; *DL* dentate ligament; *FM* posterior border of foramen magnum partially opened; *PICA* posterior inferior cerebellar artery; *T* tonsil; *XI* accessory nerve

series of six to eight rootlets that fan out to enter the posterolateral surfaces of the spinal cord. The dorsal roots of the first two cervical nerves pass posterior to the dentate ligament and accessory nerve [2, 9].

The lateral posterior spinal vein, which courses along the line of origin of the dorsal roots in the posterior lateral spinal sulcus, is continuous above with the lateral medullary vein that courses along the retro-olivary sulcus, dorsal to the olive [4, 14].

1.4 Anterolateral Perspective of the CVJ

1.4.1 Bony Structures

The anterolateral perspective of the CVJ is directed to the jugular foramen and transverse process of C1 and C2 (Fig. 1.20).

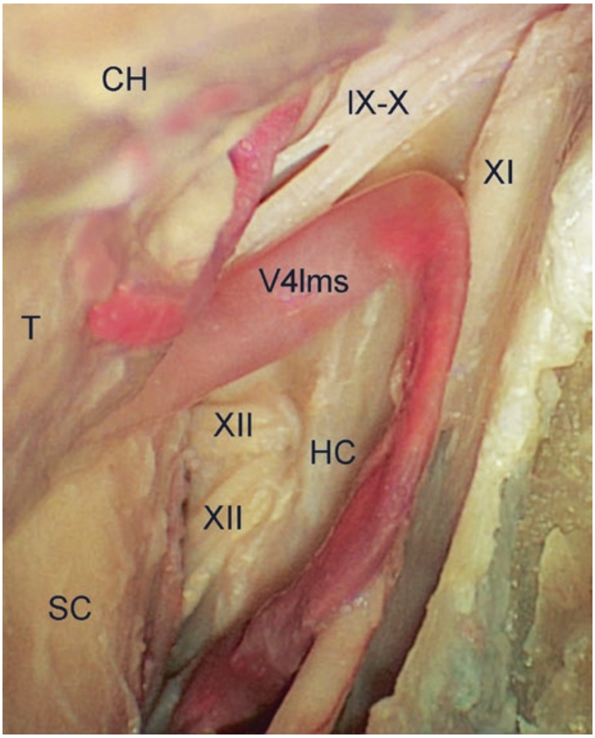


Fig. 1.19 Posterolateral intradural perspective of the CVJ. The lateral medullary segment of the vertebral artery begins at the dural foramen and passes anterior and superior along the lateral medullary surface to terminate at the pre-olivary sulcus in the cerebello-medullary fissure. The hypoglossal nerve arises as a line of rootlets that exit the brainstem along the anterior margin of the lower olive in the pre-olivary sulcus. The medullary trunk of the accessory nerve running toward the jugular foramen together with the glossopharyngeal and vagal nerves is exposed. *CH* cerebellar hemisphere; *HC* hypoglossal canal; *SC* spinal cord; *T* cerebellar tonsil; *V4lms* lateral medullary segment of the fourth segment of the vertebral artery; *IX-X* glossopharyngeal and vagal nerves; *XI* accessory nerve; *XII* hypoglossal nerve

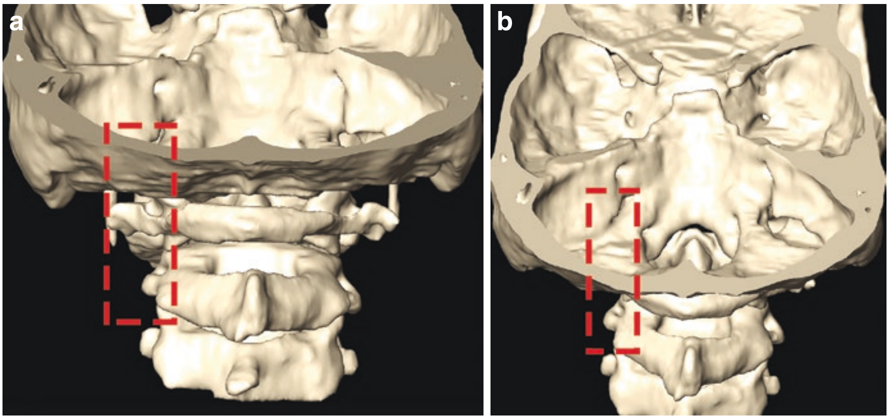


Fig. 1.20 3D reconstruction of the anterolateral perspective to the CVJ limited by a red dotted rectangular area on the extracranial (**a**) and intracranial (**b**) surfaces from a posterior view

The jugular foramen (JF) is a canal-like aperture, which is formed by the combination of the most indented parts of the occipital and temporal bones. The jugular process consists of a quadrilateral plate of bone that extends laterally from the posterior half of the condyle to form the posterior border of the jugular foramen. It serves as a bridge between the condylar and squamosal portions of the occipital bone and forms the posteromedial wall of the foramen. The jugular process is penetrated by the hypoglossal canal. It articulates laterally with the jugular surface of the temporal bone. The jugular process also serves as the site of attachment of the rectus capitis lateralis muscle behind the jugular foramen. The upper surface of the jugular process at the junction of the basilar and condylar parts of the occipital bone presents an oval prominence, the jugular tubercle. It is situated above the hypoglossal canal and medial to the lower half of the intracranial end of the jugular foramen [28, 30–32].

The transverse foramen of the atlas, which transmits the vertebral artery, is situated between the lateral mass and the transverse process. The transverse process of the atlas projects in the area between the mastoid process and the angle of the mandible, further lateral than the transverse processes on the adjacent cervical vertebrae. It has an apex that gives attachment to several muscles: the rectus capitis lateralis arises from the anterior portion; the superior oblique arises from the posterior portion of the upper surface of the transverse process; the inferior oblique muscle inserts on the lateral tip of the transverse process; the levator scapulae, splenius cervicis, and the scalenus medius attach to the inferior and lateral surface of the transverse process [2, 9, 22].

The transverse processes of the axis are small. Each transverse foramen faces supero-laterally, thus permitting the lateral deviation of the vertebral artery as it passes up to the more widely separated transverse foramina in the atlas [5, 9].

1.4.2 Muscular Relationships

The sternocleidomastoid muscle that passes obliquely downward from the lateral half of the superior nuchal line and mastoid process divides the side of the neck into an anterior triangle and a posterior triangle. The anterior triangle corresponds to the anterolateral aspect of the CVJ. It is bounded posteriorly by the anterior border of the sternocleidomastoid, laterally by the mandible and parotid gland, superiorly by the region of the jugular foramen and the mastoid process and anteriorly by the median line of the neck. In the fatty pad situated deep to the sternocleidomastoid runs the accessory nerve that supplies the muscle. In a deeper layer the posterior belly of the digastric muscle arises in the digastric groove located medial to the mastoid process and the longissimus capitis. Reflecting the digastric muscle exposes the transverse process of the atlas, which is covered by the attachments of numerous muscles, including the superior and inferior obliques, which form the upper and lower margins of the suboccipital triangle (Figs. 1.21 and 1.22) [3, 6–8]. The rectus

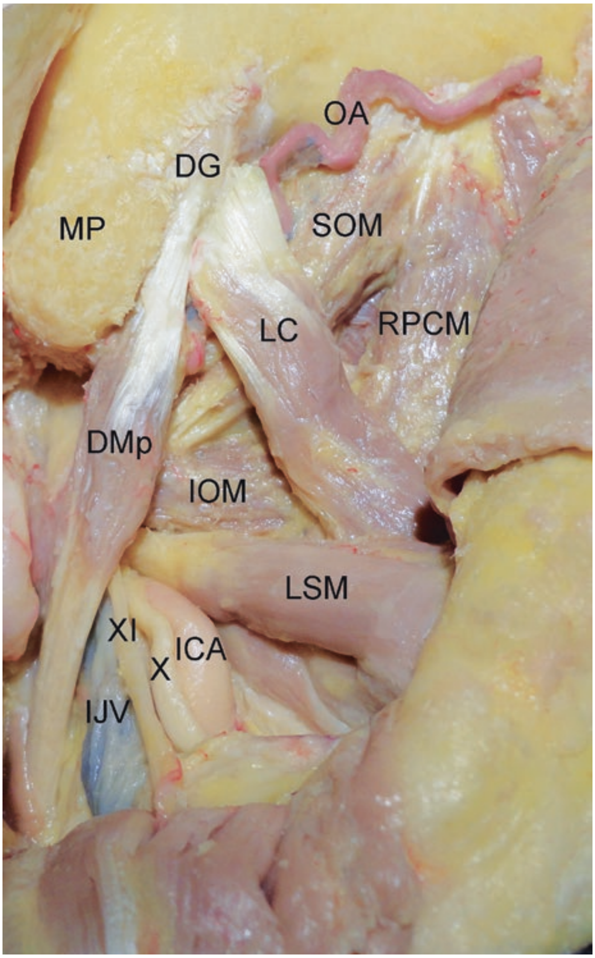


Fig. 1.21 Anterolateral perspective of the CVJ: muscular relationships. The sternocleidomastoid muscle has been reflected inferiorly and the semispinalis capitis laterally. Deeper to the sternocleidomastoid muscle, the posterior belly of the digastric muscle arises in the digastric groove located medial to the mastoid process and the longissimus capitis. Reflecting the digastric muscle exposes the transverse process of the atlas, which is covered by the attachments of numerous muscles, including the superior and inferior obliques, which form the upper and lower margin of the suboccipital triangle. *DG* digastric groove; *DMp* posterior belly of digastric muscle; *ICA* internal carotid artery; *IJV* internal jugular vein; *IOM* inferior oblique muscle; *LC* longissimus capitis muscle; *LSM* levator scapulae muscle; *MP* mastoid process; *OA* occipital artery; *RCPM* rectus capitis posterior major muscle; *SOM* superior oblique muscle; *X* vagal nerve; *XI* accessory nerve

capitis lateralis muscle is the muscle most intimately related to the jugular foramen. It is considered together with the anterior vertebral muscles. It extends vertically behind the internal jugular vein from the transverse process of the atlas to the jugular process of the occipital bone (Fig. 1.23) [34].

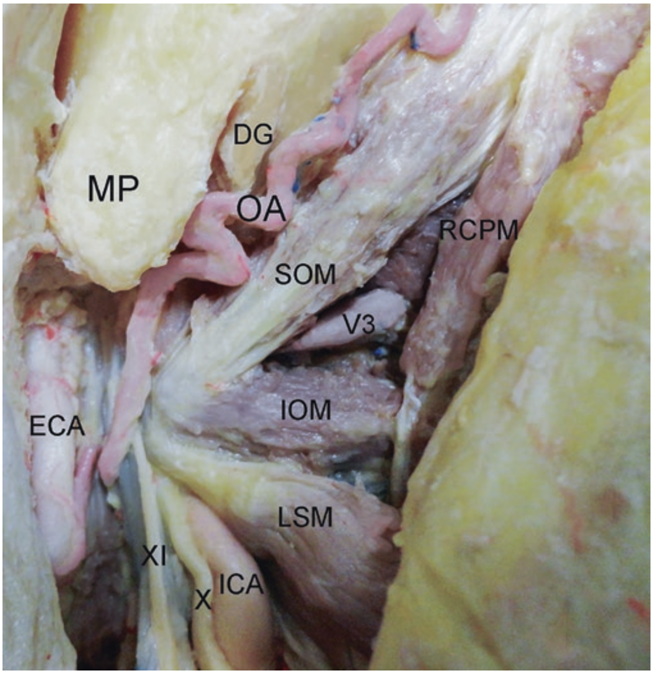


Fig. 1.22 Anterolateral perspective of the CVJ. The relationship between the occipital artery and the muscles on the anterolateral aspect of the CVJ is exposed. It arises from the posterior surface of the external carotid artery at the level of the angle of the mandible and courses obliquely upward between the posterior belly of the digastric muscle and the internal jugular vein, to reach the area posteromedial to the styloid process. At that point, it changes its course to posterior and lateral, passing posterior to the rectus capitis lateralis and then between the superior oblique and the posterior belly of the digastric where it courses in the occipital groove medial to the mastoid notch, in which the posterior belly of the digastric muscle arises. After exiting the area between the superior oblique muscle and the posterior belly of the digastric, it courses medially, being related to the longissimus capitis and semispinalis capitis. It courses medially behind the semispinalis capitis just below the superior nuchal line in the upper part of the posterior triangle to pass between the upper attachment of trapezius and the semispinalis capitis, where it pierces the attachment of the trapezius muscle to the superior nuchal line and ascends in the superficial fascia of the posterior scalp. *DG* digastric groove; *ECA* external carotid artery; *ICA* internal carotid artery; *IOM* inferior oblique muscle; *LSM* levator scapulae muscle; *MP* mastoid process; *OA* occipital artery; *RCPM* rectus capitis posterior major muscle; *SOM* superior oblique muscle; *V3* third segment of the vertebral artery; *XI* accessory nerve; *X* vagal nerve

1.4.3 Extradural Structures

The endocranial surface of the jugular foramen is generally divided into three intrajugular compartments: two venous and a neural compartment (Fig. 1.24). The neural and vascular compartments are generally separated by a bone projection called the intrajugular process. The larger posterolateral venous compartment, the sigmoid compartment, receives the flow of the sigmoid sinus. The sigmoid sinus drains into the internal jugular vein at the jugular bulb. The smaller anteromedial venous

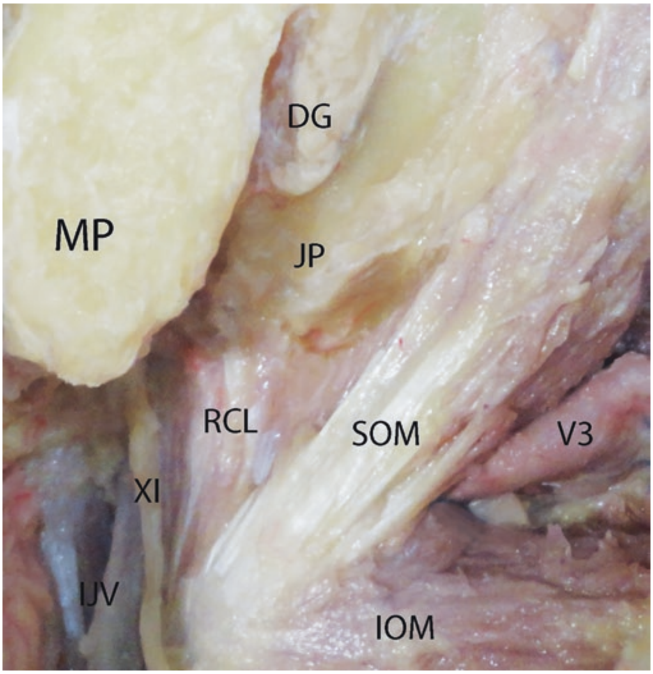


Fig. 1.23 Anterolateral perspective of the CVJ. The rectus capitis lateralis muscle is the muscle most intimately related to the jugular foramen. It is considered together with the anterior vertebral muscles. It extends vertically behind the internal jugular vein from the transverse process of the atlas to the jugular process of the occipital bone. *DG* digastric groove; *IJV* internal jugular vein; *IOM* inferior oblique muscle; *JP* jugular process; *MP* mastoid process; *RCL* rectus capitis lateralis muscle; *SOM* superior oblique muscle; *V3* third segment of the vertebral artery; *XI* accessory nerve

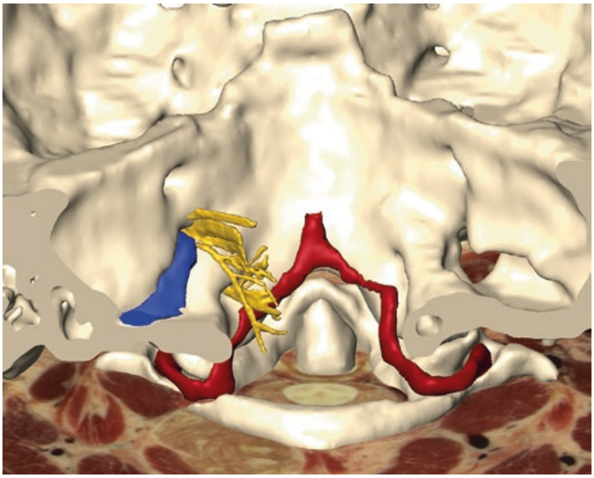


Fig. 1.24 The intracranial surface of the jugular foramen is shown by means of a 3D reconstruction. The neural part is represented in yellow, the venous compartment in blue, and the vertebral arteries joining to form the basilar artery in red

channel, the petrosal part, receives the drainage of the inferior petrosal sinus, besides receiving tributaries from the hypoglossal canal, petroclival fissure, and vertebral venous plexus. The neural part, through which the glossopharyngeal, vagus, and accessory nerves course, is located between the sigmoid and petrosal parts at the site of the intrajugular processes of the temporal and occipital bones, which are joined by a fibrous or osseous bridge. The dura over the neural part of the foramen has two characteristic perforations, a glossopharyngeal meatus, through which the glossopharyngeal nerve passes, and a vagal meatus, through which the vagus and accessory nerves pass. Along their exit from the jugular foramen, the glossopharyngeal, vagus, and accessory nerves penetrate the dura on the medial margin of the intrajugular process of the temporal bone to reach the medial wall of the internal jugular vein [28, 30, 33].

The glossopharyngeal nerve exits the jugular foramen and then turns forward, crossing the lateral surface of the internal carotid artery deep to the styloid process. At the external orifice of the jugular foramen, it gives rise to the tympanic branch (Jacobson's nerve) that provides innervation to the parotid gland. At the level of the vagal meatus, the vagal nerve is joined by the accessory nerve and gives rise to the Arnold's nerve, an auricular branch that join the facial nerve in the temporal bone. The vagal nerve exits the jugular foramen vertically, retaining an intimate relationship to the accessory nerve. At the level the two nerves exit the jugular foramen, they are located behind the glossopharyngeal nerve on the posteromedial wall of the internal jugular vein. As the vagal nerve passes lateral to the outer orifice of the hypoglossal canal, it is joined by the hypoglossal nerve medially. The accessory nerve exiting the jugular foramen descends obliquely laterally between the internal carotid artery and internal jugular vein and then backward across the lateral surface of the vein to reach its muscles. The hypoglossal nerve does not traverse the jugular foramen. However, it joins the nerves exiting the jugular foramen just below the skull and runs with them in the carotid sheath. The nerve exits the inferolateral part of the hypoglossal canal and passes adjacent to the vagal nerve, descends between the internal carotid artery and the internal jugular vein to the level of the transverse process of the atlas, where it turns abruptly forward along the lateral surface of the internal carotid artery toward the tongue (Figs. 1.25 and 1.26) [18, 19, 29, 35].

The internal jugular vein is the most volumetric structure in the JF. The proximal dilated part is called the jugular bulb. Anteriorly the inferior petrosal sinus and posteriorly the sigmoid sinus are the venous structures that drain into the jugular bulb. The top of the jugular bulb may reach out the porus acusticus internus in the temporal bone. The internal jugular vein and its tributaries form the most important drainage system in the craniocervical area [36, 37].

The internal carotid artery passes, almost straightly upward, posterior to the external carotid artery and anteromedial to the internal jugular vein, to reach the carotid canal. At the level of the skull base, the internal jugular vein courses just posterior to the internal carotid artery, being separated from it by the carotid ridge. Between them, the glossopharyngeal nerve is located laterally and the vagus, accessory, and hypoglossal nerves medially [7, 28].

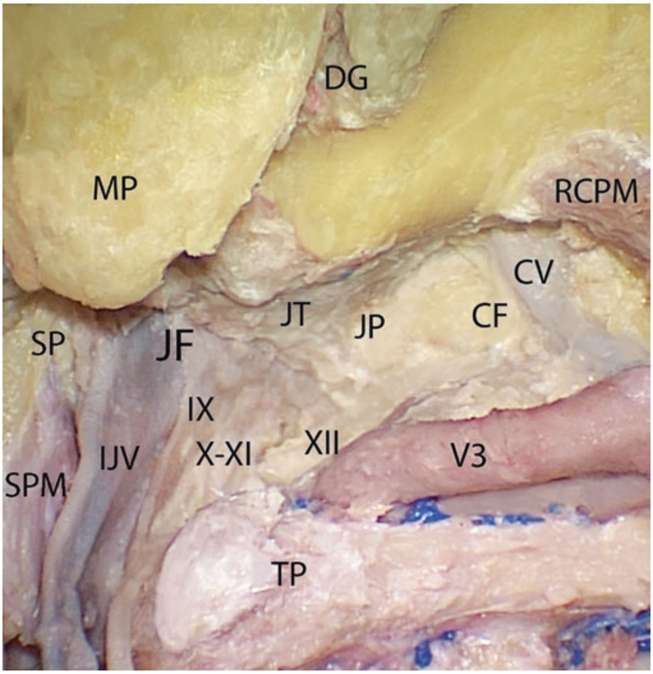


Fig. 1.25 Anterolateral perspective of the CVJ. The extracranial opening of the jugular foramen is exposed. The glossopharyngeal nerve exits the jugular foramen and then turns forward, crossing the lateral surface of the internal carotid artery deep to the styloid process. The vagal nerve exits the jugular foramen vertically, retaining an intimate relationship to the accessory nerve. At the level the two nerves exit the jugular foramen, they are located behind the glossopharyngeal nerve on the posteromedial wall of the internal jugular vein. As the vagal nerve passes lateral to the outer orifice of the hypoglossal canal, it is joined by the hypoglossal nerve medially. The accessory nerve exiting the jugular foramen descends obliquely laterally between the internal carotid artery and internal jugular vein and then backward across the lateral surface of the vein to reach its muscles. The hypoglossal nerve does not traverse the jugular foramen. However, it joins the nerves exiting the jugular foramen just below the skull and runs with them in the carotid sheath. The nerve exits the inferolateral part of the hypoglossal canal and passes adjacent to the vagal nerve, descends between the internal carotid artery and the internal jugular vein to the level of the transverse process of the atlas, where it turns abruptly forward along the lateral surface of the internal carotid artery toward the tongue. *CF* condylar fossa; *CV* condylar vein; *DG* digastric groove; *IJV* internal jugular vein; *JF* jugular foramen; *JP* jugular process; *JT* jugular tubercle; *MP* mastoid process; *RCPM* rectus capitis posterior major muscle; *SP* styloid process; *SPM* stylopharyngeus muscle; *TP* transverse process of the atlas; *V3* third segment of the vertebral artery; *IX* glossopharyngeal nerve; *X* vagal nerve; *XI* accessory nerve; *XII* hypoglossal nerve

The external carotid artery ascends anterior to the internal carotid artery. Proximal to its terminal bifurcation into the maxillary and the superficial temporal arteries, it gives rise to the posterior branches that are related to the jugular foramen: the ascending pharyngeal artery, the occipital artery and the posterior auricular artery [1, 7].

The occipital artery is the largest branch of the posterior group. It arises from the posterior surface of the external carotid artery at the level of the angle of the

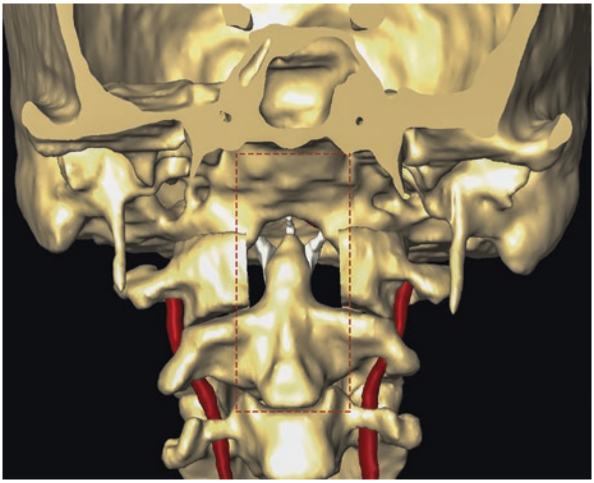


Fig. 1.26 The anteromedial perspective of the CVJ with removal of the anterior arch of C1 is limited by a red dotted rectangular area on a 3D model

mandible and courses obliquely upward between the posterior belly of the digastric muscle and the internal jugular vein, to reach the area posteromedial to the styloid process. At that point, it changes its course to posterior and lateral, passing posterior to the rectus capitis lateralis and then between the superior oblique and the posterior belly of the digastric where it courses in the occipital groove medial to the mastoid notch, in which the posterior belly of the digastric muscle arises. After exiting the area between the superior oblique muscle and the posterior belly of the digastric, it courses medially, being related to the longissimus capitis and semispinalis capitis. It courses medially behind the semispinalis capitis just below the superior nuchal line in the upper part of the posterior triangle to pass between the upper attachment of trapezius and the semispinalis capitis, where it pierces the attachment of the trapezius muscle to the superior nuchal line and ascends in the superficial fascia of the posterior scalp [2, 25].

The vertebral artery, above the transverse foramen of the axis, veers laterally to reach the transverse foramen of the atlas, which is situated further lateral than the transverse foramen of the axis (second segment of the vertebral artery, V2). The artery, after ascending through the transverse process of the atlas, is located on the medial side of the rectus capitis lateralis muscle. From here it turns medially behind the lateral mass of the atlas and the atlanto-occipital joint and is pressed into the groove on the upper surface of the posterior arch of the atlas (V3) [5, 9, 17].

1.5 Anteromedial Perspective of the CVJ

The anteromedial perspective of the CVJ provides exposure of the clival portion of occipital bone, anterior border of foramen magnum, anterior arch of C1, and the odontoid process (Fig. 1.26).

1.5.1 Bony Structures

The clivus, or basilar part of the occipital bone, is a thick quadrangular plate of bone that extends forward and upward, at an angle of about 45° from the foramen magnum. It joins the sphenoid bone at the spheno-occipital synchondrosis just below the dorsum sellae. The clivus is separated on each side from the petrous part of the temporal bone by the petroclival fissure. This fissure has the inferior petrosal sinus on its upper surface and ends posteriorly at the jugular foramen. 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. On the inferior surface of the basilar part, in front of the foramen magnum, a small elevation, the pharyngeal tubercle, gives attachment to the fibrous raphe of the pharynx (Fig. 1.27) [4, 38, 39].

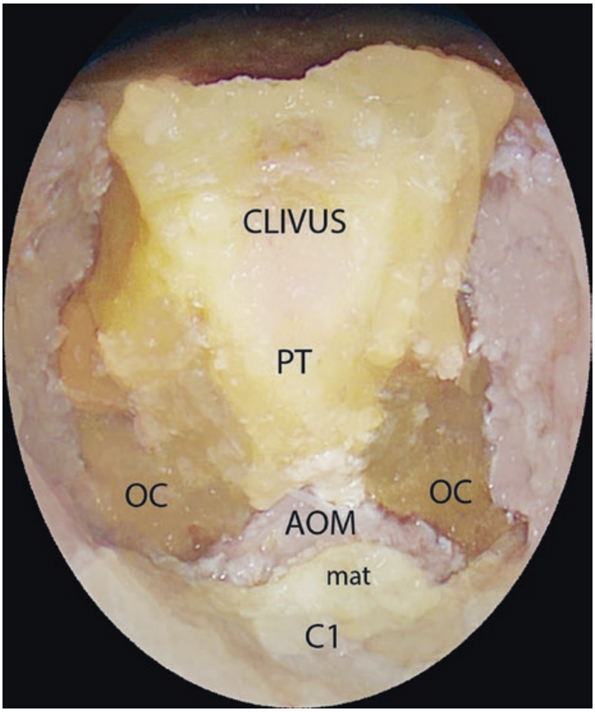


Fig. 1.27 Endoscopic endonasal exposure of the anteromedial aspect of the CVJ. The clivus, or basilar part of the occipital bone, is a thick quadrangular plate of bone that extends forward and upward, at an angle of about 45° from the foramen magnum. On the inferior surface of the basilar part, in front of the foramen magnum, a small elevation, the pharyngeal tubercle, gives attachment to the fibrous raphe of the pharynx. The anterior arch of the atlas is short and convexed forward and has a median anterior tubercle. The anterior atlanto-occipital membrane is a thin structure that attaches the anterior aspect of the atlas to the anterior rim of the foramen magnum. It is located just posterior to the pre-vertebral muscles of the neck. *AOM* anterior occipital membrane; *C1* atlas; *mat* middle anterior tubercle; *OC* occipital condyle; *PT* pharyngeal tubercle

The atlas lacks a vertebral body, whose usual position is occupied by the odontoid process of the axis. The anterior arch is short and convexed forward and has a median anterior tubercle. The internal wall of the anterior arch is in contact with odontoid process forming a facet (fovea dentis). It is the widest cervical vertebra, with its anterior arch approximately half as long as its posterior arch [1, 39, 40].

The dens of the axis, or odontoid process (dens), projects upward from the body of vertebra. The dens has a pointed apex, has a flattened side where the alar ligaments are attached, and is grooved at the base of its posterior surface where the transverse ligament of the atlas passes [1–3].

1.5.2 Muscular Relationships

The anterior vertebral muscles insert on the clival part of the occipital bone anterior to the foramen magnum. The longus colli is located on the anterior aspect of the cervical spine and consists of three portions. The superior oblique portion originates from the anterior tubercle of the transverse processes of the third through fifth cervical vertebrae and inserts on the tubercle of the anterior arch of the atlas; the inferior oblique and vertical portions extend from the fifth cervical vertebra downward to the third thoracic vertebra. The longus capitis originates from tendinous slips from the anterior tubercles of the transverse processes of the third through sixth cervical vertebrae, rising to insert on the basilar portion of the occipital bone. It is supplied by the anterior ramus of first through the third cervical spinal nerves. The rectus capitis anterior, located just deep to the superior aspect of the longus capitis, originates from the anterior surface of the lateral mass and the root of the transverse process of C1. It inserts on the foramen magnum anteriorly and on the basilar portion of the occipital bone. The rectus capitis lateralis has already been described as related to the jugular foramen (Fig. 1.28) [4, 8, 38, 40]. The anterior vertebral muscles are covered by the basipharyngeal fascia and on the midline by the median raphe. 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 [12, 39].

1.5.3 Extradural Structures

The two atlanto-occipital joints are true synovial joints. They contain synovial membrane and are covered by capsular ligaments. The atlas and the occipital bone are united anteriorly by the anterior atlanto-occipital membrane. The anterior atlanto-occipital membrane (AAO) is a thin structure that attaches the anterior aspect of the atlas to the anterior rim of the foramen magnum. It is located just posterior to the pre-vertebral muscles of the neck and serves as the anterior wall of the supra-odontoid space, which houses the alar and apical ligaments, as well as fat and veins (Fig. 1.29). The alar ligament attaches the lateral aspects of the odontoid process to the base of the skull on the medial aspect of the occipital condyles. The

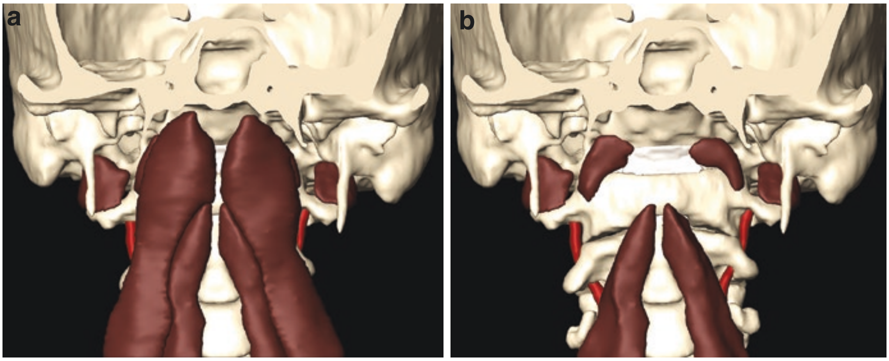


Fig. 1.28 Muscles related to the anteromedial perspective of the CVJ are represented through a 3D model. The superficial layer of the anterior vertebral muscles is exposed. The longus capitis originates from tendinous slips from the anterior tubercles of the transverse processes of the third through sixth cervical vertebrae and inserts on the basilar portion of the occipital bone. Below, the superior oblique portion of the longus colli originates from the anterior tubercle of the transverse processes of the third through fifth cervical vertebrae and inserts on the tubercle of the anterior arch of the atlas (**a**). The rectus capitis anterior, located just deep to the superior aspect of the longus capitis, originates from the anterior surface of the lateral mass and the root of the transverse process of C1. The rectus capitis lateralis extends vertically behind the internal jugular vein from the transverse process of the atlas to the jugular process of the occipital bone (**b**). The anterior vertebral muscles are covered by the basipharyngeal fascia and on the midline by the median raphe. 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

apical ligament, also known as the middle odontoid ligament or suspensory ligament, attaches the tip of the odontoid process to the middle point of the anterior border of the foramen magnum (basion). The ligament runs in the supra-odontoid space between the left and right alar ligaments and travels just posterior to the alar ligaments and just anterior to the superior portion of the cruciform ligament. The cruciform ligament has transverse and vertical parts that form a cross behind the dens. The transverse ligament is the key component of the cruciform ligament and is one of the most important ligaments in the body. It is the largest, strongest, and thickest craniocervical ligament. The superior and inferior limbs of the vertical part of the cruciform ligament are extremely thin. The transverse ligament runs posterior to the odontoid process of the axis and attaches to the lateral tubercles on the lateral mass of the atlas bilaterally. The transverse ligament maintains stability at the CVJ by locking the odontoid process anteriorly against the posterior aspect of the anterior arch of the atlas, and it divides the ring of the atlas into two compartments: the anterior compartment houses the odontoid process and the posterior compartment contains primarily the spinal cord and spinal accessory nerves. A synovial capsule is located between the odontoid process and the transverse ligament. The tectorial membrane, epidural fat, and dura mater are located dorsal to the transverse ligament. The tectorial membrane is a thin structure at the CVJ that serves as the posterior border to the supra-odontoid space. It runs posterior to the cruciform ligament

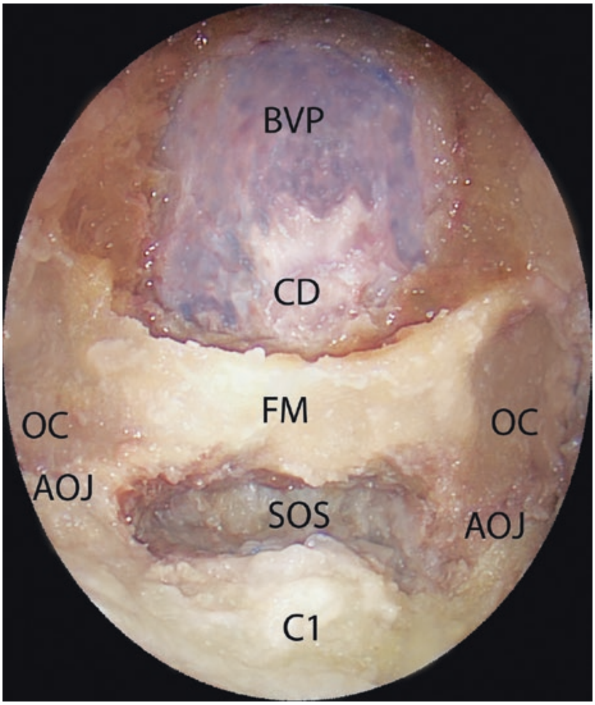


Fig. 1.29 Endoscopic endonasal exposure of the anteromedial aspect of the CVJ. The atlanto-occipital joints consist of the articulation between the upper facet of each lateral mass of the atlas and the occipital condyle that protrudes from the condylar part of the occipital bone. The two atlanto-occipital joints are true synovial joints. They contain synovial membrane and are covered by capsular ligaments. The supra-odontoid space between the anterior arch of the atlas and the anterior border of foramen magnum is exposed. The basilar venous plexus is located between the layers of the dura mater on the clivus. It is formed by interconnecting venous channels that anastomose with the inferior petrosal sinuses laterally, the cavernous sinuses superiorly, and the marginal sinus and epidural venous plexus inferiorly. *AOJ* atlanto-occipital joint; *BPV* basilar venous plexus; *CD* clival dura; *C1* atlas; *FM* foramen magnum; *OC* occipital condyle; *SOS* supra-odontoid space

in intimate contact with the dura mater of the clivus posteriorly. The tectorial membrane firmly adhered to the cranial base and body of the axis, where it is continuous with the posterior longitudinal ligament, but not to the posterior odontoid process. The posterior longitudinal ligament is attached below to the posterior surface of the body of the axis, and above to the transverse part of the cruciform ligament and the clivus. In front, the atlas and axis are connected by the anterior longitudinal ligament, which is a wide band fixed above to the lower border of the anterior arch of the atlas and below to the front of the body of the axis (Fig. 1.30, 3D model with reconstruction of the dens and ligaments) [4, 12, 38].

The basilar venous plexus is located between the layers of the dura mater on the upper clivus. It is formed by interconnecting venous channels that anastomose with

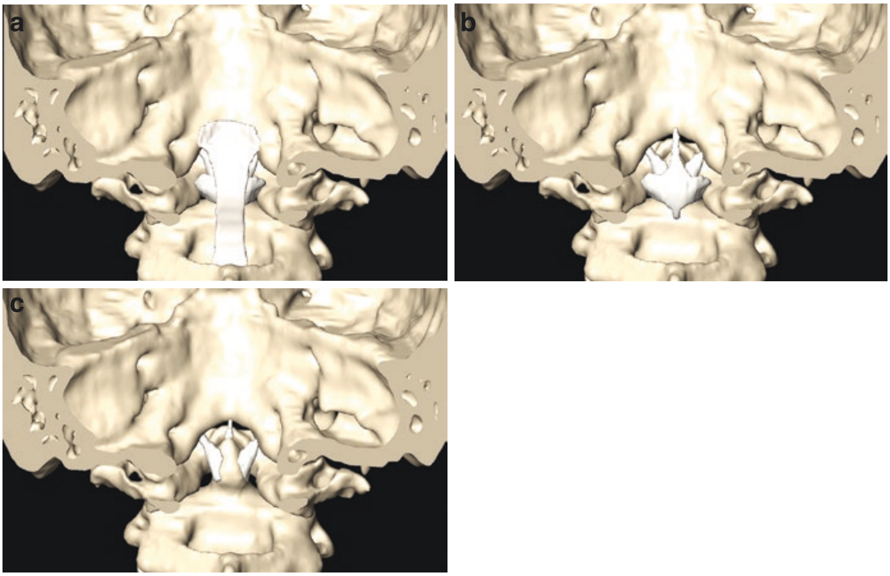


Fig. 1.30 3D model of the odontoid process and ligaments as seen through a posterior view after removal of the posterior arch of C1. The tectorial membrane is a thin structure at the CVJ that runs posterior to the cruciform ligament in intimate contact with the dura mater of the clivus posteriorly. The tectorial membrane firmly adhered to the cranial base and body of the axis, where it is continuous with the posterior longitudinal ligament, but not to the posterior odontoid process. The posterior longitudinal ligament is attached below to the posterior surface of the body of the axis and above to the transverse part of the cruciform ligament and the clivus (**a**). The cruciform ligament has transverse and vertical parts that form a cross behind the dens. The transverse ligament is the key component of the cruciform ligament and is one of the most important ligaments in the body. It is the largest, strongest, and thickest craniocervical ligament. The superior and inferior limbs of the vertical part of the cruciform ligament are extremely thin (**b**). The alar ligament attaches the lateral aspects of the odontoid process to the base of the skull on the medial aspect of the occipital condyles. The apical ligament attaches the tip of the odontoid process to the middle point of the anterior border of the foramen magnum (**c**)

the inferior petrosal sinuses laterally, the cavernous sinuses superiorly, and the marginal sinus and epidural venous plexus inferiorly [4, 38, 39].

On the anteromedial aspect of the CVJ, at the level of the superior surface of the occipital condyle, the supracondylar groove corresponds to an area formed by the insertion of the rectus capitus anterior muscle, anterior atlanto-occipital membrane, and atlanto-occipital capsule joint. The hypoglossal canals are situated posterior and lateral to the supracondylar groove (Fig. 1.31) [41–43].

1.5.4 Intradural Structures

The intradural anteromedial aspect of the CVJ corresponds to the medullary pyramids, which face the clivus, the anterior edge of the foramen magnum, and the

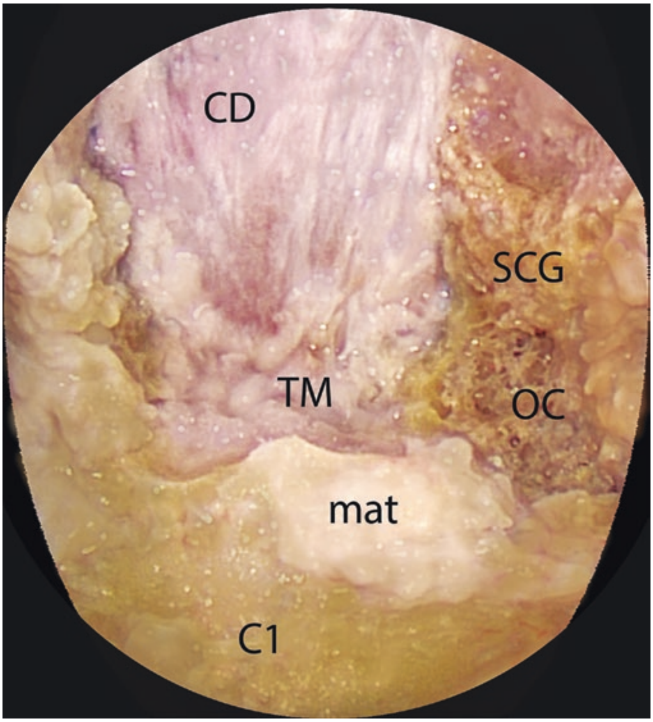


Fig. 1.31 Endoscopic endonasal exposure of the anteromedial aspect of the CVJ. The supracondylar groove corresponds to an area at the level of the superior surface of the occipital condyle formed by the insertion of the rectus capitis anterior muscle, anterior atlanto-occipital membrane, and atlanto-occipital capsule joint, which have been removed. The tectorial membrane is a thin membranous structure at the anteromedial CVJ that serves as the posterior border to the supra-odontoid space. It runs posterior to the cruciform ligament in intimate contact with the dura mater of the clivus posteriorly. The tectorial membrane firmly adhered to the cranial base and body of the axis, where it is continuous with the posterior longitudinal ligament. *CD* clival dura; *C1* atlas; *mat* median anterior tubercle; *OC* occipital condyle; *SCG* supracondylar groove; *TM* tectorial membrane

rostral part of the odontoid process. The anterior median sulcus divides the medulla between the pyramids and is continuous caudally with the anterior median fissure of the spinal cord. The rootlets forming the hypoglossal nerve, the glossopharyngeal, vagus, and accessory nerves run laterally from the lateral surface of the brainstem in the cerebello-medullary cistern (Figs. 1.32 and 1.33) [38–45].

The anterior medullary segment of the vertebral artery (V4) begins at the pre-olivary sulcus, courses in front of, or between, the hypoglossal rootlets, and crosses the pyramid to join with the other vertebral artery at or near the ponto-medullary sulcus to form the basilar artery. Branch of the anterior medullary segment is the anterior spinal artery. The anterior spinal artery is formed by the union of the paired anterior ventral spinal arteries near the origin of the basilar artery. The artery descends through the foramen magnum on the anterior surface of the

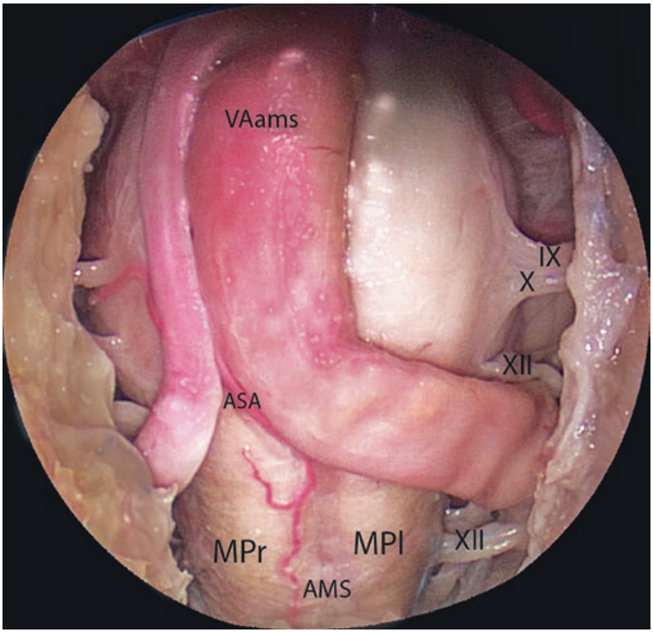


Fig. 1.32 Endoscopic endonasal exposure of the intradural anteromedial aspect of the CVJ. The intradural anteromedial aspect of the CVJ corresponds to the medullary pyramids, which face the clivus, the anterior edge of the foramen magnum, and the rostral part of the odontoid process. The anterior median sulcus divides the medulla between the pyramids and is continuous caudally with the anterior median fissure of the spinal cord. The fourth segment of the vertebral artery (V4) in its anterior medullary segment is visible. This segment begins at the pre-olivary sulcus, courses in front of, or between, the hypoglossal rootlets, and crosses the pyramid to join with the other vertebral artery at or near the ponto-medullary sulcus to form the basilar artery. The anterior spinal artery is formed by the union of the paired anterior ventral spinal arteries near the origin of the basilar artery. The artery descends through the foramen magnum on the anterior surface of the medulla and the spinal cord in or near the anteromedian fissure. The rootlets forming the hypoglossal nerve, the glossopharyngeal, and vagal nerve run laterally from the lateral surface of the brainstem in the cerebello-medullary cistern. The only location where the glossopharyngeal nerve may consistently be distinguished from the vagal nerve is just proximal to its entrance at the jugular foramen. *AMS* anterior median sulcus; *ASA* anterior spinal artery; *MPl* left medullary pyramid; *MPr* right medullary pyramid; *VAams* vertebral artery anterior medullary segment; *IX* glossopharyngeal nerve; *X* vagal nerve; *XII* hypoglossal nerve

medulla and the spinal cord in or near the anteromedian fissure. On the medulla, it supplies the pyramids and their decussation, the medial lemniscus, the interolivary bundles, the hypoglossal nuclei and nerves, and the posterior longitudinal fasciculus. It anastomoses with the anterior branches of the radicular arteries entering the cervical foramina [1, 2, 43]. The median anterior spinal vein, that courses in the anteromedian spinal fissure deep to the anterior spinal artery, is continuous with the median anterior medullary vein that courses on the anteromedian sulcus of the medulla [38–40].

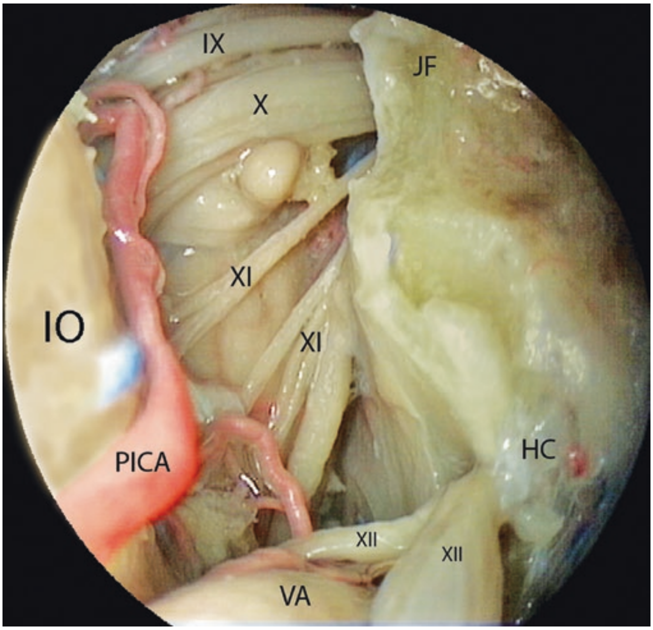


Fig. 1.33 Endoscopic endonasal exposure of the cerebello-medullary fissure through an antero-medial perspective. The glossopharyngeal, vagal, and medullary portions of the accessory nerve origin from the posterior edge of the inferior olive in the post-olivary sulcus. In the cerebello-medullary cistern, the medullary and spinal portions of the accessory nerve unite and run together with the glossopharyngeal and vagal nerves to the jugular foramen. The hypoglossal nerve arises as a line of rootlets that exit the brainstem along the anterior margin of the lower olive in the pre-olivary sulcus, a groove between the olive and medullary pyramid. The rootlets of the hyploglossal nerve pass behind the vertebral artery to reach the hypoglossal canal. The posterior inferior cerebellar artery enters the cerebello-medullary cistern after originating from the fourth segment (V4) of the vertebral artery intradurally. In the cerebello-medullary cistern the artery passes around the rootlets of the glossopharyngeal, vagal, and accessory nerves and pursues a posterior course around the medulla. *HC* hypoglossal canal; *IO* inferior olive; *PICA* posterior inferior cerebellar artery; *IX* glossopharyngeal nerve; *X* vagal nerve; *XI* accessory nerve; *XII* hypoglossal nerve

1.6 Conclusions

The complex anatomy of the CVJ deserves to be unlocked through a chamaleontic perspective based on microsurgical posterior and lateral and anterior endoscopic investigation. The integration of the anatomic knowledge coming from different and complementary perspectives with three-dimensional computer-based information is mandatory to create a safe and effective surgical decision-making process.

References

1. Suchomel P, Choutka O. Reconstruction of upper cervical spine and craniovertebral junction. Berlin: Springer-Verlag; 2011.
2. Rhoton AL Jr, De Oliveira E. Anatomical basis of surgical approaches to the region of the foramen magnum. In: Bambakidis C, Dickman A, Spetzler F, et al., editors. Surgery of the craniovertebral junction. 2nd ed. New York: Thieme; 2013. p. 13–51.
3. Lang J. The cranio-cervical junction—anatomy. In: Voth D, Glees P, editors. Diseases in the cranio-cervical junction. Anatomical and pathological aspects and detailed clinical accounts. Berlin, New York: Gruyter; 1987. p. 27–61.
4. Rhoton AL Jr. The foramen magnum. Neurosurgery. 2000;47(3 Suppl):S155–93.
5. Heller JG, Pedlow FX Jr, Gill SS. Anatomy of the cervical spine. In: Clark CR, editor. The cervical spine. 4th ed. Philadelphia: Lippincott Williams & Wilkins; 2005. p. 3–36.
6. Rhoton AL Jr. The far-lateral approach and its transcondylar, supracondylar, and paracondylar extensions. Neurosurgery. 2000;47(3 Suppl):S195–209.
7. Rhoton AL Jr. Jugular foramen. Neurosurgery. 2000;47(3 Suppl):S267–85.
8. Jhawar SS, Nunez M, Pacca P, et al. Craniovertebral junction 360°: a combined microscopic and endoscopic anatomical study. J Craniovertebr Junct Spine. 2016;7(4):204–16.
9. Pimenta NJ, Gusmão SS, Kehrli P. Posterior atlanto-occipital and atlanto-axial area and its surgical interest. Arq Neuropsiquiatr. 2014;72(10):788–92.
10. Youssef AS, Uribe JS, Ramos E, et al. Interfascial technique for vertebral artery exposure in the suboccipital triangle: the road map. Neurosurgery. 2010;67(2 Suppl Operative):355–61.
11. Dean NA, Mitchell BS. Anatomic relation between the nuchal ligament (ligamentum nuchae) and the spinal dura mater in the craniocervical region. Clin Anat. 2002;15(3):182–5.
12. Tubbs RS, Hallock JD, Radcliff V, et al. Ligaments of the craniocervical junction. J Neurosurg Spine. 2011;14:697–709.
13. Reis CV, Yagmurlu K, Elhadi AM, et al. The anterolateral limit of the occipital lobe: an anatomical and imaging study. J Neurol Surg B Skull Base. 2016;77(6):491–8.
14. Mussi AC, Matushita H, Andrade FG, et al. Surgical approaches to IV ventricle—anatomical study. Childs Nerv Syst. 2015;31(10):1807–14.
15. Matsushima K, Yagmurlu K, Kohno M, et al. Anatomy and approaches along the cerebellar-brainstem fissures. J Neurosurg. 2016;124(1):248–63.
16. Wanibuchi M, Fukushima T, Zenga F, et al. Simple identification of the third segment of the extracranial vertebral artery by extreme lateral inferior transcondylar-transtubercular exposure (ELITE). Acta Neurochir. 2009;151(11):1499–503.
17. Cacciola F, Phalke U, Goel A. Vertebral artery in relationship to C1-C2 vertebrae: an anatomical study. Neurol India. 2004;52(2):178–84.
18. Overland J, Hodge JC, Breik O, et al. Surgical anatomy of the spinal accessory nerve: review of the literature and case report of a rare anatomical variant. J Laryngol Otol. 2016;130(10):969–72.
19. Lloyd S. Accessory nerve: anatomy and surgical identification. J Laryngol Otol. 2007;121(12):1118–25.
20. Verma R, Kumar S, Rai AM, et al. The anatomical perspective of human occipital condyle in relation to the hypoglossal canal, condylar canal, and jugular foramen and its surgical significance. J Craniovertebr Junct Spine. 2016;7(4):243–9.
21. Kalthur SG, Padmashali S, Gupta C, et al. Anatomic study of the occipital condyle and its surgical implications in transcondylar approach. J Craniovertebr Junct Spine. 2014;5(2):71–7.
22. Barut N, Kale A, Turan Suslu H, et al. Evaluation of the bony landmarks in transcondylar approach. Br J Neurosurg. 2009;23(3):276–81.
23. Muthukumar N, Swaminathan R, Venkatesh G, et al. A morphometric analysis of the foramen magnum region as it relates to the transcondylar approach. Acta Neurochir. 2005;147(8):889–95.
24. Cavalcanti DD, Garcia-Gonzalez U, Agrawal A, et al. A clear map of the lower cranial nerves at the superior carotid triangle. World Neurosurg. 2010;74(1):188–94.

25. Alvernia JE, Fraser K, Lanzino G. The occipital artery: a microanatomical study. Neurosurgery. 2006;58(1 Suppl):ONS114–22.
26. Karasu A, Cansever T, Batay F, et al. The microsurgical anatomy of the hypoglossal canal. Surg Radiol Anat. 2009;31(5):363–7.
27. Sreenath SB, Recinos PF, McClurg SW, et al. The endoscopic endonasal approach to the hypoglossal canal: the role of the eustachian tube as a landmark for dissection. Otolaryngol Head Neck Surg. 2015;141(10):927–33.
28. Roche PH, Mercier P, Sameshima T, et al. Surgical anatomy of the jugular foramen. Adv Tech Stand Neurosurg. 2008;33:233–63.
29. Ozveren MF, Türe U, Ozek MM, et al. Anatomic landmarks of the glossopharyngeal nerve: a microsurgical anatomic study. Neurosurgery. 2003;52(6):1400–10.
30. Tekdemir I, Tuccar E, Aslan A, et al. Comprehensive microsurgical anatomy of the jugular foramen and review of terminology. J Clin Neurosci. 2001;8(4):351–6.
31. Suslu HT, Gayretli O, Coskun O, et al. Anatomical and morphometrical evaluation of the jugular tubercle. Br J Neurosurg. 2014;28(4):503–6.
32. Gupta C, Kurian P, Seva KN, et al. A morphological and morphometric study of jugular foramen in dry skulls with its clinical implications. J Craniovertebr Junct Spine. 2014;5(3):118–21.
33. Mei-Hua L, Geng-Sheng X, Zhi-Qun J, et al. Supracondylar transjugular tubercle approach to intradural lesions anterior or anterolateral to the craniocervical junction without resection of the occipital condyle. Turk Neurosurg. 2013;23(2):202–7.
34. Cohen MA, Evins AI, Lapadula G, et al. The rectus capitis lateralis and the condylar triangle: important landmarks in posterior and lateral approaches to the jugular foramen. J Neurosurg. 2017;27:1–9.
35. Keles B, Semaan MT, Fayad JN. The medial wall of the jugular foramen: a temporal bone anatomic study. Otolaryngol Head Neck Surg. 2009;141(3):401–7.
36. Kawashima M, Tanriover N, Rhoton AL Jr, et al. Comparison of the far lateral and extreme lateral variants of the atlanto occipital transarticular approach to anterior extradural lesions of the craniovertebral junction. Neurosurgery. 2003;53:662–74.
37. George B, Dematons C, Cophignon J. Lateral approach to the anterior portion of the foramen magnum: application to surgical removal of 14 benign tumors—technical note. Surg Neurol. 1988;29:484–90.
38. 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;23:665–71.
39. Alfieri A, Jho HD, Tschabitscher M. Endoscopic endonasal approach to the ventral cranio cervical junction: anatomical study. Acta Neurochir. 2002;144:219–25.
40. Kassam AB, Snyderman C, Gardner P. The expanded endonasal approach: a fully endoscopic transnasal approach and resection of the odontoid process: technical case report. Neurosurgery. 2005;57(1 Suppl):E213.
41. Morera VA, Fernandez Miranda JC, Prevedello DM, et al. "Far medial" expanded endonasal approach to the inferior third of the clivus: the transcondylar and transjugular tubercle approaches. Neurosurgery. 2010;66(6 Suppl):211–9.
42. Sekhar LN, Tariq F, Osbun J. Far lateral and far medial approaches to the foramen magnum: microsurgery or endoscopy? World Neurosurg. 2014;81(2):283–4.
43. Solari D, Cappabianca P. Far medial versus far lateral approach: the need of a chamaleontic perspective to unlock a skull base region. World Neurosurg. 2014;81(2):279–80.
44. 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 Neurosurg. 2014;81(2):385–96.
45. Morera VA, Fernandez-Miranda JC, Prevedello DM, et al. "Far-medial" expanded endonasal approach to the inferior third of the clivus: the transcondylar and transjugular tubercle approaches. Neurosurgery. 2010;66(6 Suppl Operative):211–9.