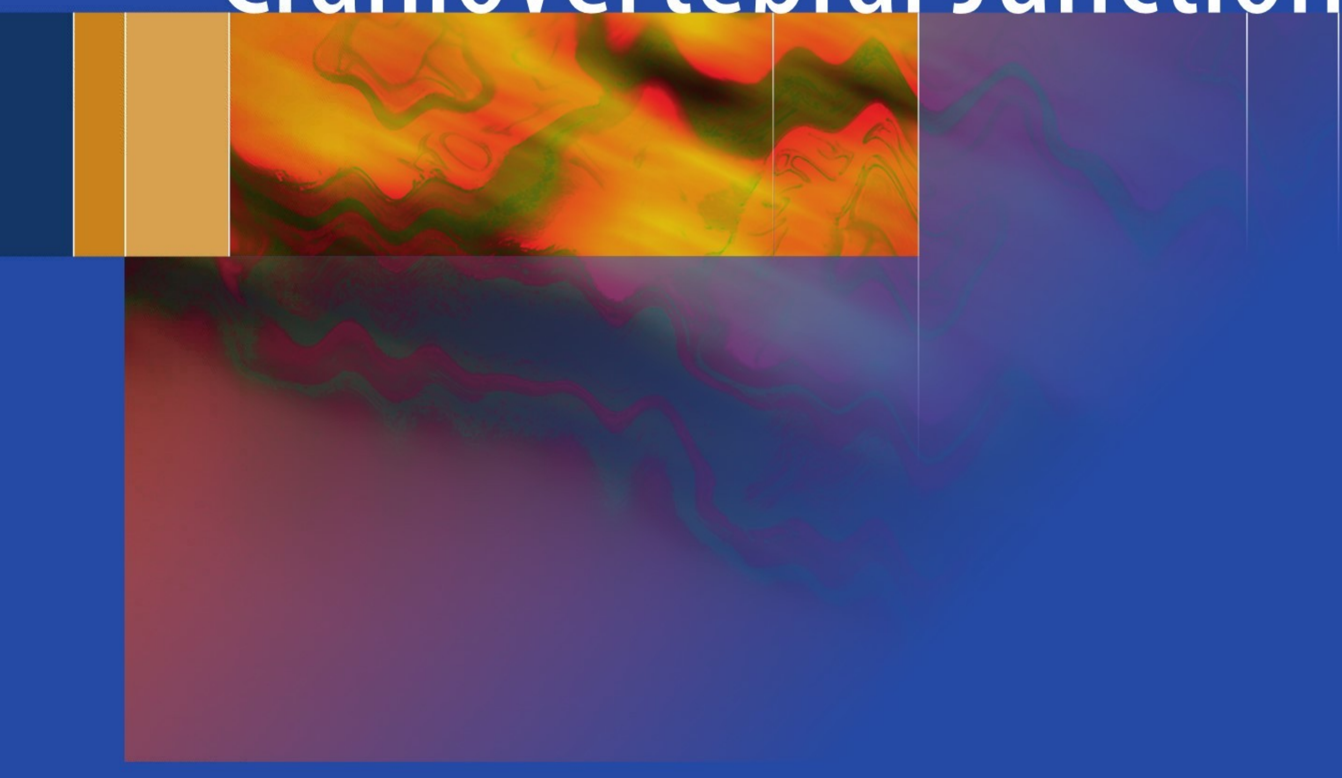
Petr Suchomel
Ondřej Choutka

Reconstruction of Upper Cervical Spine and Craniovertebral Junction



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With contributions by

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To my wife Jana. She has unconditionally supported my efforts for 25 years and without her patience and love, this book would never have been finished.

Petr Suchomel

To my wife Petra and my boys Honzik and Lukas.
Your eternal patience, support, tolerance, and love made this endeavor possible.

Ondřej Choutka

Preface

The spine is a “scaffold” for the erect human body and spinal cord that allows for information to travel between the central nervous system and the peripheral movement executers. Without good signal transition or intact scaffold, a human being cannot walk efficiently. Last century has seen a growing interest and need by many surgeons to strengthen collapsing scaffold and to improve relay of neural signals along the spinal cord. Craniovertebral junction represents the ultimate link between the head and spine with its absolute need for structural support as well as mobility.

Historically, orthopedic surgeons and neurosurgeons became intimately involved in the care of the spinal patient, rarely working together. One was more interested in the strength and shape of the scaffold; the other was more concerned about the quality of information passing through the spinal cord and assuring it remained free from compression. The two differing approaches resulted in two schools of spinal practice: one perfecting reconstructive and fusion techniques, the other mastering microsurgical decompressive aspects of spinal care. Both sides failed to realize that for a patient to enjoy a functional, ambulatory life, they are both necessary. The multilevel decompressive procedure that potentially results in spinal instability may require good structural support with anatomical alignment. The era of admiration of beautiful constructs without respect for neural structures or microsurgical decompression without the thought for good structural support is over. Spine surgery has undergone tremendous development in last 30 years allowing surgeons to operate safely and effectively in previously forbidden or dangerous areas. Development of imaging modalities, surgical instruments, implants, intraoperative monitoring, and anesthetic techniques allowed for spinal techniques to flourish with improved safety and ambulating patients! The new generation spine surgeon is here to stay and rid us off the artificial separation between structure and nervous system.

Our daily work clearly demonstrates that there is a whole array of common spinal problems treated frequently. On the other hand, there are certain, more complex diagnoses even in spinal care that require special expertise, skills, and equipment.

There are still some super specialized topics which, in our opinion will remain under the wings of original specialties. It is the orthopedic correction of thoracolumbar deformities namely those congenital and neurosurgical microsurgery of spinal cord pathologies. All the other surgically treatable diseases would encompass the “general spine surgery.” Spinal trauma, degenerative disorders, tumors, and inflammatory diseases all need fully devoted people able to be at service in a 24 h regime.

This book, based on our own experience with nearly 300 upper cervical spine reconstruction surgeries, should serve to all those who would not only like to begin with surgery in this region but also to those who are already involved, offering them a summarized information about the current possibilities of upper cervical spine reconstruction and a step by step guide of modern potential treatment options for disorders in the CVJ.

This book would not be complete without the beautiful illustrations of Petr Polda and radiographic contributions by Dr. Ladislav Endrych, Chairman of the Radiology Department in Regional Hospital Liberec. Last but not least, our thanks goes to Drs. Jan Hradil, Vladimir Benes, Pavel Buchvald, Radek Frič (currently Rikshospitalet Oslo), Pavel Barsa, Robert Frohlich, Lubomir Jurak, Miroslav Kaiser, and Radim Brabec for their significant contributions to this book. Their relentlessness reflects the team spirit of the Neurosurgery Department in Liberec, Czech Republic.

Liberec, Czech Republic Petr Suchomel
Cincinatti, Ohio, USA Ondřej Choutka

Contents

Abbreviations

2D	Two dimensional
3D	Three dimensional
AA	Atlantoaxial
AAD	Atlantoaxial dislocation
AADI	Anterior atlantodental interval
AAI	Atlantoaxial instability
AAOA	Atlantoaxial osteoarthritis
AARF	Atlantoaxial rotatory fixation
ABC	Aneurysmal bone cyst
ACDF	Anterior cervical discectomy and fusion
ALL	Anterior longitudinal ligament
AO	Atlantooccipital
AOI	Atlantooccipital interval
AOD	Atlantooccipital dislocation
AP	Anteroposterior
AREZ	Anterior root exit zone
ASA	Anterior spinal artery
AT	Anterior translation
ATB	Antibiotic
BAI	Basion-posterior axial line interval
BDI	Basion-dental interval
BMP	Bone morphogenetic protein
CCI	C1-condyle interval
CAD	Computer aided design
CCJ	Craniocervical junction
CEP	Condylar entry point
CMA	Cervicomedullary angle
CN	Cranial nerve
CTA	CT angiography
CTA 3D	Spatial, 3 dimensional CT angiography
CVJ	Craniovertebral junction
DRA	Dynamic reference array
DREZ	Dorsal root entry zone
EEA	Expanded endonasal approach
EOP	External occipital protuberance
EP	Evoked potentials
ES	Ewing sarcoma

ETO	Endoscopic transcervical odontoidectomy
FOM	Foramen occipitale magnum
FT	Foramen transversarium, transverse foramen
GCT	Giant cell tumor
IAAD	Irreducible atlantoaxial dislocation
IAR	Instantaneous axis of rotation
ICA	Internal carotid artery
INL	Inferior nuchal line
IOM	Intraoperative electrophysiological monitoring
LCH	Langerhans cells histiocytosis
LTA	Ligamental tubercle avulsion
IOP	Internal occipital protuberance
MDCT	Multi-detector row CT
MRA	Magnetic resonance angiography
MRI	Magnetic resonance imaging
MVA	Motor vehicle accidents
NPV	Negative predictive value
NSAID	Nonsteroidal antiinflammatory drugs
OAA	Occipito-atlanto-axial
OC	Occipitocervical
OCF	Occipital condyle fracture
OF	Odontoid fracture
OS	Osteogenic sarcoma
PADI	Posterior atlantodental interval
PLL	Posterior longitudinal ligament
PICA	Posterior inferior cerebellar artery
PMA	Posterior meningeal artery
PSA	Posterior spinal artery
RA	Rheumatoid arthritis
SAC	Space available for the spinal cord
SAS	Space available for screw
SCM	Sternocleidomastoid muscle
SNL	Superior nuchal line
SOMI	Sternal occipital mandibular immobilizer
TAL	Transverse atlantal ligament
TBC	Tuberculosis
TBI	Traumatic brain injury
TO	Transoral
UCS	Upper cervical spine
VA	Vertebral artery
VAAII	Vertical atlantoaxial instability index

Section I

Anatomy, Biomechanics and Radiology

Surgical Anatomy

1

P. Suchomel, O. Choutka, and P. Barsa

The goal of surgical anatomy is to avoid the descriptive aspect of "pure form." On the other hand, it emphasizes important structures with respect to the pathological condition and surgical approach.

In descriptive anatomy of bony structures, one has to realize what the origin of its data is. Obviously, there are differences owing to gender variations (e.g., lower values in females); however, other factors also can influence anatomical variations, such as race or age. For example, data from Asian population show lower values in general relative to their population height. Old anatomical data can show slightly lower values due to a change in the average population height over a longer time period. The other differences can arise from the study design. CT measurements are frequently performed in young individuals due to traumatic injuries in another spinal region, whereas cadaveric data are often obtained from old or diseased people with possibly smaller vertebral sizes. In general, the exact descriptive anatomical data can only be used to give the proportional anatomical relationships. The absolute values have to be used cautiously and cannot be blindly applied to the individual patient.

Pure anatomical knowledge has to be supported by the exact imaging and precise measurements of each individual patient. Nowadays, bony structures can be clearly visualized by CT with 3D reconstructions, the status of soft tissue (spinal cord, disks, and ligaments) by MRI, and vascular structures by CTA and/or MRA. Plain films, although a good initial screening tool, are, in general, less helpful in surgical planning. Modern surgical anatomy should be comprehensive but practical so that readers can follow the guidelines and confirm the data in their daily experience. In this chapter, we are provide such a guide through the surgical anatomy the craniovertebral junction.

1.1 Bony Structures

1.1.1 Occipital Bone (C0)

Understanding occipital bone anatomy is important as the posterior squamous part is often used as cranial anchor in occipito-cervical constructs. Foramen magnum is the exit foramen of the skull and is frequently involved in surgical procedures. Occipital condyles are unique joint projections connecting the spine to the skull. Anteriorly, the clivus is a structure also frequently involved in decompressive or reconstructive procedures.

1.1.1.1 Occipital Squama

This part of occipital bone creates an externally convex surface directly visible during most dorsal approaches to CVJ. From surgical viewpoint, it is not just the bone thickness that is relevant, it is the relationship of exterior landmarks to the underlying intracranial venous sinuses and neural tissue that is of utmost importance when it comes to occipital bone.

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There are only a few external landmarks visible during surgery – superior nuchal lines (SNL) and inferior nuchal lines (INL), external occipital protuberance (EOP, Inion), external midline occipital crest, and the edge of foramen magnum. There is great variability in the position of the superior nuchal line and therefore, it does not reflect the internal position of transverse sinus accurately. The relation of confluence of sinuses (torcular Herophili) to EOP is more consistent [47]. According to work of Nadim et al. [39], the safe zones where the injury of transverse sinuses and torcular can be avoided are located more than 2 cm caudal from EOP and SNL. The bone thickness is greatest at the EOP and decreases radially [11, 61]. Most authors describe bone thickness in the region of EOP round 15 mm in males and 12 mm in female Caucasian population but approximately 6 mm or less is available over the cerebellar hemispheres [11, 14, 42]. The safe zone for an 8 mm occipital squama screw insertion covers an area 2 cm laterally from EOP and narrows down inferiorly. So, at 1 cm below EOP, the safe zone is only within 1cm of the midline, and at 2 cm below the EOP, it falls to 0.5 cm of the midline (Fig. 1.1). The thinnest bone (sometimes less than 1 mm) was measured laterally from midline between INL and foramen magnum [47]. The outer cortex contributes 45% to bone thickness whereas the inner table only 10% [61].

Practical conclusion: The thickest bone is available around the SNL and EOP and then along the midline occipital crest, but one has to be aware of injury of intracranial venous sinuses in this region. The exact preoperative bone thickness as well as localization of principal venous sinuses should be determined on preoperative CT in each individual patient planned for occipital bone fixation.

1.1.1.2 Occipital Condyles

There is a great variability in the shape and size of occipital condyles. Most often, the occipital condyles are kidney shaped, biconvex, and medially oriented bone structures localized in the anterior half of foramen magnum. The mean distance between both condyles is 41.6 mm posteriorly and 21 mm anteriorly [38].

The mean condyle length is 23.6 mm (15–30.6), the width 10.5 mm (6.5–15.8), and the height 9.2 mm (5.8–18.2) [28, 29, 36, 38].

Both condyles form an angle of 50°–60° in transverse plane and 124°–127° (male-female) in frontal plane (atlanto-occipital joint angle) [29]. The single condyle axis angle to midline is in average 30° but can vary 10°–54° in adults [36, 38].

Hypoglossal nerve canal is passing transversally through the bone just above the base of the condyle antero-laterally in an axial angle of 45°. It is directed slightly superior with the mean distance of 11.5 mm between the hypoglossal foramen and the inferior border of the condyle [36]. The canal itself is 6.2 mm long, ovoid in shape with 4 mm internal diameter [28]. Jugular foramen with its important contents (jugular vein, n IX,X,XI.) is located 12–25 mm antero-laterally from the condyle.

Condylar emissary vein can be identified in the dorsal superolateral condyle border during dissection.

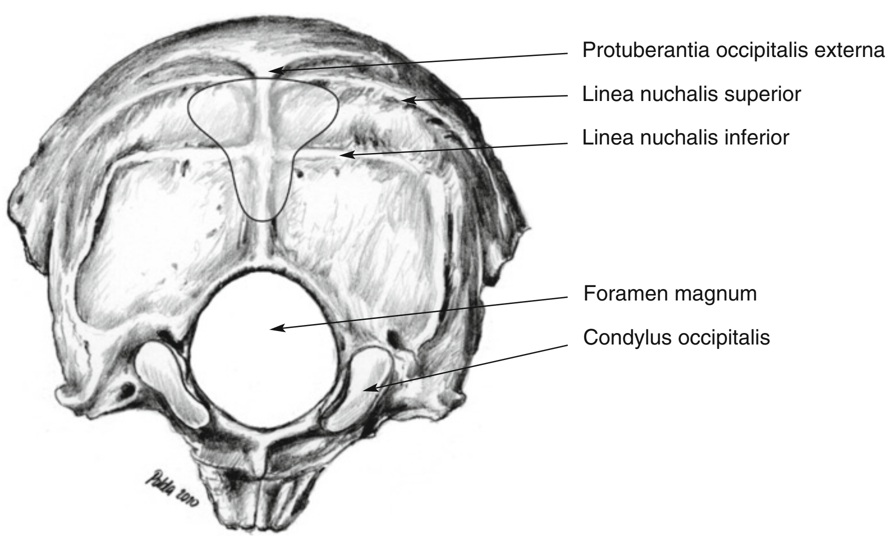

Fig. 1.1 Schematic drawing of the occipital bone external surface with depicted areas for safe occipital squama screw purchase

Carotid artery is often located more than 5 mm anterolateral to the anterior condylar cortex [28]. The condyles are separated by intra-occipital synchondrosis in two (anterior, posterior) parts until the age of six but it can sometimes persist bifacet into adulthood. Third occipital condyle (condylus tertius) is an ossified remnant of the hypochondral bow of the fourth sclerotome (proatlas) at the distal end of clivus that can occasionally be seen as an individual or multiple ossicles directly above and anterior to arch of C1.

Practical conclusion: The occipital condyle is normally twice as long (approx. 20 mm) as it is wide (approx. 10 mm), medially oriented structure (20°–30°). Because of its variability, only CT scan can depict its exact shape, orientation, mass, and relationship to neighboring structures in each individual case.

1.1.1.3 Clivus

The upper part of clivus belongs to sphenoid bone whereas the lower part to basilar portion of occipital bone. These two parts are separated by spheno-occipital synchondrosis till the age of 16.5 (13–18) in males and 14.4 (12–15) in females [50]. The suture allows for growth and correct formation of the skull. In normal adults, the length of the entire clivus is 4.5 cm (3.7–5.2), with the basilar portion of occipital bone representing 3.1 cm (SD 0.3). In occipital hypoplasia, the basilar portion could be as short as 1.7 cm [29]. The thicker part of clivus is located anterosuperiorly and contains cancellous bone. The thinner part, formed by cortical bone only, is in the region of foramen magnum (FOM). Usually, the outer cortex is more solid and thicker than the inner one [29].

Practical conclusion: The clivus can vary in shape and size especially in developmental anomalies. As a part of bone firmly connected to skull, it can be navigated using the skull data.

1.1.2 Atlas (C1)

The atlas is a ring-shaped unique vertebra having no vertebral body and no intervertebral disk attached. It consists of two lateral masses connected with short anterior and longer posterior arches (Fig. 1.2). Its anatomic integrity is crucial for stability of the CVJ and movement of the head.

In older European anatomical studies of atlas, the average outer distance between anterior and posterior tubercle (length) was 46.3 mm in males and 43.2 mm in females. The external transverse diameter (width) was 83 mm and 72 mm, respectively [6]. Exact measurements performed later by Doherty [7] on 80 European C1 specimens, generally confirmed the old anatomical data. An average atlas outer length was 45.8 mm (SD = 2.9) and outer width 78.6 mm (SD = 8.1). The internal width was 32.2 mm (SD = 2.3) and internal length was 31.7 mm (SD = 2.2). Similar values were obtained by Kandziora from 50 dry specimens [25] and also when later measured electronically by Rocha in 20 cadaveric bones [48]. Atlas is the vertebra with the widest internal diameter. The internal length and width were 32.6 mm (range 29.6–36.4 mm) and 29.7 (25.7–32.2 mm), respectively [48]. The transverse ligament tubercles serve as an attachment place of the ligament and are located internally on the medial wall of the lateral masses. Rocha measured the internal "intertubercle" distance to be 22.9 mm (18.7–27.9 mm) [48]. The largest published anatomical series was done by Christensen et al. [4] who measured 120 dried atlases from a defined American population (average age 52.9 years, average height 169.7 cm). Electronic caliper was used with the average outer width being 75.61 mm (SD = 5.94) and outer length 45.67 mm (SD = 3.61).

Anterior arch is a strong structure that harbors anterior tubercle in the midline. The anterior tubercle is regularly visible on plain lateral radiographs and often serves as anatomical and radiographic landmark during surgical procedures especially during instrumentation.

The internal wall of the anterior arch is in contact with odontoid process forming a facet (fovea dentis). The height of the anterior ring is 15.4 mm (SD = 3.2) [7], the length is 30 mm [25, 29], and the thickness is 6 mm in the midline [4]. This thickest cortical bone of the whole C1 is in agreement with its biomechanical load demands.

Posterior arch is longer (usually 2/5 of C1 circumference) and weaker because of the bony groove for horizontal segment of the vertebral artery. The posterior arch has the thinnest cortex of the entire vertebra [7]. The posterior midline arch height is 9.58 mm (SD = 2.26) and its thickness is 7.82 mm (SD = 2.64) [4], in the area of vertebral artery(VA) groove, the height is a mere 4.5 mm (4.3–6.1) [48]. The distance between the posterior midline tubercle and the most medial aspect of the VA groove is approximately 15 mm [37, 48].

Lateral masses are in fact the most voluminous bony parts of atlas forming four facet joints. The superior

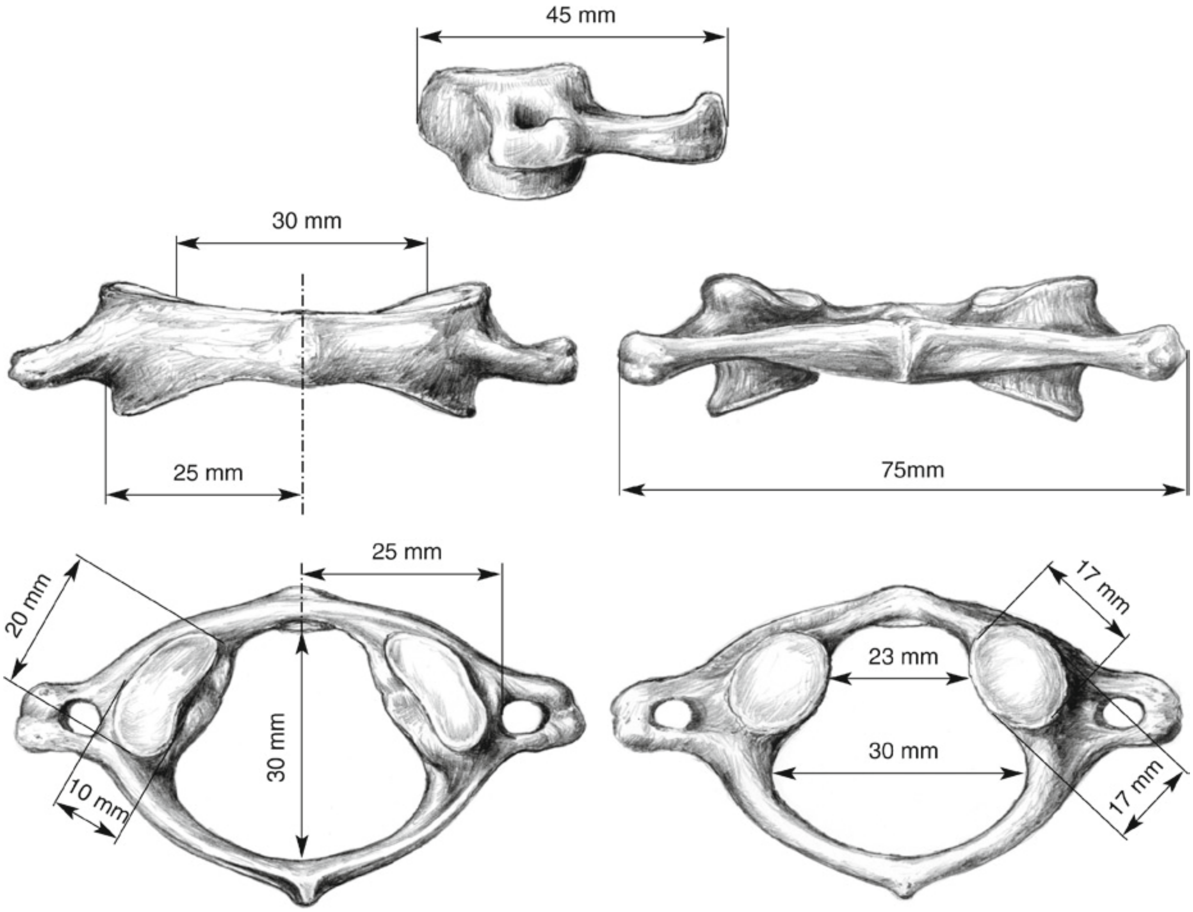

Fig. 1.2 Artistic drawing of C1 with marked parameters simplified for practical purpose

joints differ from the inferior ones in size and shape. Its average midportion (central) length is 16.82 mm (SD 1.0), width 16.06 mm (SD 0.91), and height 15.68 mm (SD 0.98) [51]. The lateral mass cones in medially in the coronal plane and wedges posteriorly in the sagittal plane. Medial wall height was measured 11 mm (SD = 1.21) and lateral 22 mm (SD = 1.89) [25]. Its mean height anteriorly is 18.5 mm (SD = 2.39 mm) and posteriorly 10.2 mm (SD = 2.0) [1].

The superior articular surface (fovea articularis superior) is a medially tilted, concave ellipsoid (kidney shaped), with an approximate length of 20 mm and width of 10 mm [4, 29, 56]. This naturally corresponds to the shape and size of the articular surface of the condyle. In coronal plane, it overlaps the smaller lower facet. Sometimes it can be developmentally divided into two contact surfaces. Superior facet angle to midline was measured in horizontal plane 22.4° (SD = 1.52) [25].

The lower articular surface (fovea articularis inferior) is less concave, round shaped, and smaller than the upper one with a common length of 17 mm (14–23 mm) and width 17 mm (14–23 mm) [1, 13, 29, 32]. The pillar between lower facet and posterior arch is often used for screw anchorage. The height of this "working window" is 3.6 mm (2.13–4.09 mm) and width 9.5 mm (6.98–13.34 mm) [15]. Other studies on non Indian population are suggestive of a larger area with the mean height of 4.5 mm, ranging from 4.1 to 6.1 mm [48, 51].

Normally, the transverse process forms a *transverse foramen* (*FT*) for vertebral artery (VA). It has a variable diameter and position and can be opened in an anterolateral direction. Relatively often (15.6%), there is a partial or total covering (arcuate foramen) of artery (Fig. 1.3) in the C1 groove creating a so called "ponticulus posticus" [20, 30, 60]. This can be very

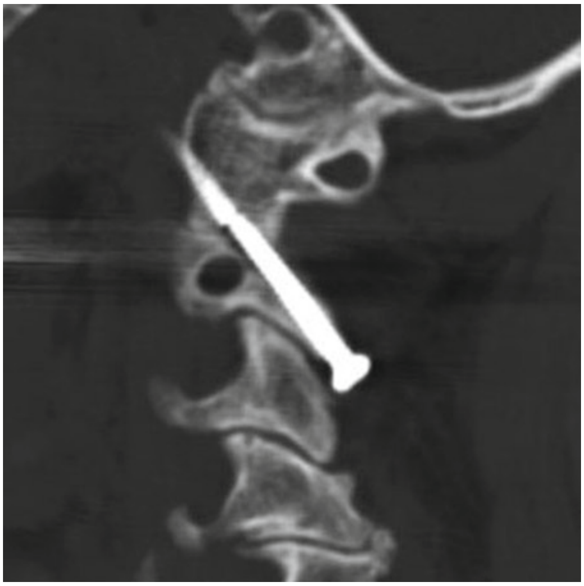

Fig. 1.3 Arcuate foramen of C1 and high riding VA in C2 pars. Sagittal CT reconstruction. Note the broken transarticular screw (case referred for revision from another department)

important during sub-periosteal exposure of C1 lamina and during C1 lateral mass screw placement. One can suppose that the lamina is too broad and the VA could thus be injured through a poor planning of the entry point. The distance of medial FT border to midline is approximately 25 mm [19, 25, 54].

For practical surgical purposes we can summarize: In average the atlas outer width is approximately 75 mm and outer length 45 mm. Internal AP diameter is usually 30 mm. Anterior arch is the strongest bony structure approximately 30 mm long, 15 mm high, and 6 mm thick. Posterior arch is the weakest part of atlantal ring having a medial height of approximately 10 mm but in the region of VA groove only 5 mm or less. The lateral mass is wedge shaped in sagittal and frontal planes. Superior facet is approximately 20 mm long and 10 mm wide with the axis angled in at about 20°–30° medially. Lower facet is round shaped with a 17 mm diameter. The lateral mass pillar below the posterior arch has a rectangular shape with 4.5 mm height and 10 mm width forming the working window for eventual screw introduction. The VA containing transverse foramina are approximately 25 mm from midline but the VA containing groove comes as close as 15 mm to midline.

1.1.3 Axis (Epistropheus, C2)

Second cervical vertebra is also a unique spinal structure. It is composed of vertebral body with upward directed odontoid process, which articulates with the posterior aspect of anterior C1 arch (Fig. 1.4). The body is connected to the lateral mass by short and strong pedicles. Lateral mass pillar between upper and lower articular processes is pars interarticularis and its narrowest part is the isthmus. Transverse foramen can vary in shape and size. Posterior arch is similar to other subaxial cervical arches but is larger, in general. The spinous process is often bifid. The cortical bone covering the anterior aspect of odontoid process, its tip, and the anterior vertebral body surface is extremely thick, especially in the area of an anterior midline ridge named "promontory" by Doherty [17]. The thickness here is approximately 1.7 mm whereas the lateral and posterior parts of odontoid and body are covered by only a 1.0 mm or less thick cortical bone. The inside dens trabecular bony architecture is organized to resist the antero-posterior and lateral forces. Strong trabeculae that span fanlike from the upper facets to the inferior bony endplates assist to bear and transmit the axial load. The weakest bone density is in the body below the base of odontoid [17]. The external axis width is 56 mm (48–69 mm) [25] and length approximately 55 mm.

Vertebral body is connected to C3 by intervertebral disk. The C2 endplate shape is sagittally concave with a prominent anterior edge. The distance between this edge and the base of dens is on an average 22 mm (17–31 mm) [25]. The caudal body width is 18–19 mm and AP diameter 15–17 mm [25, 27, 59]. Both parameters decrease superiorly. Consequently, the internal spinal canal AP diameter is smaller at the C2 body base (14.8 mm) than at the level of odontoid process attachment 17.35 mm [59]. The average canal width, measured as 21.6 mm [59], does not change throughout the height of the vertebra.

The *odontoid process* diameter is usually smaller at the base (waist) than in the middle of its shaft. The process is composed of thick cortical bone surrounding internal cancellous component with an internal diameter reaching 4.3–6.2 mm [18]. It is usually 20 mm (15–25.4 mm) long and posteriorly tilted in an angle of 64° in respect the endplate [25, 59]. Anterior surface forms an articulation with the atlas. Basal (waist) odontoid diameter is approximately 9 mm

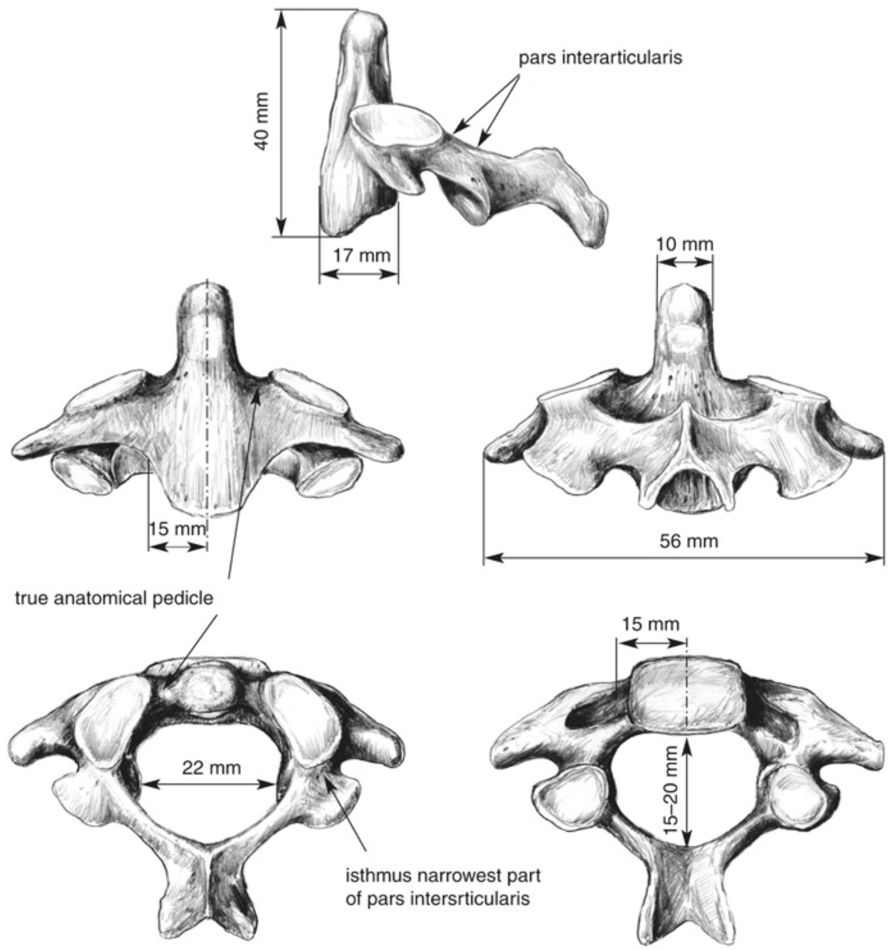

Fig. 1.4 Artistic drawing of C2 with marked parameters simplified for practical purpose

(7.8–14.1 mm) and the maximal one 11 mm (8.4–14.1 mm) [25, 59].

The pedicles of C2 vertebra, despite being very short, are the strongest and widest pedicles in the cervical spine connecting the body to lateral masses nearly in right angle to sagittal plane. From a surgical viewpoint, the most critical value is the mean transverse pedicle diameter at the level of the VA. It was measured 6.4 mm (2.09–13.2 mm) [35].

Lateral masses form an oblique column between upper and lower facets. This part of bone is very important for possible screw purchase is usually called *pars interarticularis* or simply "*pars*" in the anatomical literature. This pillar is more or less thinned by the groove of VA in its narrowest point called the *isthmus*.

Despite the above nomenclature corresponding exactly to that of the other spine regions, one has to be careful when interpreting publications even from well-accepted authors [11, 26, 31, 33, 34, 46, 53, 59], who commonly refer to the pars interarticularis as the C2 pedicle. The pars is inclined 35.2° (29°–41°) medially and 38.8° (22°–52°) rostro-caudally [21]. The width and height of the isthmus at the level of the transverse foramen is 7.9–8.6 mm (female vs. male) and 6.9–7.7 mm (female vs. male), respectively [59]. It can, however, vary to values less than 3.5 mm at least on one side in approximately 18–23% of patients [23, 45, 46].

The upper facet is slightly convex and faces upward and outward with the shape and size corresponding to the inferior articular process of C1. The outward angle in coronal plane is approximately 24° [25]. Its length and width are similar, approximately 17 mm [25], depending on gender and body size. The articular surface atypically arises directly from the C2 pedicle laterally.

The lower facet forms a typical, forward-facing subaxial spine joint surface to articulate with C3.

C2 arch is the strongest arch in cervical spine usually containing enough cancellous bone to accommodate a

3.5 mm laminar screw. The mean laminar thickness was measured 5.77 mm (1.35–9.77 mm) [3]. On 37 adult specimens, Xu et al. [58] measured the C2 laminar height to be 11.2 mm (SD = 1.1 mm), its half length 15.6 mm (SD = 1.2 mm), and average thickness 4.3 mm (SD = 0.9 mm). Both the laminas formed an angle of 99.1° (SD = 8.0°) called laminar width, which is the narrowest in the spine. The downslope laminar angle was determined as 111.7° (SD = 9.3°). The spinous process is likewise a strong structure serving as an attachment point of important suboccipital triangle muscles and the nuchal ligament.

Transverse foramen incorporating VA is of utmost surgical importance. Usually, the VA enters the C2 transverse foramen vertically approximately 15 mm from the midline, passes cranially, and then courses 45° laterally to form an upward loop around the transverse process to reach the vertically oriented C1 transverse foramen. In about 80% of population, the VA bends sharply outward inside the C2 VA groove, leaving enough bone of the isthmus for transisthmic or transpedicular screw purchase. The VA curve located directly below the superior articular process of C2 can occasionally be more superior, dorsal, or medial than expected, thus directly influencing the pars and pedicle size. Such "high riding VA" occurs at least unilaterally in up to 23% of patients undergoing craniocervical procedures [34, 40, 45]. Despite this, it is clear that the diameter of the bony VA canal and foramen does not represent the external diameter of the actual artery [2, 35]. The artery is surrounded by venous plexus and connective and periostial tissue, and this fact often allows for certain amount of foraminal breach during screw placement.

For practical surgical purposes we can summarize: On an average, the axis outer width is around 56 mm and outer length 55 mm. Internal AP diameter increases from 15 mm at the level of C2/3 disk to 17 mm at the base of odontoid process. The internal width remains relatively constant measuring approximately 22 mm. The odontoid process has an average diameter of 10 mm and is tilted backwards relatively to the C2 endplate in an approximately 60° angle and about 10° relatively to horizontal plane. The distance from the anterior inferior edge of C2 body to the odontoid tip is approximately 40 mm (shorter in females). The AP C2 body diameter decreases with upward direction. The diameter of the isthmus (the narrowest part of the pars) is approximately 7–8 mm but in 18–23% of patients it can be significantly thinner due to a high riding VA.

1.2 Ligaments and Joints

The UCS and CVJ ligamentous connections are very complex (Fig. 1.5) providing one of the most complicated movement patterns in the human body. Atlanto-occipital together with atlantoaxial joints are always working together in a synchronized fashion. Upper cervical spine is the most mobile part of the entire vertebral column with a unique anatomical structure. There are no intervertebral disks and yellow ligament. Movement is restricted not only by the bony shape of the vertebra but mostly by the strong ligaments.

The axis is firmly connected to the occiput and atlas is quite freely floating in between.

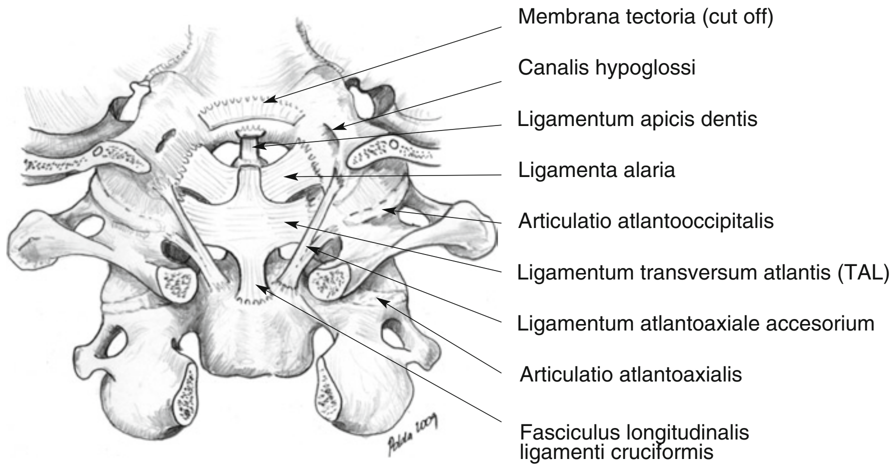

Fig. 1.5 Schematic picture of UCS ligamentous structures (internal posterior view)

Posterior atlanto-occipital and atlantoaxial membranes are relatively weak structures compared to the interarcual subaxial ligamentum flavum. The anterior longitudinal ligament (ALL) loosely attaches to the vertebral bodies of the subaxial spine. However, it is firmly connected to the disk annulus at each level and finally inserts to the anterior tubercle of atlas. Anterior atlanto-occipital membrane replaces the ALL between atlas and the clivus.

The posterior surface of C2 body and odontoid process is covered by tectorial membrane which is, in fact, a strongly developed cranial part of the posterior longitudinal ligament (PLL). Cranially, it is inserted into the clivus with lateral extend to hypoglossal canals. Caudally, the membrane is attached to C2 body continuing into the PLL. The most important structure for atlantoaxial translational stability is the transverse ligament. This ligament is the strongest of the entire complex and attaches to the bony tubercles located on the medial surface of lateral masses of atlas. It is 10 mm high and 2 mm thick with an average length of 23 mm [29, 48]. Together with the longitudinal bundles attached to the posterior aspect of C2 body and anterior edge of foramen magnum, the transverse ligament forms the cruciate (cruciform) ligament. The axis is connected to the occipital bone with three other ligamentous structures. The apical ligament, a possible remnant of chorda dorsalis, connects the tip of the dens to the anterior edge of foramen magnum. This relatively weak band runs forward in a 20° angle and is around 8 mm long and 2–5 mm wide [29, 43, 44]. Symmetrical allar ligaments are extended between the lateral odontoid apex and the medial surface of each occipital condyle. Regularly, these 10 mm-long ligaments also have small insertions into the lateral masses of atlas [9, 10]. Atlantoaxial accessory ligaments found irregularly on both sides are not only connecting the atlas to the axis but also continued cephalically to the occipital bone. The approximate length of this structure is 30 mm and thickness 5 mm [57]. Occasionally, one can also find atlantodental ligament connecting the base of the odontoid process with the anterior arch of atlas [9, 10].

1.2.1 Atlanto-Occipital Joints

The two atlanto-occipital joints are true synovial joints similar to the others in UCS. The articulation between the condyle and the upper C1 articular process allows mainly flexion and extension. The shape, angle, and congruence of joint surfaces are natural restraints of other movement directions. The joints contain synovial membrane and are covered by capsular ligaments.

1.2.2 Atlantoaxial Lateral Joints

These two most mobile joints in the entire spine provide predominantly rotational movement; however, movement in other directions and planes is also possible. This is due to the naturally incongruent articular surfaces that do not limit any direction of movement and due to the laxity of restricting ligamentous structures. They consist of encapsulated synovial joint between inferior articular process of C1 and superior process of C2. Their capsular ligaments are reinforced by medial and posterior accessory ligaments.

1.2.3 Atlantodental Joint

This synovial joint forms anterior and posterior articulation between the odontoid process and anterior arch of C1 and the odontoid process and transverse atlantal ligament, respectively. The transverse ligament is obviously so rigid to keep the odontoid process in contact with anterior arch of C1 under all circumstances. There is only a very limited freedom for lateral movement of the odontoid process. Further, a greater degree of elasticity in childhood allows for greater movement in this joint.

1.3 Muscles of CVJ and UCS

Several complex muscular attachments of the upper cervical spine act together to provide three main functions: muscular tension stabilizes the position of head in space; multiple small muscles attached to the skull, C1, and C2 provide movement of the head in all directions; and the massive posterior muscular layer aids in protection of the CVJ from external violence. Good working knowledge of the muscular attachments allows for anatomical dissection during exposures of the CVJ and prevents unnecessary damage to soft tissues.

Similarly to the other spine regions, the musculature can be divided in musculi brevii (proprii) connecting one motion segment only and musculi longi bridging two or more segments. In UCS, the short muscles are more important and more specifically developed than in subaxial cervical spine (Fig. 1.6).

The nuchal ligament has two portions and knowledge of the presence of fatty areolar tissue between the two leaves of the deeper lamellar portion can prevent blood loss during posterior exposure of cervical spine [24].

The large, *posterior* superficial muscles of the neck consist of trapezius, semispinalis, sternocleidomastoid, and splenius capitus. They merely cross/attach at the CVJ but are encountered during posterior, posterolateral, and lateral approaches to the region. The deep short muscles are more specific in their structure and function as head extenders, rotators, and lateral benders. The atlas is connected to the skull through a series of short capitis muscles (posterior rectus capitis minor and superior obliquus capitis). The axis is connected to the atlas by inferior obliquus capitis and to the skull by rectus capitis posterior major. The insertion of this muscle to the spinous process of C2 merges with the insertion of inferior obliquus capitis. These muscles allow mostly for rotation and extension.

The *anterior* muscles of the CVJ include the paired, short rectus capitis anterior that connect the atlas to the clivus. Rectus capitis lateralis runs vertically between the transverse process of C1 and the jugular process of the occipital bone. These two muscles are separated by the ventral ramus of the first cervical nerve. The longus capitis muscle originates on transverse processes of lower cervical vertebrae crosses the CVJ anteriorly to attach to the base of the skull. The function of the anterior muscle group is mostly stabilization of the skull on the vertebral column.

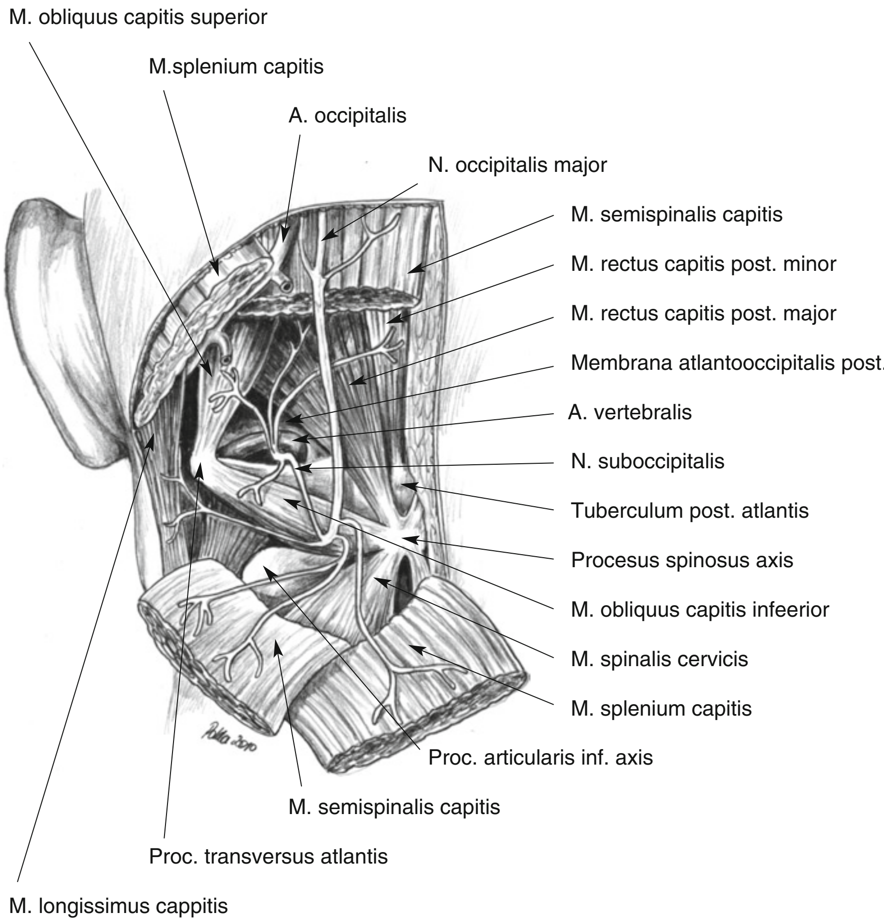

Fig. 1.6 Schematic drawing of anatomical structures of suboccipital triangle

1.4 Vascular Anatomy of CVJ and UCS

1.4.1 Vertebral Artery (VA)

Vertebral artery course in the cervical spine can be divided in four segments (V1–4). The first segment represents the course of the artery between its origin on the subclavian artery and its entrance into the transverse foramen of the C6 vertebra (most frequently). The second segment involves the cervical transverse foraminal portion of the VA course (C6 to C1). The horizontal portion of the VA (V3) is from the transverse foramen of the atlas to entrance to the dura. The VA runs in the groove of the C1 lamina, is surrounded by venous plexus, and ultimately passing the posterior wall of the condyle to pierce the atlanto-occipital membrane in its lateral aspect. The intradural course of the VA represents the fourth segment (V4) to terminate in the formation of basilar artery after joining the contralateral VA.

The left VA is dominant in 35.8% of patients, hypoplastic in 5.7%, and absent in 1.8%. The right VA is dominant in 23.4% of subjects, hypoplastic in 8.8%, and absent in3.1%. Equivalent right and left VA can be detected in 40.8% of subjects; however, a great diversity exists in the percentual representation of these varieties [55].

The VA course in the region of upper cervical spine is curved and with some redundancy, particularly between C1 and C2 to allow not only for flexion and extension but for rotation so prominent at this spinal segment (Fig. 1.7). The VA redundancy decreases with age [8].

In subjects with a healthy upper cervical spine, the typical five-curve course of VA at the CVJ was seen in 81.8% of CTA evaluations. The rest of the subjects carried various anomalies of the VA course at the CVJ [8]. Surprisingly, in up to 15.6% of patients, one can discover a partial or total bony covering (arcuate foramen) of the horizontal segment of VA, so called "ponticulus posticus" [4, 20].

It is important to be aware of a rather dangerous variable that is, the persistent primitive first cervical intersegmental artery. This aberrant vessel may partially or completely substitute the VA and course below the posterior arch of atlas. Such course would complicate a subarcuate approach to the posterior lateral mass of C1 for screw insertion. In a very large series of 1,013 patients with CT angiography, Hong et al found persistent first

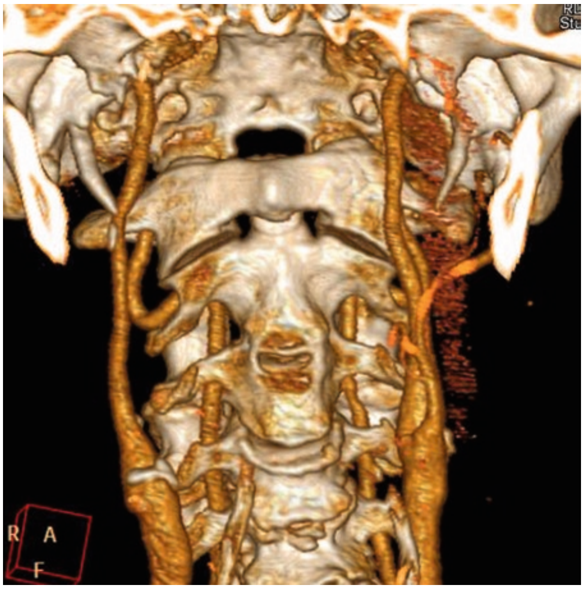

Fig. 1.7 CT angiogram showing the AV redundancy below the C1 entry allowing free C1–2 rotation

intersegmental artery on one side in 3.8% and bilaterally in 0.8 % [20]. Reports of tortuous VA coursing below the posterior arch of atlas without passing through the transverse foramen were also described [22].

1.4.1.1 Branches of VA

Certain branches of the VA may have anomalous origins and thus become susceptible to injury during procedures of the CVJ. The *posterior inferior cerebellar artery* (PICA) usually originates from the fourth segment of the VA intradurally. However, an extradural origin of PICA may be present in 5–20% of people [12]. This makes it a relatively common variation. An extradural origin may be highly variable and PICA can arise close to the entrance of the VA into the dura or as far as atlantoaxial portion of the artery and course below the C1 arch. An extradural origin PICA, usually, does not supply anterior medulla. PICA may originate from other vessels in the region (ascending pharyngeal, ICA etc.) also.

Posterior meningeal artery (PMA) should not be confused with an extradural PICA. It usually arises from the extracranial segment of VA and supplies posterior fossa dura and falx cerebelli and cerebri. It originates from the left VA in 17–30% of people and right VA 8–40% [16, 41]; however, just like PICA, it can originate from other vessels in the area (ascending pharyngeal, ICA, and occipital artery).

Posterior spinal artery (PSA) usually originates from the VA, 50% intradurally and 46% extradurally from V3 [52]. However, PSA has also been described to originate from PICA, usually with an extradural origin.

Anterior spinal artery (ASA) arises invariably intradurally from the vertebral arteries; however, the relationship of its origin to PICA and vertebrobasilar junction varies. ASA was a direct branch of left VA in 30% of cadaveric specimens, right in 8%, and directly from basilar artery in 2%. The "typical" pattern of dual anterior ventral spinal arteries merging into a single ASA was observed only in 18% of examined brainstems [49].

1.4.2 Internal Carotid Artery (ICA)

Although, the ICA is not directly involved in UCS and CVJ, its adjacent position could be of importance in some UCS reconstructive techniques. The lumen of internal carotid artery (ICA) is medial to the transverse foramen of C1 in more than 80% of cases [5] (Fig. 1.8). In such cases, it lies directly in front of C1 lateral masses. With tortuous ICA, the vessel may even be located in front of the C2 vertebral body. Knowledge of ICA variation becomes relevant during direct anterior or anterolateral exposure of CVJ or during posterior reconstruction with instrumentation potentially perforating anterior cortex of vertebrae of UCS and putting the ICA at risk.

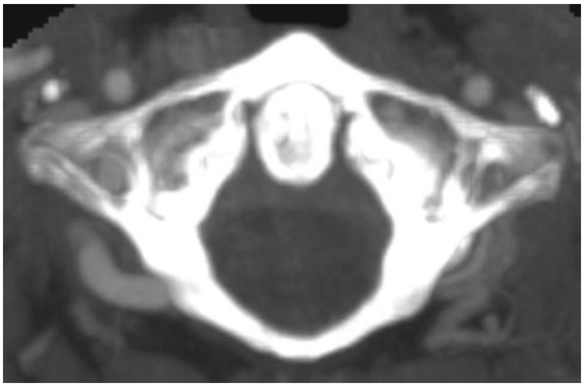

Fig. 1.8 Axial CT with contrast media application depicting the normal position of carotid artery in front of the atlas

1.5 Neural Anatomy

1.5.1 Spinal Cord

Neural structures are occupying funnel-like cavity of craniocervical junction. The medulla oblongata merges into the *spinal cord* at the CVJ. The upper limit of spinal cord is defined by anatomists as an exit point of the uppermost root fibers of C1 or the lower end of pyramidal tract decussation. The morphology of spinal cord changes at different levels. There is significant individual variation in size. Nonetheless, it is flattened in anteroposterior direction and usually has a larger transverse diameter. Its surface is divided by the longitudinal fissure and several sulci. The anteromedial fissure and posteromedial sulcus divide spinal cord sagittally into symmetrical halves. The central canal originating from the fourth ventricle passes in the midline and is surrounded by an inner butterfly-shaped gray matter. The gray matter consists of cell columns that extend in posterolateral directions almost to the surface (the posterior horns) and anterolaterally, not reaching the anterior surface of the cord (the anterior horns). Posterior horns contain somatosensory neurons while anterior horns somatomotor neurons. A gray commissure connects the gray substances encircling the central canal.

The white matter comprises ascending and descending fibers organized into distinct tracts. Anatomically, it is divided into three columns symmetrically in both halves of the cord: posterior, lateral, and anterior. The posterior column is ascending one localized between the posterior horns of the gray matter. Medially, it is symmetrically divided by the posteromedial sulcus that cranially extends to the caudal cusp of the fourth ventricle in the brain stem. Lateral column is located between anterior and lateral root entry zones and consists of the lateral corticospinal tract intermediating voluntary discrete and skillful motor function and the lateral spinothalamic tract transmitting painful and thermal sense from contralateral side. The anterior columns lie between the anterior entry zones and are symmetrically divided by the anterior spinal fissure. Its most important structure is the descending corticospinal tract concerned with fine motor skills. Of descending corticospinal axons localized in the anterior columns, 75–90% decussates, forming the crossed lateral corticospinal tract and anterior corticospinal tract involving uncrossed fibers.

1.5.2 Cervical Spine Nerves

Spinal nerves arise from anterior and posterior root filaments. Ventral root filaments exit the anterolateral aspect of the cord in the anterolateral sulcus, in the region termed the anterior root exit zone (AREZ) and are purely motor. Posterior rootlets enter the spinal cord in dorsal root entry zone (DREZ), the region along the posterolateral sulcus and are sensitive ones. The rootlets pass obliquely and laterocaudally within the canal of craniocervical junction entering the root sleeve where the sensory and motor filaments are separated by the interradicular septum, a lateral extension of dura. The dorsal rootless present an oval bulge, the ganglion as it approaches or enters the intervertebral foramen. Distally to the ganglion, the dorsal and ventral roots combine to form a spinal nerve. The cervical nerve root occupies approximately one third of the foraminal section area, usually its inferior aspect. The residual foraminal space is filled with fat and associated veins. The first spinal cervical nerve leaves the canal through the orifice between the occiput and C1. Further cervical nerves exit above correspondingly numbered vertebrae.

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Biomechanical Remarks

2

P. Suchomel and P. Buchvald

Knowledge of normal biomechanics of the cervical spine is very important as it can be modified by various pathological situations. The changes that occur during injury and/or in consequence with other pathological conditions or surgical procedures can substantially influence the stability of this most important spinal joint complex.

It is difficult to determine what the normal motion of the cervical spine is as it depends on the size, weight, anatomy, degree of degeneration, bone quality, and age of each person or specimen. Both in vivo and in vitro investigations have been undertaken to accumulate the clinically important biomechanical data. Performing the in vitro studies, various fresh cadaver spine specimens were tested. Most often, the six motion components were evaluated: flexion/extension, axial rotation, lateral bending, and translation about each axis. A number of techniques have been developed to apply loads and to measure these motion components. Pioneering work in this field is credited to Panjabi et al. [21]. They monitored the three- dimensional motion by an optoelectronic system based on the principles of stereophotogrammetry. In vivo motion analyses are usually based on the CT investigations [27], the electrogoniometer gauging technique, [1] or the stereophotogrammetry [25].

The occipitoatlantoaxial complex (*C0-C1-C2*) is a very complicated structure with motion determined by the bony morphology and orientation of the articular processes and limited by ligaments and joint capsules. It is composed of the occipitoatlantal (C0-C1) and atlantoaxial (C1-C2) joint complexes. We should emphasize that these two motion segments are intimately linked and the motion is always coupled.

The atlantooccipital joints (*C0-C1*) are anteromedially oriented, concave spheroid articulations connected by very tight capsules. Their mechanical properties are determined mainly by the shape of bony elements. Flexion and extension reported between 13° and 25° (in total range), according to different investigators, is their dominant movement [10, 23, 26, 30, 33]. Flexion is limited by the tip of the dens impinging on the anterior margin of the foramen magnum (bursa apicis dentis) [33] and extension is restricted mainly by the tectorial membrane inserted to the body of axis and the anterior rim of the foramen magnum; nevertheless, the exact function of tectorial membrane is still a matter of debate [18, 30, 31, 33]. Translation at this junction is minimal under normal conditions and during sagittal movement should not change more than 1 mm [24, 37]. Allowed lateral bending is between 3° and 5° to each side [23, 26, 30]. Although the idea of possible axial rotation had been refused in the past, more recently some authors have documented existence of minimal axial rotation in this joint. The one-side rotational movement range was measured between 1° and 7.2° [4, 10, 23, 27]. The rotation and lateral bending of C0-C1 is controlled mainly by the joint capsules but also the allar ligaments. The instantaneous axis of axial rotation (IAR) for the C0-C1 articulation is ventral to foramen magnum.

The atlantoaxial complex (*C1-C2*) is composed of four joints: two AA lateral joints, the atlantoaxial median joint (between the anterior arch of the atlas and the dens axis), and the joint between the posterior surface of the dens and the transverse ligament. Stability at this highly mobile junction is dependent predominantly on ligamentous structures. Sagittal plane motion (flexion-extension) in C1-C2 has been reported to be on an average 20° (10°–30°) by several authors [7, 16, 33]. Lateral bending limited by allar ligaments is inconsequential under normal conditions by some authors [33] but reaching 7°–10° to

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one side by others [23, 27]. In the occipitoatlantoaxial complex, 85–90% of all axial rotation comes from the atlantoaxial segment [10, 23]. Penning and Wilmink [27] found that atlantoaxial complex accounted for 56% of the whole cervical rotation with respect to the first thoracic vertebra. Normal range of rotation between C1 and C2 is determined on an average about 40° to each side [3, 17, 34]. Range of axial rotation to one side in C1-C2 has been reported in the various studies to be between 23° [10] and 47° [33]. The great differences in the results are mostly due to the differences in the methods used and dissimilarities of in vitro and in vivo studies. For example, Dvorak et al. reported in their in vivo (CT) tests an average range of axial rotation 32.2° and consecutively, 43.1° [4]. The high rotational motion range is facilitated by very loose AA joint capsules and limited quite freely by allar ligaments. The allar ligaments (connecting the dens axis with occipital condyles and the anterior arch of the atlas) consist of high amount of collagen fibers and their major function is to prevent redundant axial rotation to the contralateral side [6, 22, 33]. These ligaments together with tectorial membrane also limit the flexion of the occiput and during lateral bending are responsible for the forced rotation of the axis [3]. The cruciate ligament is formed by horizontally oriented TAL and vertically oriented longitudinal fibers (Fig. 1.5, Chap. 1). Between the odontoid process and transverse ligament is a thin layer of cartilage, which allows for TAL to move freely during rotation and preserves it from friction damage. The transverse ligament consists of collagen fibers and is very resistant to breakage. Spence et al. in their original cadaver tests reported stress necessary to TAL rupture in average 580 N (38–104 kg) [29]. Dvorak et al. described experimental failure of TAL only under the force 170–700 N (corresponding about 17–70 kg) [8]. Restriction of anterior translation of the atlas during flexion of the head is the main function of TAL while still permitting its axial rotation around the dens. The secondary restriction of this motion is secured by atlantodental component of the allar ligaments. The tertiary stabilizers are the accessory atlantoaxial ligaments and capsular ligaments [5, 6]. TAL partially protects the C1-C2 joint also from a rotary dislocation. Posterior translation is prevented by mechanical bracing of the anterior portion of C1 on the dens. The apical ligament due to its laxity probably has no important function is movement restriction [15]. The IAR for sagittal plane motion is located in the region of the middle third of the dens and for axial rotation in the central axis of the dens, respectively [33].

2.1 CVJ and UCS Axial Load Distribution

The motion characteristics of UCS are unique; nevertheless, the axial load distribution in CVJ represents another exceptional situation irreproducible in other parts of spine (Fig. 2.1). The weight of the head and the axial

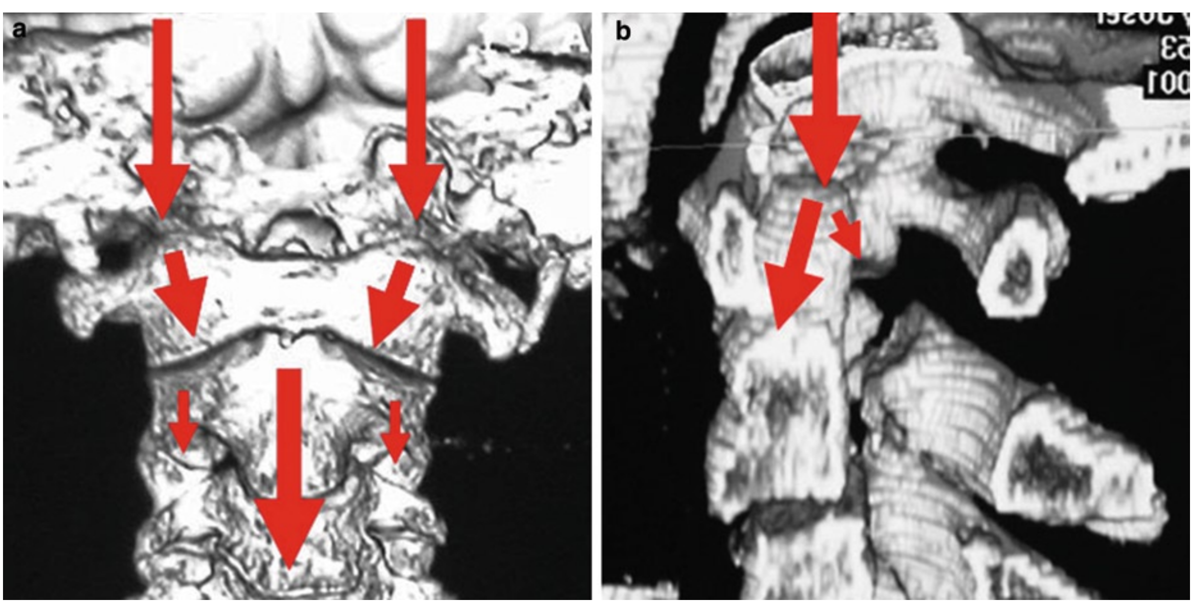

Fig. 2.1 Diagram showing the axial load distribution changing from two to three force vectors at the C2 level. (**a**) CT in 3D reconstruction in frontal plane. (**b**) CT in 3D reconstruction in sagittal plane. Note the consequent hangman type fracture

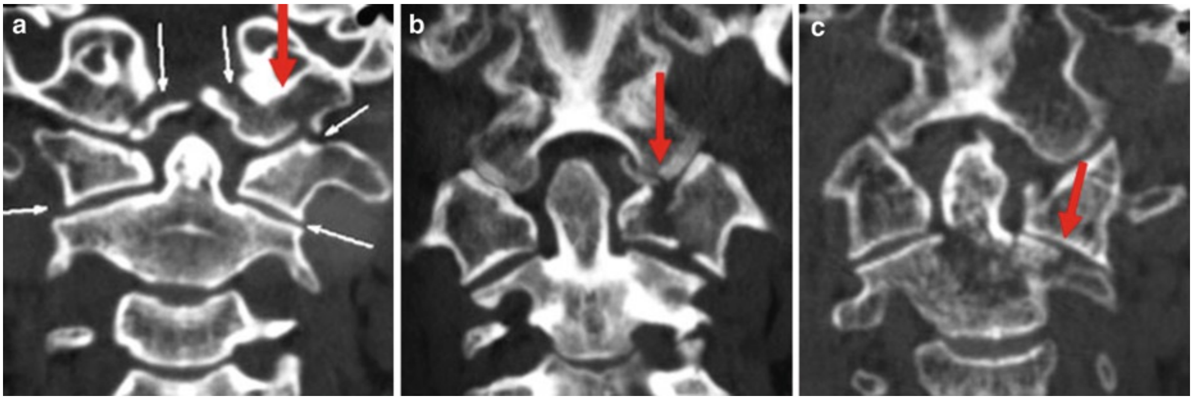

Fig. 2.2 Traumatic consequences of atypical axial load distribution in CVJ and UCS depicted on coronal CT reconstructions. (**a**) fracture of occipital condyle. (**b**) lateral C1 mass fracture simultaneous with condyle fracture. (**c**) fracture of lateral facet C2 pillar. Note the TAL avulsion fragment and type III odontoid fracture

loads applied to the head are transmitted through the two occipital condyles to two AO joints. The wedge-shaped lateral masses of C1 transfer the weight downwards with logical tendency to distract laterally. If the C1 ring and TAL act properly, the force is further transmitted to two C2 facets; however, further load distribution in C2 vertebra is divided from two force vectors into three points at the C2-C3 interface [14]. Most of the load is thus transmitted to the C2-C3 disk and less to the posterior C2/C3 facetal joints. The force transmission divergence has some critical places where consequently fractures can arise in the case of overload (Fig. 2.2). First critical place is the atlas. Wedge-shaped lateral masses and the C1 free floating "washer" ring have to buffer the axial force and if overloaded the atlas bursting leading to Jefferson-like fractures can happen (Chap. 10). The second critical location is the C2 pars interarticularis and mainly its isthmus as locus of minor resistance. The axial force overload can lead to overstressing of the bone resistance and create the hangman type fractures. Certainly, previously described model situations can be further modified by concomitant rotation, lateral bending of sagittal movement. This physiological CVJ and UCS load distribution has to be respected during reconstruction procedures also.

2.2 Clinical and Morphological Instability of CVJ and UCS

It is of utmost importance to decide whether the UCS is stable or not in order to determine correct treatment choice in various types of pathological lesions in this region.

Clinical stability at the C0-C1 and C1-C2 joints is intimately linked to their functional anatomy. *Clinical instability* can occur as a result of trauma, degenerative conditions, tumors, inflammation, or surgery; however, its definition is still controversial. Significant disagreement exists even among experts. White and Panjabi [35] defined clinical instability as the loss of the ability of the spine under physiologic loads to maintain relationships between vertebrae in such a way that there is neither initial nor subsequent damage to the spinal cord or nerve roots, and in addition, there is neither development of incapacitating deformity nor severe pain. They further defined physiological loads as loads that are incurred during normal activity. Incapacitating deformity was defined as gross deformity that the patient finds intolerable. Severe pain was defined as pain that cannot be controlled by non-opioid analgesic medications.

In short, it means that the spine is unable to resist the physiological loads without pain, deformity and/or neurological deficit. Such a broad definition, in fact, encompasses nearly all the pathological conditions detectable in UCS.

The definition of *mechanical instability* is more exactly specified than clinical one.

In fact, whatever static or dynamic position of UCS beyond the physiological limits is detected must be considered as instability.

Static and dynamic radiographic investigations with consecutive exact measurements are providing us information necessary to decide if the spine is stable or not (see Chap. 3).

Table 2.1 Morphological criteria for upper cervical spine instability [35]

>8°	Axial rotation C0-C1 to one side (measurable only on CT)
>1 mm	C0-C1 translation (measurable only on C)
>7 mm	Overhang C1-C2 (total right and left, on anteroposterior radiograph)
>45°	Axial rotation C1-C2 to one side
>3 mm	C1-C2 translation at anterior atlantodental interval (AADI)
<13 mm	posterior atlantodental interval (PADI)

Avulsed transverse ligament

2.3 Occipitoatlantal Joint Stability and Instability

Stability in this joint is secured mainly by their tight capsules, the anterior and posterior atlanto-occipital membrane, and through the ligaments between the occiput and the axis: the tectorial membrane, allar ligaments, and apical ligament [13]. Instability in the C0-C1 joints is less common than at the C1-C2 level. It can be result of trauma, rheumatoid arthritis, infection, tumor, or destabilizing surgery.

Vishteh et al. experimentally demonstrated the AO hypermobility caused by resection of occipital condyle. They found flexion-extension, lateral bending, and axial rotation increased 15.3%, 40.8%, and 28.1%, respectively after 50% condylectomy [32].

The AO joint is relatively unstable in children because of its structural characteristic and ligamentous laxity. Its stability increases in adulthood due to a decrease in elasticity of the ligaments [24]. OA dislocations (AOD) can be in the anterior, posterior, or longitudinal directions. Normally, the AO joint sagittal translation should not exceed 1mm, and the distraction distance (CCI) can reach 2 mm maximally on parasagittal CT images [19, 20, 36]. From other parameters used to evaluate the AOD, the Powers ratio is most frequently used [28]; however, the basion-dental interval (BDI) and basion-posterior axial line interval (BAI) both of which should not exceed 12 mm ("rule of twelve") are considered as the most exact and AOD-specific measurements [2, 11, 12]. Greater than 8° of unilateral axial rotation as other instability sign can be seriously measured only on superimposed CT scans [4, 6]. Basilar invagination and/or basilar impression represent the vertical instability. It appears most often in developmental anomalies and rheumatoid arthritis but also can occur in tumors or trauma. Methods of determining vertical CVJ instability are described in detail in appropriate chapters (see Chaps. 3 and 20).

2.4 Atlantoaxial Joint Stability and Instability

The transverse atlantal ligament has a key role in the maintaining AA stability. Especially, allar ligaments but also atlantoaxial accessory ligaments, apical ligament, and joint capsules provide secondary security [13, 22]. Instability at the AA joint is often presented as abnormal translation and/or axial rotation; nevertheless, other dislocations are also possible. Mainly TAL limits anterior translation of C1 on C2 as it will be described in further chapters. Fielding et al. [9] noted that anterior AADI is normally not more than 3 mm. AADI of 3–5 mm implies damage of the transverse ligament, and AADI measured 5 mm or more indicates that the accessory stabilizing system (especially, the allar ligaments) has been also damaged. A PADI of less than 13 mm may also denote anterior translational instability. The allar ligaments alone are not capable of preventing excessive anterior horizontal displacement if the transverse ligament is ruptured. If the odontoid process is hypoplastic, fractured, or resected logically the ligaments also cannot provide their stabilizing function. Posterior AA translation, despite being rare, can be detected in trauma, tumor, or other pathologies destroying odontoid – TAL catch system as well. Nonetheless, more frequently, the rotational dislocations of different types are diagnosed [3, 4, 6].

The rotation-limiting ability of the alar ligament was investigated by Dvorak et al. [6] in cadaver studies. They observed a mean increase of 9° or 30% of the original mean rotation divided equally between the C0-C1 (+5°) and C1-C2 (+4°) complexes in axial rotation in response to an alar ligament lesion on the opposite side. The laboratory findings of Dvorak and Panjabi were verified with a clinical CT study of 9 healthy adults and 43 patients with cervical spine instability with conclusion that axial rotation of the C0-C1-C2 complex can be increased after trauma-lesions of the alar ligaments [5]. In general, these studies showed that the main function of the alar ligament is to limit axial rotation to the contralateral side. The transverse ligament also protects the atlantoaxial joint from a rotatory dislocation. Fielding et al. [9] described that with the intact transverse ligament, a complete bilateral rotational AA dislocation can occur if 65° or more is reached. With transverse ligament disruption dislocation can occur at 45° of rotation already. Total lateral displacement of more than 6.9 mm of the lateral masses of C1 over the C2 facets, as measured on the cadaver tests, determines disruption or avulsion of the transverse ligament [29].

2.5 For Practical Purposes We Can Summarize

The motion of AO-AA joint complex is always coupled. UCS is responsible for 60% of rotation and 40% flexion and extension of the whole cervical spine. Atlas has the widest range of motion of any vertebra in the spine. It is almost freely floating in between the occiput and C2 buffering the axial loads coming from head to spine.

The *AO joint* mainly provides flexion and extension in the range of 20°, lateral bending is possible up to 10°. Negligible rotation is possible; however, translation of more than 1 mm is considered as pathological. The joint distraction measured on CT should not exceed 2 mm.

The *AA joint* is responsible for 90% of axial rotation of the UCS complex with the average range of rotational motion to one side of 40°. Flexion-extension is possible at an average of 20° and the lateral bending can reach up to 10°.

Whatever parameter measured beyond the physiological limits has to be considered as mechanical instability. Performing complex reconstruction of the UCS the load distribution typical for this spine region has to be respected and the non-affected segments spared to preserve as much movement as possible.

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Special Radiology

3

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The anatomy and pathology of the craniovertebral junction (CVJ) may be complex but can be readily visualized by a variety of radiological means. The primary modalities include simple plain radiographs, computer tomography (CT), and magnetic resonance imaging (MRI). Each clinical scenario warrants a different imaging modality or, more commonly, a combination of multiple modalities. This chapter describes these imaging modalities as they pertain to the CVJ. Specific pathologies are discussed in separate chapters.

Historically, plain films have been the radiographic gold standard for assessment of the spine in general and form an essential part of spinal evaluation today, more than 100 years since Wilhelm Roentgen shared the first-ever radiograph of his wife's hand in 1895 [23]. Bony and some soft tissue abnormalities are well visualized on plain films. Lateral cervical radiographs are the most commonly used images in acute evaluation of the cervical spine. For example, they are used while patient is still on the stretcher and further determine the way patient can be handled through their traumatic work up. This is even more important for the unconscious patient. The most commonly missed traumatic injuries are at the lower end of the cervical spine [44] and different projections such as swimmer's ("flying angel") view have been designed to enhance the visibility of the cervicothoracic junction. Similarly, multiple views exist to carefully delineate CVJ.

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Lateral projection allows for a good assessment of the alignment of the bony components of the spine and also sagittal balance when performed upright. Any abnormality detected on bony spinal canal (fracture, subluxation) necessitates further examination to determine its cause.

Prevertebral soft tissue swelling can point one to the area of injury as it often indicates a presence of a hematoma secondary to a fracture. Anteroposterior view is commonly obliterated by the jaw; so, open-mouth view films are particularly useful in assessing odontoid pathology as well as the integrity of the atlantoaxial and atlanto-occipital relationships.

Allesandro Vallebona proposed to represent a single slice of a body part on a radiograph, the so-called tomography, a technique that remained the pillar of radiology until the late 1970s [32]. However, the availability of computers and transverse axial scanning resulted in the development of CT by Godfrey Hounsfield and Allan McLeod Cormack [36]. Since then, multi-slice CT has revolutionized cross-sectional imaging with scanning time down to a single breath hold today. Isotropic voxels allow for two-dimensional reformatting and thus production of high quality three-dimensional images that are particularly useful when assessing complex bony abnormalities of the CVJ. However, the disadvantage of CT is increased radiation dose to patients with its ever more prevalent sequelae, particularly in pediatric population [4].

Although myelography with CT allows for excellent neural structure delineation and skeletal correlation, it has been largely replaced by MRI technology credited to Paul Lauterbur and Sir Peter Mansfield who were awarded Nobel Prize in 2003, albeit some controversy surrounds the award [40]. MRI is excellent in evaluation of neural, ligamentous, and disk structures. Sagittal images become particularly useful in CVJ, evaluation of alignment, and assessment of various craniometric lines and angles.

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