5 Sagittal Balance Concept Applied to the Craniovertebral Junction

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5.1 Comparative Anatomy and Evolution of Balance

The acquisition of vertical posture and bipedal locomotion represents the most important transformation in the history of the *Hominidae*, including the change in relationship between the foramen magnum orientation and cervical spine [1].

With the evolution of our species has come significant change in the function and alignment of the cervical spine, defined by adaptive abilities to feed, move, and breath. The amphibian typically has a singular cervical vertebra with a non-mobile craniovertebral joint (CVJ), and it may possess a long extensible tongue to eat its prey. While the reptile has a less constrained CVJ, it is constrained by the force required to lift a relatively heavy head; the tetrapod can rapidly project and retract the mouth, armed with teeth, toward its prey or aggressor.

Sagittal alignment of the CVJ has evolved in synchrony with our progression from quadruped to biped posture [2]. The center of gravity of the head in quadrupeds is located quite anterior of the CVJ due to the development of the splanchnocranium, the horizontality of the base of the skull, and the posterior position of the occipital condyles, so that the occipito-atlantal (OC1) joint alignment is almost vertical. In primates and even more markedly in humans, basicranial flexion is observed in the sphenoid, with the clivus then forming an angle with the anterior part of the base of the skull. This process, probably related to the development of the cerebral hemispheres and the reduction of the facial mass, coincides with the anterior migration of the occipital condyles, which has the effect of considerably reducing the bending moment of the center of gravity of the head. In humans, the OC1 articulation is horizontal, and the center of gravity of the head vertical line passes right in front of the dens. Head posture is governed by the ability to maintain horizontal gaze, hearing, equilibrium, nasorespirational function, and even psychological condition (Fig. 5.1).

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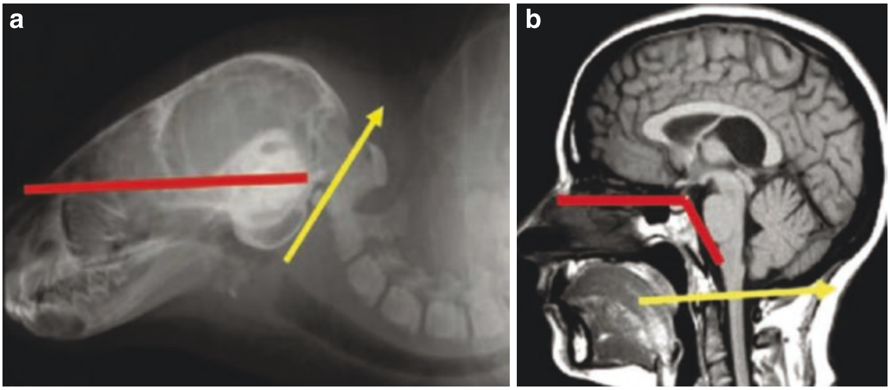

Fig. 5.1 In quadrupeds (**a**) the skull base is horizontal (platybasia), the occipital condyles are located at the back of the skull and the foramen magnum is tilted back and top. In humans (**b**) basicranial flexion is more important between the anterior floor of the skull base and clivus, the occipital condyles are almost under the skull and the foramen magnum is horizontal. (With permission from Vital JM, Anatomie de la Colonne Vertebrale)

5.2 Functional Anatomy

The CVJ functions primarily in rotation of the head and secondarily in flexion and extension. At the outset, slightly more flexion/extension occurs at the OC1 joint, and most axial rotation occurs at the C1C2 complex. Adult OC1 motion includes approximately 25° of flexion–extension, 5° of lateral bending, and 5° of rotation. C1C2 motion includes approximately 20° of flexion–extension, 5° of lateral bending, and 40° of rotation [3]. There should be no translation at the OC1 junction.

Compared with the sub-axial spine (SAS), the ratio of lordosis of OC2 to C2-C7 is 77%:23% [4]. Cranial dimensions vary significantly, but the natural head position is constant [5]. As mentioned, the center of gravity of the head sits almost directly over the centers of C1 and C2 vertebrae, as reflected by the external auditory meatus (EAM) so the associated short radii may explain why most cervical spine lordosis occurs between C1 and C2 [6]. This anatomic feature also allows assessment of *EAM tilt*, a global alignment assessment of the cervical spine, represented by the angle between the vertical and the line joining the center of C7 and the EAM.

Given the intimate relations of the occiput, atlas, and axis bones, the optimal angle for portraying alignment of the CVJ is the *occipitocervical angle*, the OC2 angle between McGregor's line (external occipital cortex to hard palate) and the lower end plate of C2 [7, 8]. Its mean value is 14° (±7°) in asymptomatic subjects over 18 years, 12° (±6°) in those over 60 years and significantly greater in females [8, 9]. The *C1C2 angle* is defined as the angle between the horizontal axis of C1 and the lower end plate of C2, found to be 29° (±7°) [10]. OC2 is always lordotic in an asymptomatic normal population, whereas C2C7 may be neutral or sinusoid or kyphotic in up to a third of the normal population [10].

Sagittal alignment of the CVJ with respect to overall vertical sagittal balance has only recently been described using data from EOS imaging, a new low-dose radiographic system that images the upright skeleton. The system therefore relies on the depiction of one's natural posture. As described by Morvan et al., the individual is required to place one's fingertips on their clavicles and look straight ahead at the mirror mounted in front of them [11]. A higher C7 slope is associated with a higher lordosis in the SAS and a lower slope means a lower lordosis, but this does not affect the sagittal orientation of the CVJ. Le Huec et al. found that the median C7 slope value was 20°. They evaluated the OC2 of two groups—those with a value less than, and greater than 20°—finding that the C2C7 values were −2.5° and 11.5°, respectively, but that the OC2 value was 15.8° in both the groups. Despite significant variations in cervical spine lordosis or the slope of the C7 vertebra, the OC2 angle displayed constant values [10].

Both the OC1 and the C1C2 articulations have the capacity to contribute to sagittal alignment of the cervical spine, 25% and 20%, respectively. There are two basic postures of the neck (retraction-protraction) in primates including humans (Figs. 5.2 and 5.3). Retraction refers to an active position when the OC1C2 joints are flexed under the effect of the posterior musculature, such as in the "military tuck" position. Protraction corresponds to a passive rest position when the OC2 joint is extended (as in reading or sleep in a sitting position). This would increase the SVA, the horizontal offset distance from C2C7 causing flexion of C2C7 segments and hyperextension of C0C2 segments to maintain horizontal orientation of the head [12]. This is in fact a "push-forward with the head attitude" which one observes through efforts

Fig. 5.2 Clinical photographs of protraction (protrusion) and retraction ("military tuck") of the neck

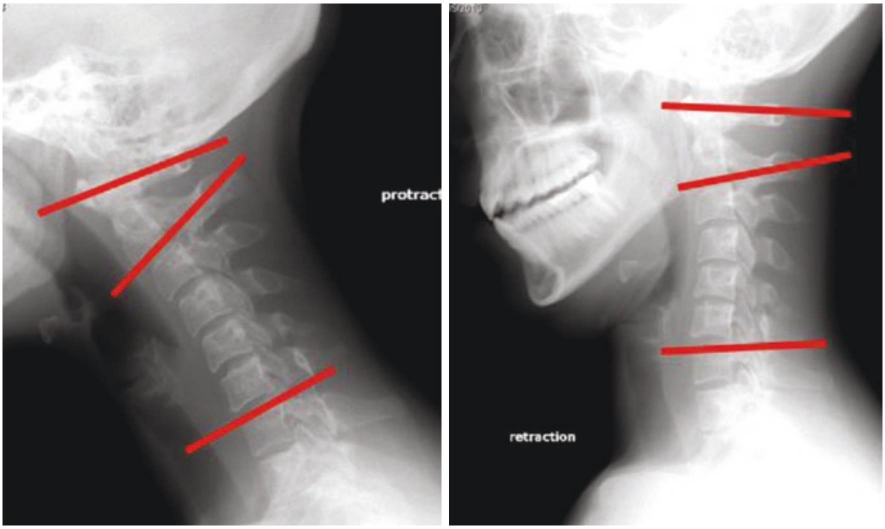

Fig. 5.3 Radiographs (lateral view) of protraction and retraction of the neck, demonstrating the reverse behaviors of the CVJ and SAS

of pushing (as in collision sports). It is in this posture that the CVJ reaches its maximum amplitude in extension [2].

The only constant variable in this context is gaze direction. A *coupling mechanism* is evident to achieve it: flexion of the subaxial cervical spine induces extension at the craniovertebral junction and vice versa [13].

What is further relevant to the CVJ is the effect that distal curves have on the cervical spine (Fig. 5.4). Given the fixed relationship between the pelvis and spine (pelvic incidence) and stiffness of the thoracic spine, the more mobile lumbar and cervical spinal articulations compensate for this as required. As thoracic kyphosis increases, cervical lordosis increases. In young adults with thoracic hyperkyphosis, for example, patients have a lordosis of 27° at C1C2 compared with 20° in the normal population [14], despite similar head positions and craniofacial morphology [15]. Furthermore, a reversal of the kyphosis induces a reduction in cervical lordosis (Fig. 5.5).

While the OC2 parameters of asymptomatic subjects remain constant despite the variables of C7 slope and C2C7 lordosis, compensatory abilities with increasing age and deformity include the CVJ as well as other mechanisms. If the global alignment predisposes to a head forward position, the CVJ can contribute to horizontal positioning of the head and gaze. This *"fine tuning" concept* is a representative feature of the CVJ, an adaption to changing alignment characteristics as required throughout both the cervical and thoracic/lumbar spine. These principles are evident in Figs. 5.2, 5.3, and 5.5 in both normal physiological functioning and as an adaptive feature in pathological conditions.

While our understanding of the compensatory alignment features of the CVJ are known in the sagittal context, we can assume that the CVJ can function to adapt to maintain a horizontal position of the head in coronal and rotatory planes as well.

Fig. 5.4 Three poses in profile with the evidence of compensation along the entire spine from the CVJ to the pelvis (erect-relaxed-slouched)

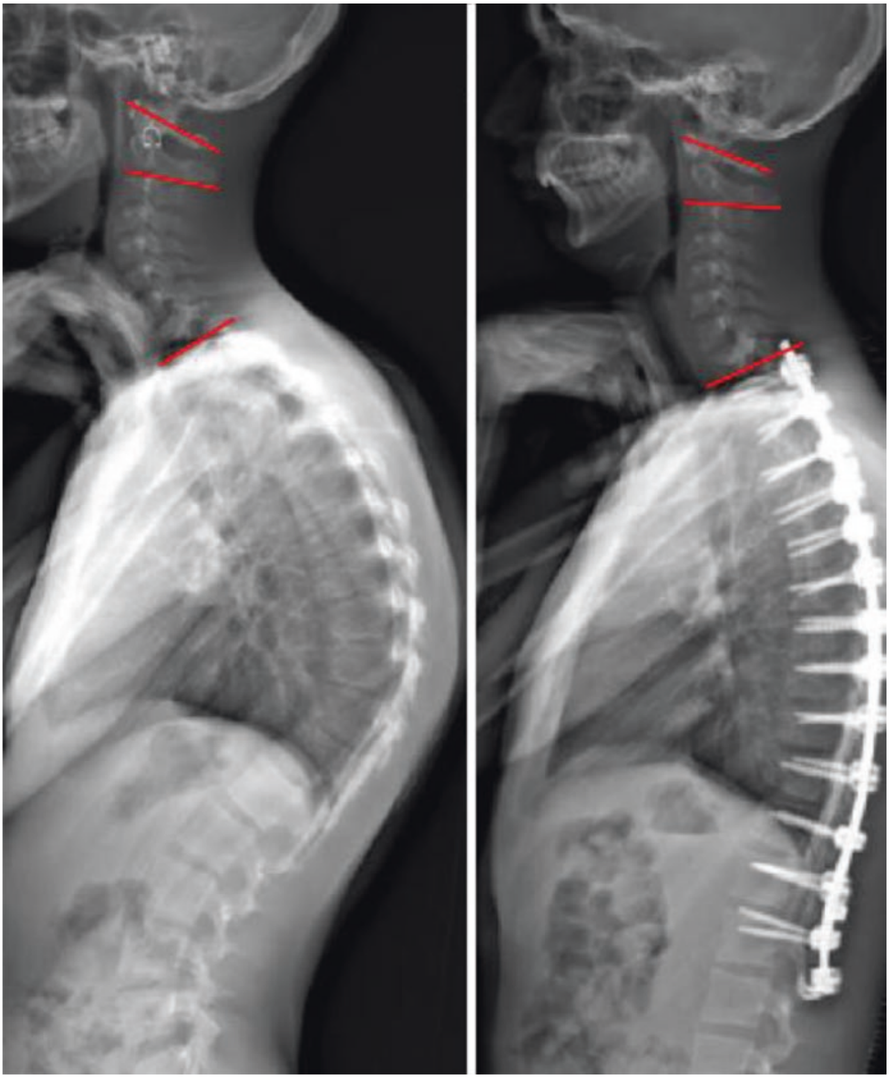

Fig. 5.5 Scheuermann's kyphosis pre- and post-deformity correction with the evidence of reduction of thoracic kyphosis and reduction of cervical lordosis

5.3 Degenerative Conditions

The most accurate method of assessing C2C7 alignment is the *Harrison method* of comparison between the tangents of each posterior wall along the subaxial cervical spine [16, 17]. It has been suggested that the Cobb C1C7 angle overestimates cervical lordosis, that the Cobb C2C7 angle underestimates cervical lordosis, and that the Harrison method (C2C7) may provide the best estimate of lordosis. Thus, little is

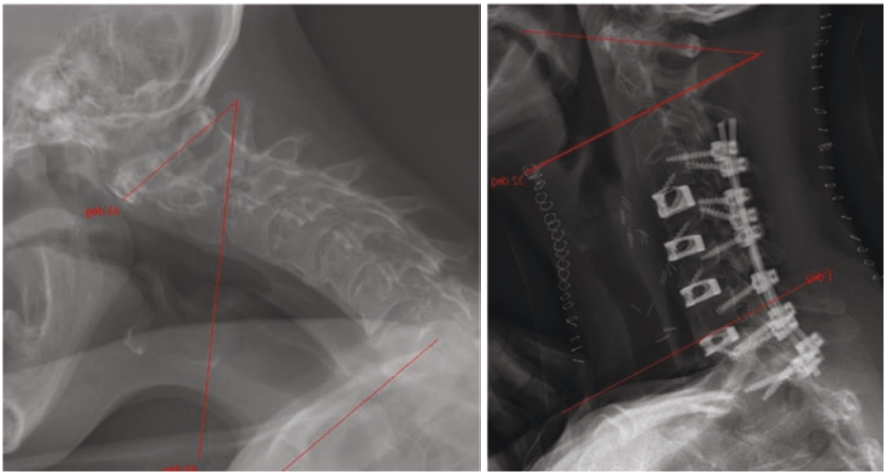

Fig. 5.6 Preoperative EOS radiograph of a degenerative cervical spine with a history of dropped-head syndrome with anterior multilevel autofusions. Postoperative radiograph with anterior osteotomies and cage placement (first stage) and posterior construct with pedicle and lateral mass screws (second stage). Notably there is a significant increase in SAS lordosis (from −44° to +1°) and decrease in CVJ lordosis (from 43° to 32°)

known on the contributions of the CVJ in cervical disc degeneration. Furthermore, despite the roles of OC1 and C1C2 articulations are quite different, their contributions are mostly quoted summarily as OC2.

Normal lordosis at the C4C7 levels only accounts for 6° (15%) of that of the cervical spine and includes the levels that undergo most degenerative change. Degenerative changes of the cervical spine are commonly associated with a reduction or loss of the segmental or global lordosis [17]. The net effect of loss of lordosis at distal levels contributes proportionally to a greater loss of sagittal alignment. This is compensated for by an increase at the CVJ, particularly OC1, to maintain horizontal gaze [18]. Appropriate correction of lordosis will reverse this (Fig. 5.6).

Traditionally, posterior-based approaches for posterior-based stenotic pathology with laminectomies of the cervical spine have been implicated in causing postoperative kyphosis and neck pain (Fig. 5.7). This is mostly due to the detachment of subaxial deep extensor muscles from the C2 or C7 spinous processes. Laminoplasty of C3 and at levels caudal to it results in less kyphosis than a dome-shaped laminotomy or especially C2 laminectomy [19]. C4–C7 laminoplasty with C3 laminectomy preserving the semispinalis cervicis insertion into C2 can reduce postoperative axial symptoms compared with C3–C7 laminoplasty and reattaching the muscle to the C2 spinous process [20]. The range of motion across OC1C2 has been shown to increase over time post-laminoplasty and is thought to represent a compensation for increasing stiffness from C2C7 [21].

Resection of C3 spinous process is thought to reduce the incidence of C2C3 spinous process autofusion post-laminoplasty which may otherwise occur in up to 53% [22]. Potentially some of what is described as neck pain may alternatively be

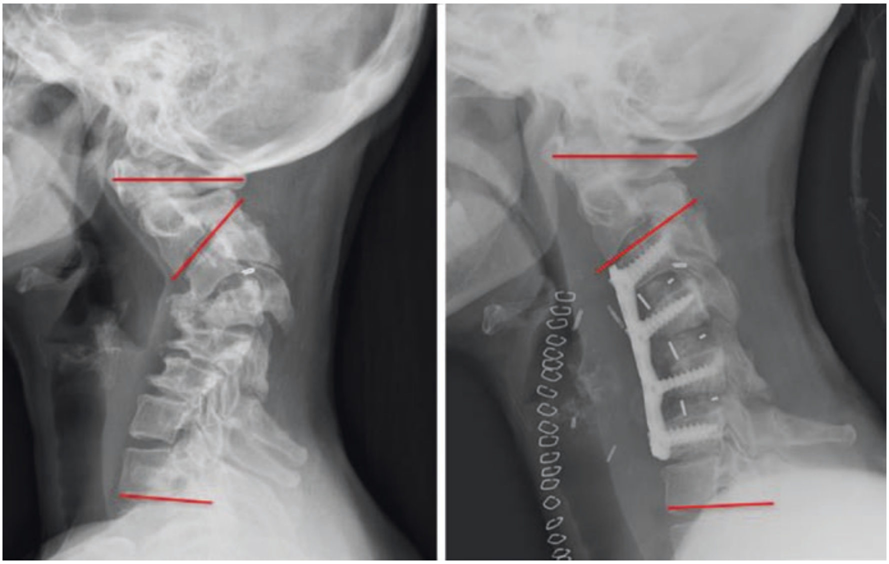

Fig. 5.7 Preoperative EOS radiograph of degenerative cervical spine with a history of a previous posterior laminectomy/laminoplasty and loss of extensor muscle action with the evidence of compensatory OC2 hyperlordosis. Postoperative radiograph with SAS lordosis increases and CVJ lordosis decreases

OC2 extension with occipital neuralgia and warrants consideration when evaluating sagittal images on MRI.

Decompensation of cervical sagittal balance can be represented as an increase in *chin brow vertical angle (CBVA)*, a reliable clinical measure of horizontal gaze. This angle reflects activities of daily living and quality of life. It is commonly used as a reference for ankylosing spondylitis and has been identified in many studies as an important parameter when correcting cervical deformity. It should be close to 0° in asymptomatic individuals. This may not be as apparent on lateral cervical spine radiographs, thus the C2 slope may be used to correlate with one's ability to maintain a horizontal gaze. Therefore, the C2 slope should be close to 15° for a comfortable horizontal gaze. What is often apparent on clinical examination are other adaptive features of compensation to maintain sagittal balance, such as thoracic extension, pelvic retroversion, and knee flexion.

Normalization of cervical spine alignment has been demonstrated after lumbar deformity correction (Fig. 5.8). A review of 31 lumbar pedicle subtraction osteotomy (PSO) cases was taken by the author with the evaluation of spinopelvic parameters [23]. A pattern resembling previous compensatory mechanisms emerged: there was a significant decrease of C7 slope, a decrease in distal C2C7 lordosis, and an increase in proximal cervical lordosis and OC2 angle. There was no significant difference between global cervical lordosis angle and EAM tilt (Fig. 5.9). The decrease in C7 tilt was caused by the corrective lumbar surgery, so the distal cervical lordosis manifested because there was no longer a requirement for compensation at this level. The

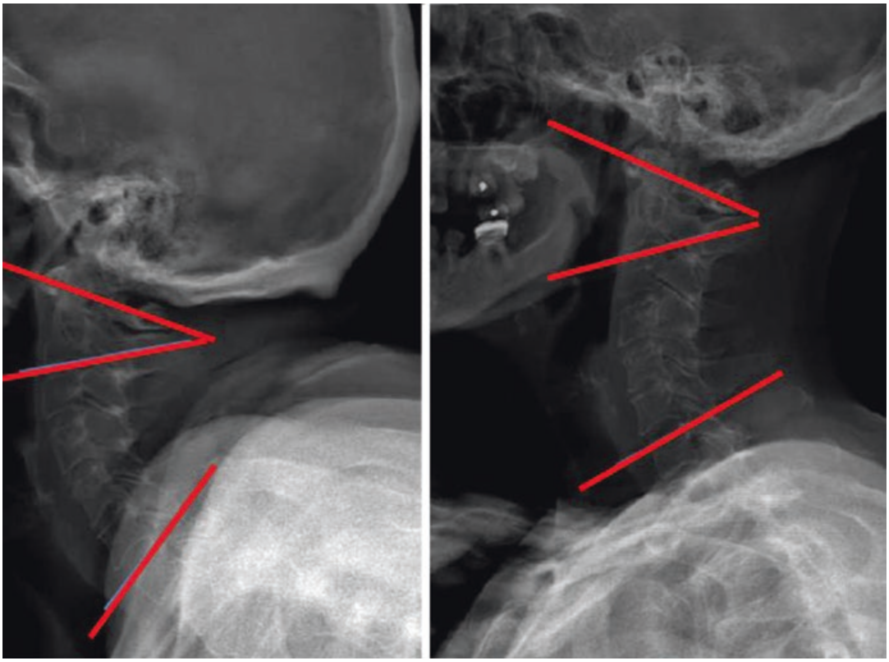

Fig. 5.8 Post-lumbar pedicle subtraction osteotomy with horizontalization of C7 and increase in C1C2 lordosis

proximal cervical spine readjusted to adapt a slightly flexed position to maintain horizontal sight. In effect, the adaptive features of the cervical spine maintained its global angulation and position relative to vertical balance.

5.4 Other CVJ Alignment Considerations

Bony malformations of the CVJ are best divided into malformations of the central pillar such as odontoid or basioccipital dysgeneses or of the surrounding rings such as pro-atlas or C1 sclerotome anomalies. Thus, relevant malformations are mostly associated with decreased skull-based height (platybasia as described in quadrupeds, Fig. 5.1) and/or, to a lesser extent, increased vertebral column height. In practical terms, structural anomalies mostly involve the occiput, including condylus tertius (third occipital condyle), basiocciput hypoplasia and atlanto-occipital assimilation. As malalignment may extend intracranially, both primary cranial angles (basal and Boogard's) and craniovertebral angles (Wackenheim clivus-canal, McGregor-C2, and OC1 joint axis angle) are relevant [24]. Platybasia may manifest as a short or horizontal clivus causing lordotic tilt of the foramen magnum and occipital condylar plane. Frequently with this condition, the odontoid is retroflexed, pointing toward the brainstem, often associated with cerebellar herniation, a syringomyelia and hypolordosis in the SAS.

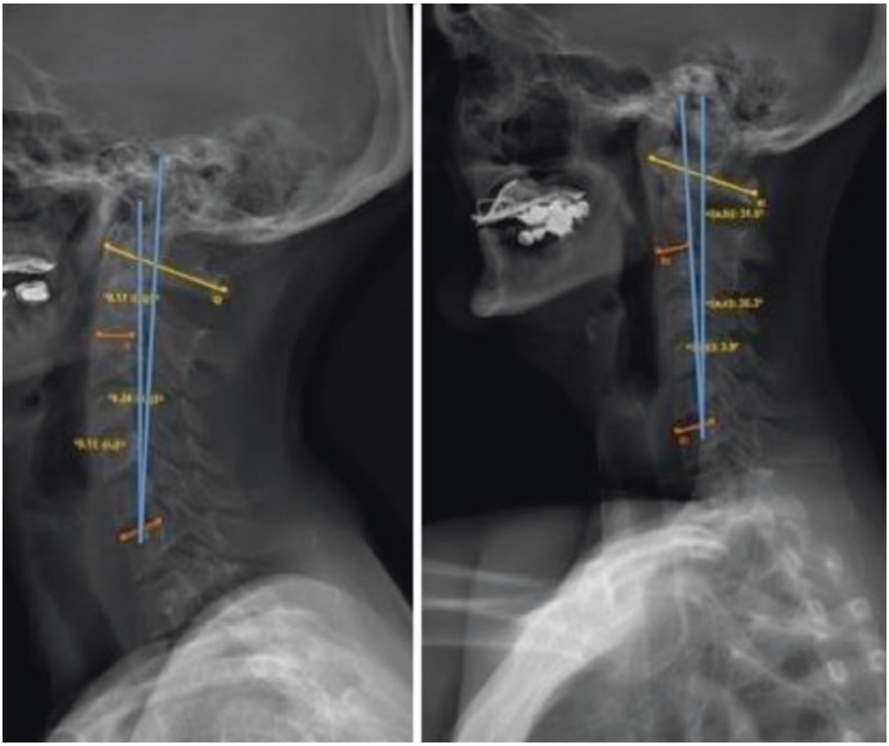

Fig. 5.9 Pre- and post-lumbar deformity measurement of cervical parameters. EAM tilt remains close to 0°, upper and lower cervical curvature changes are significant

Alignment pathology associated with trauma to the CVJ mostly involves type II fractures of the odontoid process of C2. Most of these fractures have either an oblique posterior or transverse orientation, almost half occur in combination with a fracture of C1, and 60% are posteriorly displaced [25]. Halo vest immobilization is an accepted form of treatment but not well tolerated in the elderly. Whether using halo vest or operative fixation, one must check for fracture reduction and alignment on intraoperative imaging. Displaced fractures perform poorly regardless of treatment. In attempts to reduce the fracture, one can immobilize the cervical spine in an abnormal alignment. Particularly with posteriorly displaced fractures, patients develop kyphosis of C2C7 with anterior displacement of the proximal cervical spine, in what has been described as a "Geier" or *vulture-like deformity* [26]. The underlying pathomechanism may be disequilibrium of the anterior load and posterior muscle forces in the upper cervical spine, thus posterior C1C2 stabilization may be the optimal treatment in those with osteoporosis. Forced hyperextension causes fracture of the C2 pars, as the odontoid process and cephalad structures displace anteriorly while the posterior aspect of C2 remain aligned with the caudal structures. Levine and Edwards types II and III display increasing displacement, kyphotic angulation, and instability, with increased indication for operative stabilization, including anterior, posterior, or combined approaches. Posterior approaches for operative fixation of either of these types of fractures will usually involve dissection of the C2 process and loss of extensor muscle function. This may lead to significant kyphosis at the CVJ.

5.5 Alignment Considerations When Operating on the CVJ

Preventative measures must be taken when instrumenting the CVJ to maintain a normal sagittal alignment. Using a Halo frame or Mayfield clamp for posterior cervical surgery serves to optimize three-dimensional positioning of the head as close to neutral as possible. Patients are frequently placed in a slight reverse Trendelenburg position to diminish venous congestion and bleeding. Therefore the position of the head must match that of the body. Head position is best imaged to ensure optimal CVJ alignment which in more recent times involves a trend toward intraoperative CT. Similar to fluoroscopy, the 2D facility can be used to check this. Longer occipito-cervical constructs placed in extension can be disabling, and one should err slightly toward flexion [27]. A hyperkyphotic angle at the CVJ can predispose to a higher incidence of postoperative dysphagia, dyspnea, and decreased oropharynx volumes [28]. As the trajectory of transarticular screws or pars screws is orientated cephalad, one may need to drape as far caudally as T3 to allow for this. Thus, obesity, a short neck or a hyperkyphotic thorax may compromise screw trajectory, particularly for Magerl transarticular fixation.

Multiple reports have shown that an excessive lordosis at the CVJ through surgical correction leads to compensatory kyphotic changes of the subaxial cervical spine. Yoshimoto et al. demonstrated that in a series of patients with C1C2 fixation, mean lordotic angles increased from 18° preoperatively to 26° postoperatively [29]. The fixation techniques in this series were diverse, but the authors felt that bone graft compression between the posterior elements of C1 and C2 from such techniques as Brooks (interlaminar graft) wiring or a Halifax clamp led to a C1C2 hyperlordosis with a resultant C2C7 postoperative kyphosis. The C1C7 angle did not change significantly given the segmental compensation mechanisms within the cervical spine as mentioned previously.

Likewise, in a series of mostly rheumatoid patients, corrective surgery with fusion at the CVJ has shown that restoration of lordosis at OC2 leads to a decrease in lordosis at C2C7 [26]. This has also been shown in patients with congenital atlanto-axial dislocations [30]. Distraction arthrodesis is a helpful technique at C1C2 for C2 root compression or between O-C1-C2 to disengage the odontoid process with basilar invagination. Ding et al. reported disengaging the odontoid process in congenital malformations using the application of the combined forces of extension and distraction between the occipital plate and the cervical pedicle screws [31]. Parallelism must be maintained with distraction so as not to cause kyphotic deformity. C1C2 intervertebral cages may also be used to achieve this.

When treating pathology at the CVJ, the most caudal aspect of the fixation may extend to the distal cervical spine. Sagittal balance between the proximal and distal segments of the cervical spine should be checked on imaging before the rods are secured.

5.6 Conclusions

The proximal OC2 and distal C2C7 segments of the cervical spine work synergistically to ensure that the head remains balanced over the pelvis. Within a functional range of motion, deformities of each can be compensated for by the other. The "fine-tuning" features of the CVJ allow for obtaining horizontal gaze despite the variations in relative positions of the head and spine. Furthermore, this compensatory mechanism is especially important in pathological conditions.

Correction of deformities of the subaxial C2C7 cervical, thoracic, and lumbar spine can reduce lordosis at the CVJ, so that the head and gaze remain horizontal. Surgical objectives when operating on the CVJ must include normalization of the CVJ which relies on several factors including positioning, anatomy-specific instrumentation, instrument placement, and the use of intraoperative imaging or navigation.

Glossary

CVJ Craniovertebral junction including occiput to axis (O-C1-C2, OC2)
SAS Subaxial spine, including C2-C7
OC1 Occipito-atlantal joint
C1C2 Atlanto-axial joint
SVA Sagittal vertical alignment

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