C2 Screw fixation techniques in atlantoaxial instability: A technical review

ABSTRACT

Atlantoaxial instability (AAI) is surgically a complex entity due to its proximity to vital neurovascular structures. C1-C2 fusion has been an established standard in its treatment for a considerable time now. Here, we have outlined the most common techniques for C2 screw fixation in practice at present such as C2 pedicle, C2 pars, C2 translaminar, C2 subfacetal, C2-C3 transfacetal, and C2 inferior facet screw. We have discussed in detail the technical as well as biomechanical aspects of each technique of C2 screw fixation in AAI and explored the intricacies of each technique.

Keywords: AAD, atlantoaxial instability, C2 inferior facet, C2 laminar, C2 screws, C2/C3 transfacet

INTRODUCTION

Atlantoaxial instability (AAI) is caused by excessive mobility of the C1-C2 joint as a result of a bony or ligamentous defect.[1] Goel's and Harm's posterior C1-2 screw fixation is considered the gold standard sure to its higher fusion rate and superior biomechanical stability.[2] Although there are few options for C1 (atlas) fixation, C1 lateral mass screws have been used mostly due to the consistent anatomy of C1 lateral masses. It has been documented that C1 lateral mass screws can be easily placed, even in cases with anomalous vertebral artery (VA) course after gentle VA dissection and it provides the best biomechanical construct for C1 fixation.

Many techniques for C2 screw fixation have been developed over the years to deal with the anomalous VA course and variable bony anatomy of C2 bony elements. Some are used as primary fixation procedures, while others are utilized as rescue techniques. The procedure is chosen depending on the patient's vascular-osseous architecture, the specific pathology, the surgeon's experience, and comfort level.[2] So far, no systematic review has analyzed the numerous C2 screw fixation techniques in one place and discussed their benefits and drawbacks.

In this article, we will explore the advantages and disadvantages of several C2 screw fixation procedures utilized in AAI, such as C2 pedicle, C2 pars, C2 translaminar, and C2 subfacetal, C2-C3 transfacetal, and C2 inferior facet screw with individual cases. We did not include the C1-C2 transarticular screw approach introduced by Jeanneret and Magerl *et al*. in 1992[3] as 22% of the cases were not suited for it and it had a higher risk of VA injury when compared to other techniques, making it less popular among surgeons. Furthermore, previously used C1-C2 wiring techniques introduced by Gallie and Brooks though easy to perform carried limited use due to their poor biomechanical stability and low fusion rate when compared to the newer techniques.

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CLINICALLY RELEVANT ANATOMY OF AXIS

In AAI surgery, the pedicle, pars, lamina, and course of the VA make some of the most essential clinically relevant anatomical concerns for safe and secure C2 fixation.

The C2 (Axis) is the spine's second cervical vertebra, located beneath the atlas. The axis is distinguished by a distinctive odontoid protrusion, also known as the dens, which rises dorsally from the remainder of the bone [Figure 1a-c]. The C2 Pars is the bone that joins the upper and lower facet, whereas the C2 Pedicle is the bone that connects the posterior elements (facets, lamina, and spinous process) to the vertebral body [Figure 1a].

The C2 pedicle is situated medially beneath the superior articular facet and anteriorly to the transverse foramen. When it comes to C1-C2 fusion in AAI surgery, it offers the most robust and sturdy construct. As a result, its anatomical dimensions are critical, particularly if transpedicular screw fixation is intended. The C2 pedicle, according to Panjabi *et al*.[4] and Xu *et al*.,[5] is relatively large, measuring 9–11 mm in height and 7–9 mm in breadth. C2 pedicle diameter of 5 mm is found in only 2.4%–11.7% of the population.[5-7] According to Sairyo *et al*., the minimal pedicle diameter for safe pedicle screw insertion is 3.5 mm[8] which is not always possible. Hence, new techniques were needed which would eliminate the pedicle.

The anatomy of the C2 lamina is important for putting the translaminar screws [Figure 1a]. Cassinelli *et al*.[9] discovered a mean thickness of 5.77 ± 1.31 mm in a study of 420 C2 laminae, with 92.6% of instances having a thickness of ≥4 mm and 71% having a thickness of ≥5 mm. Furthermore, Ma *et al*.[10] discovered that 2.5% of the instances exhibited C2 spinous process height = 9 mm, which is the height required for two 3.5 mm screws with 1 mm tolerance in each direction for laminar screw placement.

The course of the VA is the most crucial limiting factor for most C2 screw fixation procedures. VA, particularly the V3 segment, travels between the superior and inferior facets of C2. It ascends laterally to the C1-C2 joint in most cases, through the foramen transversarium of C1, and turns medially

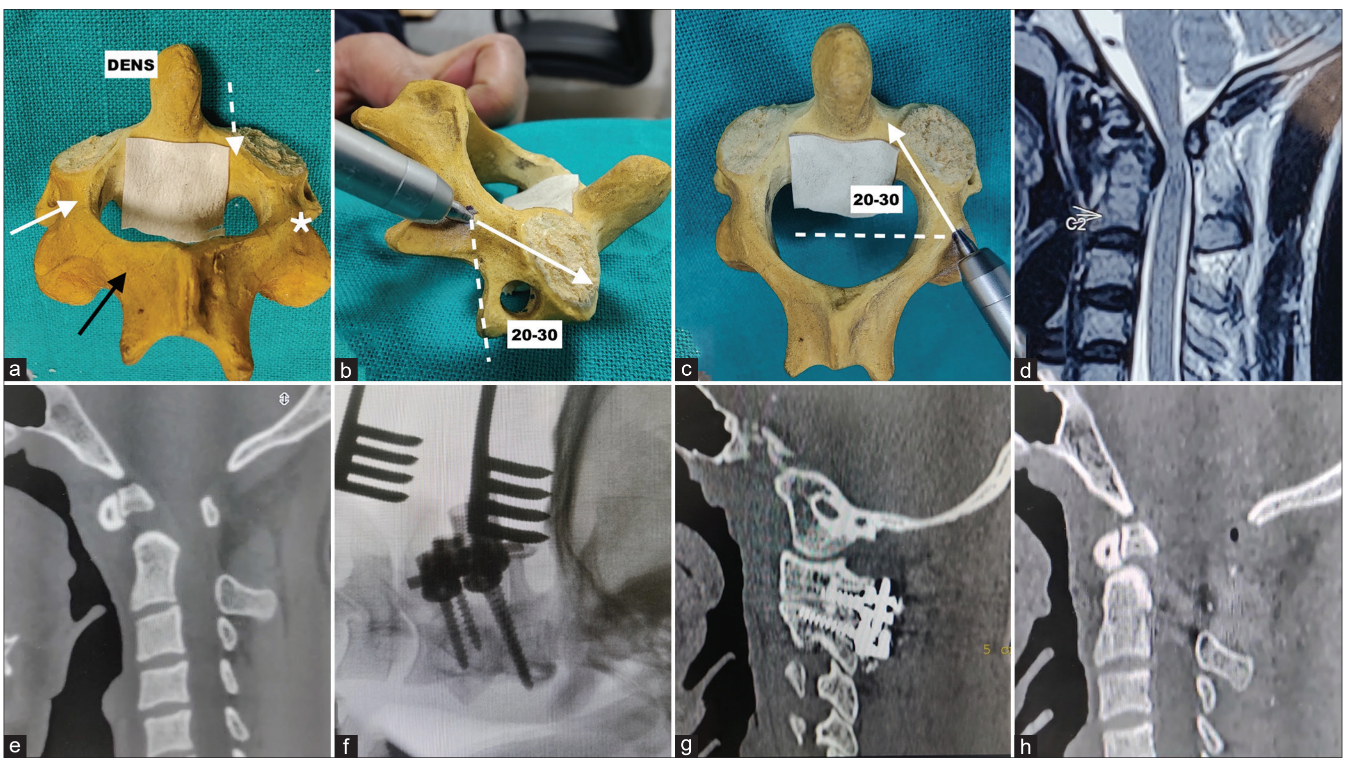

Figure 1: (Pedicle screw) Goel and Laheri and Harms and Melcher[13,15] technique for C2 (Axis) pedicle screw. (a) Entry point is at the cranial and medial quadrant of the C2 isthmus surface along the superior border of the C2 lamina denoted by the white star. DENS: Dens process of C2; C2 Pars: solid white arrow; C2 Pedicle: Interrupted white arrow; C2 lamina: Solid black arrow. (b) Cranio-caudal angulation on the sagittal plane is 20°–30° cranially. (c) 20°–30° medial angulation on the axial plane denoted by the white arrow parallel to the superomedial surface of the C2 pedicle. (d) T2-weighted MRI craniovertebral junction of a 30-year-old male presenting with spastic quadriparesis showing atlantoaxial instability and cord compression with myelomalacia changes in the cord. (e) Preoperative CT scan of the patient with mid-sagittal cuts showing Type 2 odontoid fracture with AAI. (f) Intraoperative C-arm X-ray image showing placement of bilateral C1 lateral mass and C2 pedicle screws. (g) Postoperative CT scan with sagittal cuts passing through right C1-C2 facet joint showing C1 lateral mass screw and C2 pedicle screw with rods and bone graft in joint space. (h) Postoperative CT scan with mid-sagittal cut showing opened-up canal space after reduction. MRI - Magnetic resonance imaging; CT - Computer tomography

across the superior surface of the posterior C1 arch to continue in the V4 segment.

Lee *et al*. divided VA courses into four categories based on two anatomical parameters, the medial shift in the coronal plane and the high riding in the sagittal plane. According to their findings, 25% of VA were both medially shifted and high riding.[11] Bloch *et al*.[12] classified a high-riding vertebral artery (HRVA) as a height of the C2 pedicle isthmus of 5 mm and/or an internal height of 2 mm on a sagittal picture 3 mm lateral to the cortical edge of the spinal canal wall at C2. The presence of an HRVA complicates the placement of the C2 pedicle screw.

TECHNIQUES OF C2 SCREW FIXATION

C2 pedicle screw

Goel *et al*. were the first to describe it. Goel and Laheri described plates and screws[13,14] for C1 lateral mass and C2 pedicle screw fixation in 1994. In 2001,[15] Harms and Melcher advocated the use of polyaxial screws and rods instead of plates. This approach was preferred over C1-C2 transarticular screws because it eliminated the necessity for reduction of AAI before screw insertion. In addition, it was less technically challenging than transarticular screws.[2] Many studies, including those by Goel, Laheri, and Harms, indicated that C2 pedicle screws had excellent fusion rates. Although there was still a potential for VA injury in roughly 9% of the cases, it was much lower when compared to transarticular screws.

The technique of C2 pedicle screw

The cranial and medial quadrants of the C2 isthmus surface along the superior border of the C2 lamina serve as the entry point for the C2 pedicle screw. The screw trajectory is inclined 20°–30° medially in the coronal plane and 20°–30° cranial in the sagittal plane parallel to the superomedial surface of the C2 pedicle [Figure 1a-h]. In most cases, a 3.5 mm polyaxial screw with a length of 18–22 mm sufficed.

C2 pars screw

C2 pars screws are also known as Isthmic screws. The insertion location of the pars screw is inferomedial to that of the pedicle screw. C2 pars screws provide better lateral bending stability than C2 pedicle and laminar screws. However, the risk of VA damage was equivalent to that of C2 pedicle screws.

The technique of C2 pars screw

The C2 pars screw entry point is 2–3 mm superior and lateral to the C2-C3 facet joint's medial surface. The trajectory angle is 10° to the medial side and 45° to the cranial side towards the anterior tubercle of C1 [Figure 2]. Typically, a 14–18 mm polyaxial screw with a diameter of 3.5 mm sufficed.

C2 translaminar screw

Wright[16] described the C2 translaminar screw fixation technique in 2004. Because this procedure is not dependent on the course of the VA, there are few chances of injury to the VA. The cranial to the caudal height of the spinous process, however, should be sufficient to accept both screws. The stability of a C2 translaminar screw construct was comparable to C2 pedicle screws, and in many instances, it is used as a first-line approach based on individual anatomy.

The technique of the C2 translaminar screw

For the left C2 laminar screw the entry point is at the junction of the C2 spinous process and lamina on the right, close to the rostral margin of the C2 lamina. Similarly, for the right C2 laminar screw, the entry point is at the junction of the spinous process and lamina of C2 on the left, close to the caudal aspect of the lamina. The trajectory is along and parallels the angle of the exposed contralateral C2 laminar surface [Figure 3].

C2 Subfacetal screw

C2 vertebral screw is another term for it. The pedicle and VA are completely bypassed by this screw. As a result, the likelihood of VA damage is reduced. In addition, it provides ample bone for rigid fixation, and divergent screws theoretically provide greater pull-out strength. Putting up these screws is a challenging task in high-grade irreducible AAI as screw heads of C1 lateral mass and C2 subfacetal screws tend to collide in the narrow operative corridor.

The technique of C2 subfacetal screw

The entry point is located 3–4 mm below the midpoint of the upper surface of the C2 superior facet. In the sagittal plane, the direction varies and can be superomedial in a pedicular line or directed downwards into the C2 body. Medial angulation ranges from 20° to 30° [Figure 4]. A polyaxial screw with a length of 18–24 mm sufficed.

C2 Transfacetal screw

Goel *et al*.[17] were the first to introduce C2-C3 transfacetal screws in 2017. Transfacetal screw placement is a simple procedure that carries a little risk of VA injury. Furthermore, as it incorporates four cortical surfaces, its biomechanical strength is comparable to that of pedicle screws. The sole negative is that it adds another level of fixation; however, the practical impact on a range of motion (ROM) is minor.

The technique of C2 transfacetal screw

The entry location for the C2-C3 transfacetal screw was established on the inferior facet of C2, 5 mm above the midpoint of the C2-C3 facet junction. The trajectory was straight in the coronal plane and perpendicular to the C2-C3

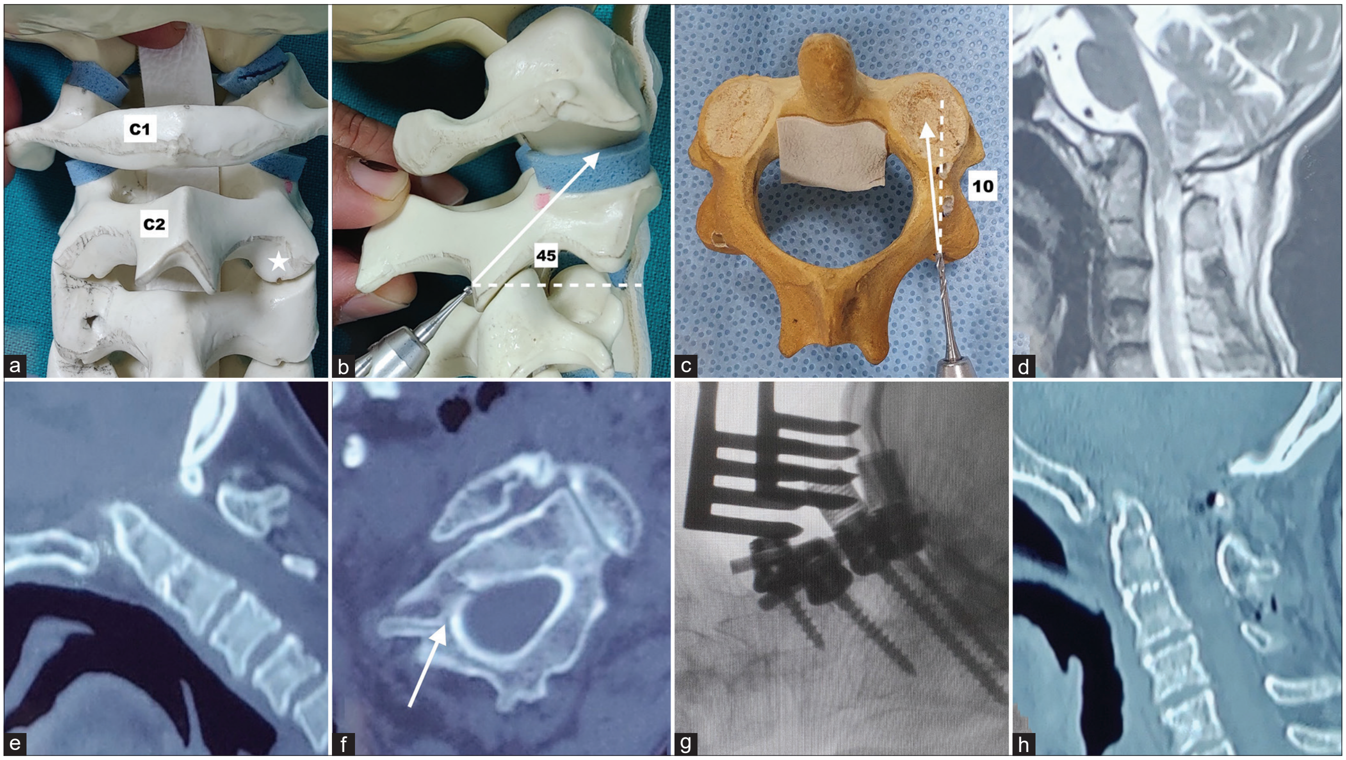

Figure 2: (Pars screw) Technique for C2 (Axis) pars screw. (a) Entry point is 2–3 mm superior and lateral to the medial aspect of the C2-C3 facet joint denoted by the white star. (b) Cranio-caudal angulation on the sagittal plane is at 45° cranially along the C2-3 facet denoted by the white arrow. (c) 10° medial angulation on the axial plane denoted by the white arrow towards the anterior tubercle of C1. (d) T2-weighted MRI craniovertebral junction of a 38-year-old male presenting with difficulty in walking showing atlantoaxial instability with basilar invagination and myelomalacia changes in the spinal cord. (e) Preoperative CT scan of the patient with mid-sagittal cuts showing atlantoaxial instability with basilar invagination. (f) Preoperative CT scan with axial cuts passing through bilateral C2 pedicles showing thin right C2 pedicle (shown with white arrow) for which pars screw placement was done. (g) Intraoperative C-arm X-ray image showing placement of bilateral C1 lateral mass with right C2 pars screw and left C2 pedicle screw. (h) Postoperative CT scan with mid-sagittal cut showing reduction of basilar invagination and AAD. C1: Atlas vertebra. MRI - Magnetic resonance imaging; CT - Computer tomography

facet joints in the sagittal plane [Figure 5]. A polyaxial screw with a length of 14–16 mm was sufficient.

C2 Inferior facet screw

Goel *et al*.[17] also described C2 inferior facet screws in 2017. In terms of the entry point, it was similar to a transfacetal screw, but instead of going transarticular to the C3 facet, it was confined to the inferior facet given the short screw length. The sole advantage it had over a transplacental screw was that it preserved C2-C3 joint mobility.

The technique of C2 inferior facet screw

The entry point of the C2 inferior facet screw is at the dorsal aspect of the lamina at its junction with the pedicle. Directed 20° laterally and 45° caudally [Figure 6]. The polyaxial screw of length 12–14 mm is sufficient.

DISCUSSION

Since Goel and Harms introduced the C1 lateral mass and C2 pedicle screw fixation approach for AAI treatment, several techniques of C2 fixation have evolved as an alternative to primary C2 pedicle fixation or as a salvage method.

Goel *et al*. were the first to develop C2 Pedicle screws in 1994.[13] Harms and Melcher revised it in 2001.[15] Many investigations, including that of Goel and Laheri, and Harms, demonstrated good fusion rates of up to 100% using C2 pedicle screws.[13,18] Pedicle screws provided 0.6° greater mobility than C1-C2 transarticular screws and have some limitations, such as the presence of thin C2 pedicles and a high-riding VA. Theplacement of C2 pedicle screws is not possible in 18% of patients because of the unusual course of the VA or thin C2 pedicles.[19] In these situations, there is a 2%–8% risk of VA injury during the placement of C2 transpedicular screws.[20]

Cacciola concluded that the width of the pedicle limited all pedicle screw trajectories.[21] According to Sairyo *et al*., the minimal pedicle diameter for safe pedicle screw insertion is 3.5 mm.[8] When comparing C2 pedicle screws to transarticular screws, Gunnarsson *et al*.[22] found a decreased rate of VA damage in C2 pedicle screws.

Aside from these drawbacks, C2 pedicle screws provided robust and secure fixation in more than 90% of cases. In terms of lateral bending and axial rotation, Claybrooks

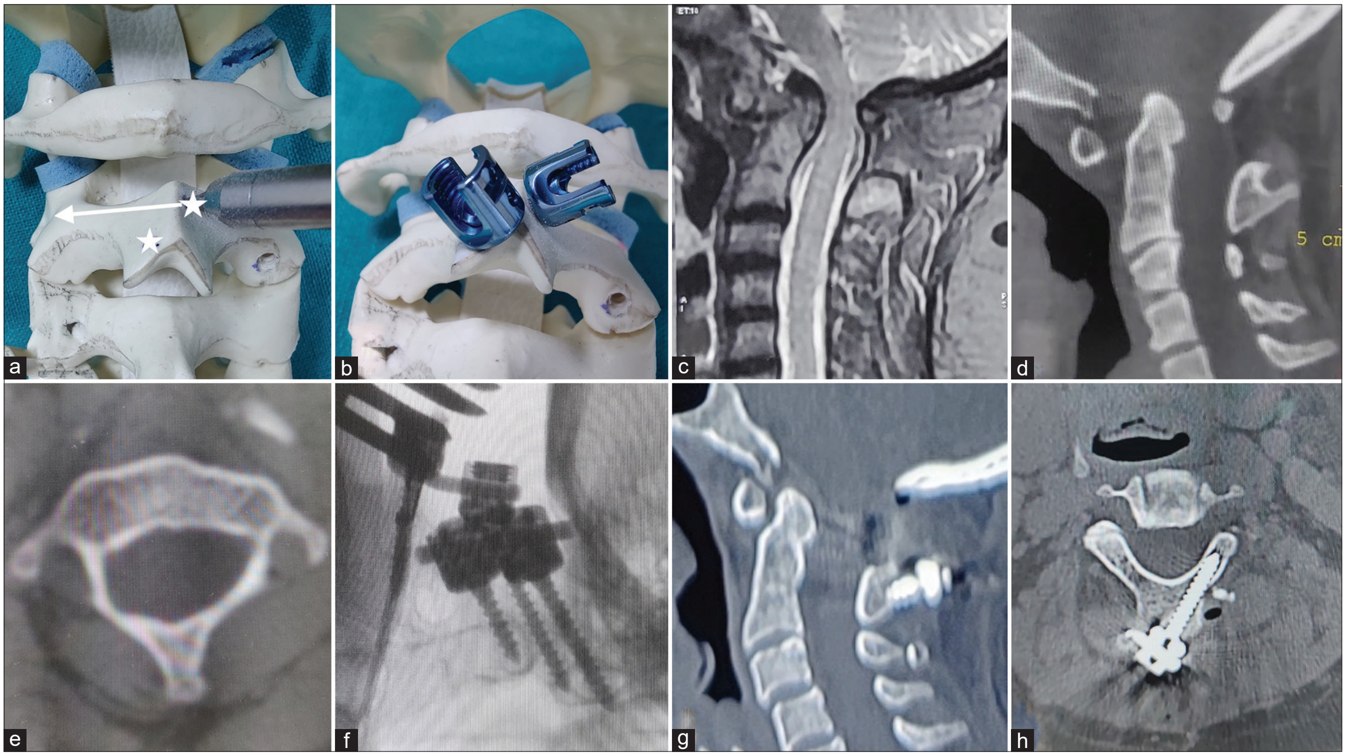

Figure 3: (Translaminar) Wrights[16] technique for C2 (Axis) translaminar screw. (a) Entry point is at the junction of the C2 spinous process and lamina on the right, close to the rostral margin of the C2 lamina denoted by the white star. Similarly, at the junction of the spinous process and lamina of C2 on the left, close to the caudal aspect of the lamina is denoted by another white star. Direction is along the angle of the exposed contralateral C2 laminar surface and Parallel to the rostral margins of the C2 lamina denoted by the white arrow. (b) Placement of bilateral translaminar screws on a saw bone model of the C2 vertebra. (c) T2-weighted MRI craniovertebral junction of a 40-year-old female presenting with neck pain and difficulty in walking showing atlantoaxial instability with basilar invagination and cord compression. (d) Preoperative CT scan of the patient with mid-sagittal cut showing atlantoaxial instability with basilar invagination. (e) Axial CT scan image of C2 vertebra through bilateral pedicle showing thin right pedicle making pedicle screw difficult on this side. (f) Intraoperative C-arm X-ray image showing placement of bilateral C1 lateral mass with right C2 translaminar screw and left C2 pedicle screw. (g) Postoperative CT scan with mid-sagittal cut showing significant reduction of basilar invagination and AAD. (h) Postoperative computer CT scan with axial cut passing through C2 lamina showing right C2 translaminar screw with the rod. MRI - Magnetic resonance imaging; CT - Computer tomography

et al.[23] demonstrated that C2 pedicle screw fixation was more stable than C2 intralaminar screw fixation. It also provides a stronger bone purchase than C2 pars screws.[13,24] Lehman *et al*.[25] discovered that the C2 pedicle had higher pull-out strength and insertional torque than the C2 pars and C2 laminar screws. C2 pedicle screw insertion is simple and can be easily achieved in the majority of patients.[26,27]

The insertion location of the pars screw is inferomedial to that of the pedicle screw. C2 pars screws are also referred to as isthmic screws. In their meta-analysis, Elliot *et al*. discovered a greater incidence of VA damage in C2 pedicle screws than in C2 pars screws.[28] Even though they discovered lower fusion rates (93.5%) in C2 pars screws than in C2 pedicle screws (97.8%), C2 pars screws outperform C2 pedicle and laminar screws in terms of lateral bending stability.[2] They give superior flexion and extension stabilization than previous constructs but provide the least security against axial rotation.[2] In the case of HRVA or VA positioned medially, a C2 pars screw that does not reach the pedicle is a superior alternative.

To counter the difficulties of the C2 pedicle and pars screw in cases of HRVA and thin pedicles, translaminar screws were introduced. Wright first used the C2 translaminar screw in 2004. Because this approach was independent of the (VA) route, it was associated with the least amount of VA harm. However, the height of the spinous process should be adequate to allow both screws. Wang[29] and Goel *et al*.[30] recommended the use of preoperative computed tomography (CT) imaging to delineate the anatomy of the lamina and ensure the viability of a laminar screw. When compared to alternative methods of C2 fixation, this procedure reduces the likelihood of neurovascular damage.

Gorek *et al*.[31] performed a biomechanical examination of the C2 pedicle and C2 laminar screws. He discovered that both offered equivalent immediate stabilization at C2 with comparable reductions in flexion/extension, lateral bending, and axial rotation. Goel *et al*.[30] in their study on 11 cases of congenital craniovertebral anomalies treated with C2 translaminar screws in occipitoaxial stabilization found it to satisfactorily fix the axial end and provided a sturdy and rigid

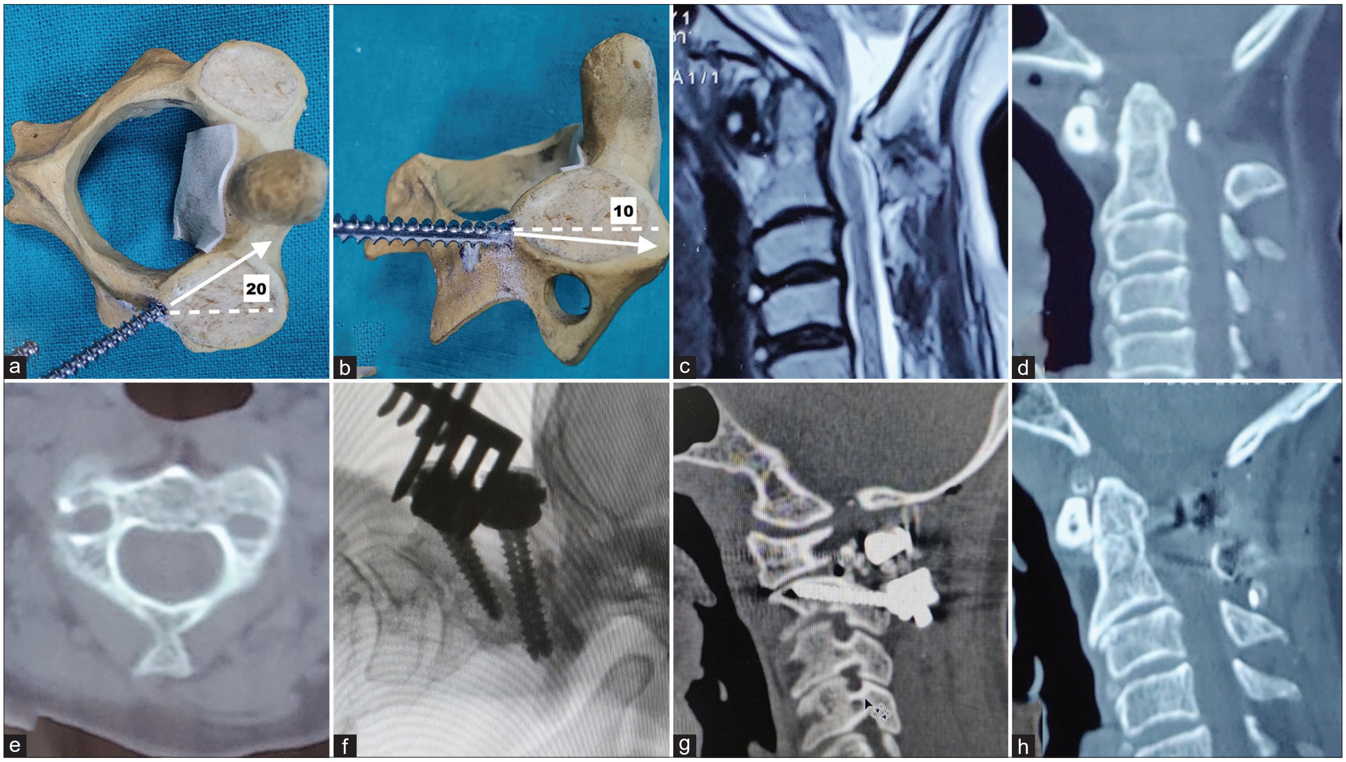

Figure 4: Technique for C2 (Axis) subfacetal screw.[36] (a) Entry point is at 3 mm–4 mm below the mid-point of the upper surface of the C2 superior facet with 20° medial angulation on the axial plane denoted by the white arrow. (b) Cranio-caudal angulation on the sagittal plane is variable usually put 10° caudally denoted by the white arrow. (c) T2-weighted magnetic resonance imaging (MRI) craniovertebral junction of a 67-year-old female presenting with neck pain and difficulty in walking showing atlantoaxial instability with cord com-pression and myelomalacia changes in the cord. (d) Preoperative CT scan of the patient with mid-sagittal cut showing atlantoaxial instability with severe canal compromise. (e) Axial CT scan image of C2 vertebra through bilateral pedicle showing thin left pedicle making pedicle screw difficult on both sides. (f) Intraoperative C-arm X-ray image showing placement of bi-lateral C1 lateral mass with bilateral C2 subfacetal screw. (g) Postoperative CT scan with sag-ittal cut passing through left C1-C2 facet joint showing C1 lateral mass screw and C2 sub-facetal screw with the rod. (h) Postoperative CT scan with mid-sagittal cuts showing reduc-tion of AAI and opening of the canal. CT - Computer tomography; AAI - Atlantoaxial instability

construct. Claybrooks *et al*.[23] discovered that when compared to C2 pedicle screws, C2 laminar screws provide equivalent resistance to flexion/extension and anterior/posterior translation but have inferior stability in lateral bending and axial rotation. Lapsiwala *et al*.[32] discovered similar outcomes when comparing C2 pedicle, transarticular, and sublaminar wiring. When C2 laminar screws were compared to C2 pars screws, Lehman *et al*.[25] discovered that they had much higher pull-out strength.

The fusion rates of C2 laminar screws ranged from 92.9% to 97.6%. In his study of 20 patients in 2005, Wright[16] discovered 100% fusion rates of C2 laminar screw fixation. However, this was linked to three cases of cortical breach. To reduce this issue, Jea *et al*.[33] modified Wright's approach by establishing an escape window on the dorsal aspect of the lamina to ensure bi-cortical screw purchase. According to Chan *et al*.,[34] the C2 laminar screw had a decreased risk of VA damage without the use of CT guidance while attaining comparable fusion rates and biomechanical stability. To handle more mechanical stress, Wang[29] advocated using a bigger C2 laminar screw. Due to the position of the VA and the difficulty of dissecting in the lateral gutter, translaminar C2 screws have been a common alternative.[35] However, the laminar thickness might vary; therefore, such screws may not be applicable in all cases.

Translaminar screws, unlike other C2 screw fixation alternatives such as C1-C2 transarticular screws, C2 pedicle screws, and so on, are less influenced by differences in a patient's anatomy. Several studies found that the biomechanical performance of the C2 translaminar screw was comparable to that of the C2 pedicle screw and C2 pars screw.

Another approach that is safe in cases of HRVA and thin C2 pedicles and is independent of the C2 laminar thickness is subfacetal screw placement. The C2 Subfacetal screw is often referred to as the C2 vertebral screw.[36] The risk of VA injury exists in both C2 pars/pedicle screws and is dependent on the path of the artery and the thickness of the C2 pedicle. Subfacetal screw completely bypasses the pedicle and VA and as a result, the risk of VA harm is averted in the majority of cases. Furthermore, it provides ample bone for rigid fixation,

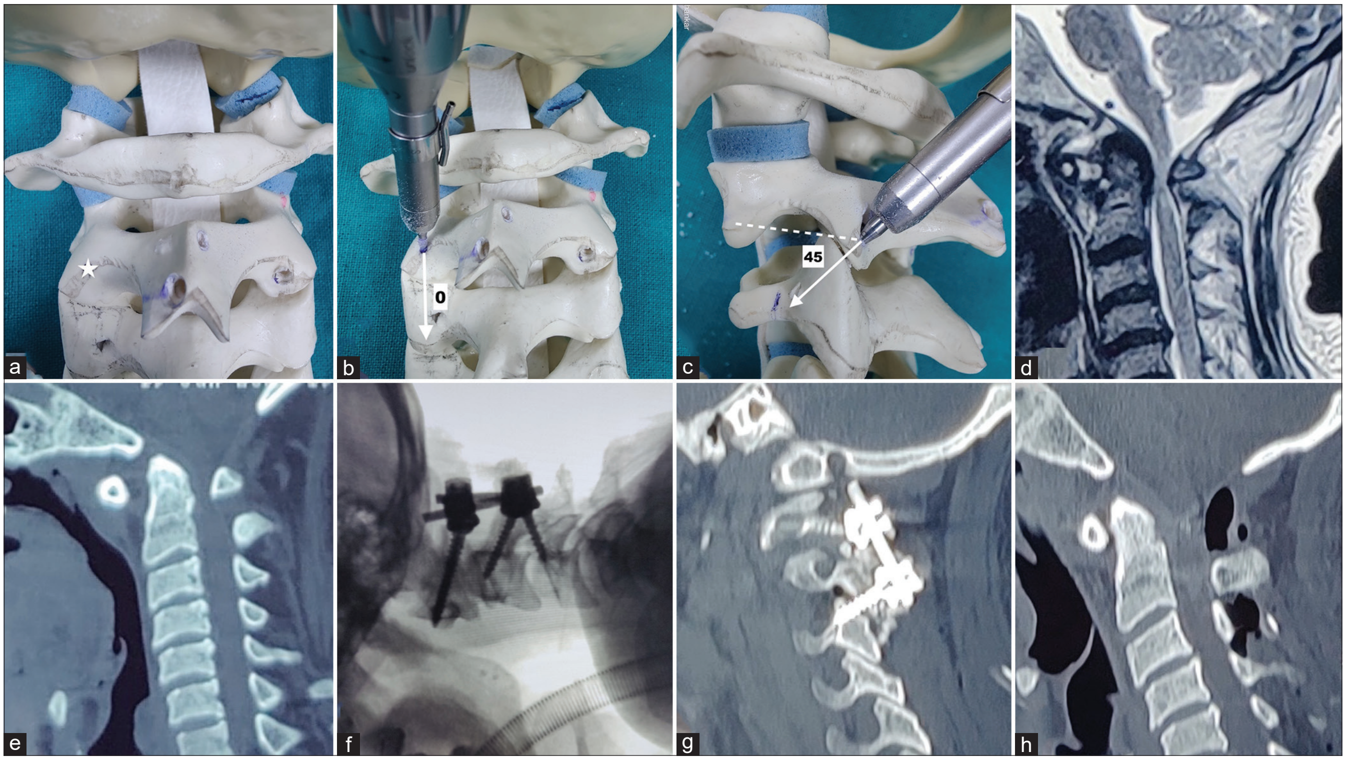

Figure 5: (Transfacet) Goel's[17] technique for C2 (Axis) transfacet screw. (a) Entry point is 5mm above the middle of the C2-C3 facet joint denoted by the white star. (b) 0° medial angulation on axial and coronal planes denoted by the white arrow. (c) Cranio-caudal angulation on the sagittal plane is 45° caudally, perpendicular to the C2-C3 facet joints denoted by the white arrow. (d) T2-weighted MRI craniovertebral junction of a 37-year-old male presenting with neck pain and spastic quadriparesis showing atlantoaxial instability and cord compression with myelomalacia changes in the cord. (e) Preoperative CT scan of the patient with mid-sagittal cut showing AAI with a compromised canal. (f) Intraoperative C-arm X-ray image showing placement of bilateral C1 lateral mass with right C2-C3 transfacet screw and left C2 pedicle screw. (g) Postoperative CT scan with sagittal cut passing through right C1-C2-C3 facet joints showing C1 lateral mass screw and C2-C3 transfacet screw with the rod. A very thin C2 pedicle is also noted. (h) Postoperative CT scan with mid-sagittal cuts showing opened-up canal space after reduction. MRI - Magnetic resonance imaging; CT - Computer tomography

and divergent screws theoretically provide greater pull-out strength than C2 pedicle and pars screws.[37]

In cases where C2 pedicle/pars have failed or laminar screw placement is not possible, inferiorly directed C2-C3 transfacetal or C2 inferior facetal screws can be used as rescue techniques. Goel was the first to introduce C2 Transfacetal screws in 2017.[17] Transfacetal screw placement is a simple procedure that has little risk of VA injury. Furthermore, because it incorporates four cortical surfaces, its biomechanical strength is comparable to or even superior to that of pedicle screws.[38] The sole negative is that it adds another level of fixation; however, the practical impact on ROM is minor.

Horn *et al*. determined that, in the case of osteoporosis, the construct must be extended to C4 to achieve good fusion and stability.[39] Transfacetal screw incorporates a C2/3 facet joint and four cortices and may serve as an ideal C2 fixation construct in these cases.

Goel *et al*.[17] compiled a list of indications for the use of transfacetal and inferior facetal screws. They include high riding VA, VA course posterior to C1-C2 joint, nonexistent or thin C2 pedicle, degenerative disorders affecting C2 pedicle or tuberculosis of C2 vertebra, Hangman's fracture, disruption of C2 pedicle during surgery, and so on. Transfacet screw fixation is technically less challenging and time-consuming, and it produces a stronger construct that may be biomechanically similar to other C2 fixation procedures.

The C2 inferior facet screw[17] takes the advantage of the solid cortical quality of the inferior facet and the absence of a VA. The inferior articular facet of the axis is positioned primarily posterior to the rostral course of the VA. Inserting a screw into the inferior articular facet substance can be a safe and strong choice in circumstances where the pedicle is not accessible due to difficulty in dissection, an atypical VA position, disruption from trauma (Hangman fracture), or direct screw insertion. The approach can be employed as an alternative option or a salvage technique in selected cases where other methods have failed.

It was found that when 3D navigation was used, C2 pars/pedicle screws have proven 100 percent accuracy.[40]

Some research contradicts these findings, claiming that freehand navigation is more accurate than CT-based navigation.[41] Azimi *et al*.[42] discovered that the accuracy rate of C2 pars/pedicle screw placement for the freehand group was comparable to that of the navigation group. Furthermore, these techniques might increase the operative time and overall cost of surgery.

Table 1 summarizes all the C2 screw placement techniques with their advantages and disadvantages.

CONCLUSION

AAI surgery is difficult due to the cervicomedullary junction's proximity and variations in the VA course and surrounding

Table 1: Detailed comparison of the C2 (axis) screw fixation techniques in atlantoaxial instability

Technique	Entry point	Medio-lateral angulation	Cranio-caudal angulation	Screw lengths	Disadvantages	Advantages
C2 Pedicle[13,15] [Figure 1]	Cranial and medial quadrant of the C2 isthmus surface along the superior border of C2 lamina	20°-30° medially parallel to super-medial surface of C2 pedicle	20°-30° cranially	Variable, 18-22 mm	9% of the cases are unsuitable due to aberrant vertebral artery courses or narrow C2 pedicles 2%-8% risk of vertebral artery injury Width of the pedicle is a limiting factor. Minimum 3.5 mm width is safe	Good fusion rates of up to 100 percent Provided robust and secure fixation Higher pull-out strength and insertional torque Simple and easy to perform by the majority
C2 pars (Isthmic screws) [Figure 2]	2-3 mm superior and lateral to the medial aspect of the C2-C3 facet joint	10° medially	45° cranially towards the anterior tubercle of C1	14-18	Lower fusion rates than pedicle screw Least amount of rotatory stability	Preferred in cases of HRVA or medially positioned VA Less incidence of VA damage than pedicle/pars screws Better lateral bending stability than pedicle and laminar
C2 Translaminar[16] [Figure 3]	For left C2 laminar screw the entry point is at the junction of the C2 spinous process and lamina on the right, close to the rostral margin of the C2 lamina. Similarly for the right C2 laminar screw the entry point is at the junction of the spinous process and lamina of C2 on the left, close to the caudal aspect of the lamina	Along and parallel to exposed contralateral C2 laminar surface	Parallel to the rostral and caudal margins of the C2 lamina	26-30	Height of the spinous process is a limiting factor Not an in-line fixation Rods bending needed to fix Least amount of reduction potential	Independent of the vertebral artery route, hence least injury Equivalent biomechanical stability as pedicle/pars screws Can be used as a rescue technique in case of failure of primary fixation
C2 Subfacetal[36] (Vertebral screw) [Figure 4]	3-4 mm below the mid-point of the upper surface of the C2 superior facet	20° medially	Directly into the vertebrae. Cranio-caudal projection is variable	18-24	Difficult to place screws in a high degree of AAD as screw heads collide in narrow corridor	No VA injury as the screw completely bypasses the pedicle and vertebral artery Divergent screws can be put, hence theoretically provide greater pull-out strength than C2 pedicle/pars
C2 Transfacetal[17] [Figure 5]	5mm above the middle of the C2-C3 facet joint	0°, straight	45° caudally, perpendicular to the C2-C3 facet joints	Variable, 14-16	Adds another level of fixation which theoretically impacts the range of motion in the subaxial spine	Simple technique No risk to the vertebral artery Useful in osteoporosis and spondylosis Four cortices purchase provides higher pullout strength than pars or laminar screws
C2 Inferior facet[17] [Figure 6]	Medial aspect of the lamina at its junction with the pedicle	20° laterally	45° caudally	12-14	Inferior stability than pedicle/pars construct Used as a rescue technique only	Simple technique No risk to the vertebral artery

HRVA - High riding vertebral artery; VA - Vertebral artery; AAD - Atlanto-axial dislocation

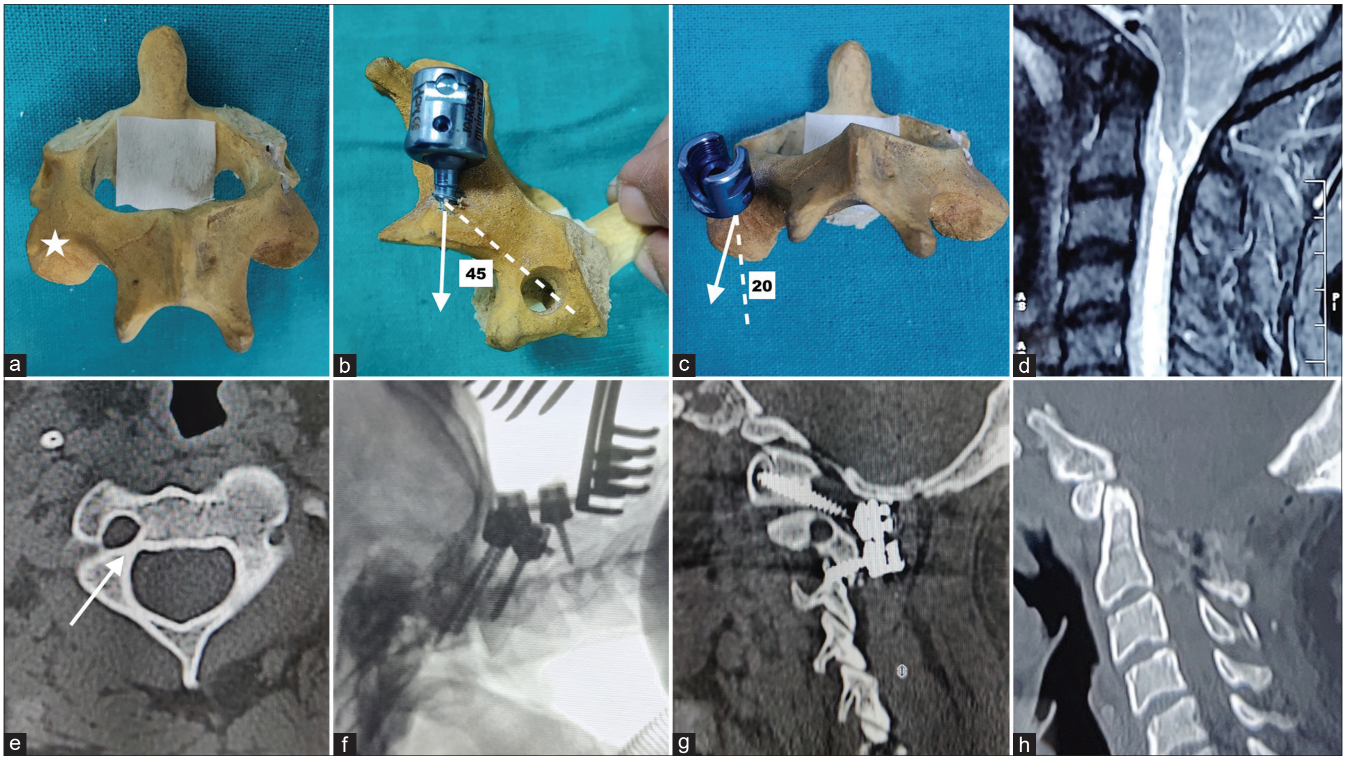

Figure 6: (inferior facet) Goel's[17] technique for C2 (Axis) inferior facet screw. (a) Entry point is at the medial aspect of the lamina at its junction with the pedicle denoted by the white star. (b) Cranio-caudal angulation on the sagittal plane is 45° caudally denoted by the white arrow. (c) 20° lateral angulation on the coronal plane denoted by the white arrow. (d) T2-weighted MRI craniovertebral junction of a 33-year-old male presenting with spastic quadriparesis showing atlantoaxial instability, Chiari malfor-mation, and syringomyelia. (e) Axial CT image of C2 vertebra through bilateral pedicle show-ing thin right pedicle (white arrow) making pedicle screw insertion difficult on this side. (f) Intraoperative C-arm X-ray image showing placement of bilateral C1 lateral mass with right C2 inferior facet screw and left C2 pedicle screw. (g) Postoperative CT scan with sagittal cut passing through right C1-C2 facet joints showing C1 lateral mass screw and C2 inferior facet screw with the rod. (h) Postoperative CT scan with mid-sagittal cut showing opened-up canal space after reduction and posterior fossa decompression. MRI - Magnetic resonance imaging; CT - Computer tomography

bony anatomy. In this section, we outlined numerous strategies for C2 screw fixation in AAI and explored the intricacies of each technique in detail. This will assist the surgeon in selecting the best solution for their patients in complex AAI cases.

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Conflicts of interest

There are no conflicts of interest

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