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Anatomical, biomechanical, and practical considerations in posterior occipitocervical instrumentation

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Abstract

BACKGROUND CONTEXT: Patients with cervical myelopathy secondary to craniocervical instability commonly present with spinal cord compression secondary to a combination of static forces and gross instability. Craniocervical arthrodesis is therefore indicated in the treatment of the majority of these conditions. In order to facilitate arthrodesis, techniques for occipitocervical instrumentation have been developed.

PURPOSE: To systematically review the anatomy, biomechanics, and practical considerations involved in posterior occipitocervical instrumentation.

STUDY DESIGN: Retrospective literature review.

PATIENT SAMPLE: Not applicable.

OUTCOME MEASURES: Not applicable.

METHODS: Retrospective literature review.

RESULTS: The anatomic elements of the craniocervical junction include the occipital bone, occipital condyles, atlas (C1), and axis (C2). The occiput–C1 and C1–C2 motion segments possess unique mechanical properties. Occipitocervical instrumentation constructs are comprised of points of fixation and longitudinal elements, each with characteristic strengths and weaknesses.

CONCLUSIONS: Analysis of the anatomy, available points of fixation, and the movements to be controlled leads to the choice of a longitudinal element which can control movement by incorporating the strongest points of fixation. By going through this process for each patient, an informed decision may be made regarding the optimal occipitocervical instrumentation construct.

Keywords: Posterior; Occipitocervical; Instability; Instrumentation; Anatomy; Biomechanics; Techniques

Introduction

Patients with cervical myelopathy secondary to craniocervical instability present some of the most challenging problems seen by spinal surgeons. Nevertheless, this is a group of patients that require surgical rather than ''conservative'' treatment. The 7-year survival rate of patients with rheumatoid arthritis and myelopathy has been reported to be zero without surgical intervention [1]. Spinal cord compression is usually secondary to a combination of static forces and gross instability. Decompression is frequently required to address the static forces, exacerbating the instability. Craniocervical arthrodesis is therefore indicated in the treatment of the majority of these conditions.

In order to facilitate arthrodesis, techniques for occipitocervical instrumentation have been developed. This technology has evolved rapidly over the last several decades, resulting in a myriad of techniques and devices. It should be noted that many of these devices are not approved by the U.S. Food and Drug Administration for this indication, and some are not even commercially available in the United States. The following, though, is an attempt to systematically review the anatomy, biomechanics, and practical considerations involved in posterior occipitocervical instrumentation.

Anatomical considerations

The relevant anatomical components of the craniocervical junction, with regard to the placement of instrumentation, include the suboccipital region of the skull, occipital

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condyles (C0), the atlas (C1) and axis (C2), as well as their associated ligaments.

Suboccipital region

The suboccipital region comprises the posterior inferior portion of the occipital bone. It is bounded superiorly by the superior nuchal line, inferiorly by the foramen magnum, and laterally by the temporal bones. Externally, one can visualize the external occipital protuberance (inion) superiorly in the midline, with the midline crest extending inferiorly. Internally, the superior nuchal line corresponds to the transverse sulci, containing the transverse sinuses. Though there is significant variability, the transverse sinus averages 0.9 mm above and 2.2 mm above the superior nuchal line on the left and on the right, respectively [2]. The location of the external occipital protuberance corresponds well to the location of the confluence of sinuses (torcula), as does the location of the external occipital crest to the internal occipital crest.

The thickness of the bone in the suboccipital region varies a great deal depending on location. In the midline, the internal occipital crest contributes to a mean thickness of 8.3 mm at the level of the inferior nuchal line, increasing to a mean of 13.8 mm at the external occipital protuberance. Lateral bone is thinner, ranging from a mean of 3.7 mm at the level of the inferior nuchal line and increasing to a mean of 8.3 mm at the level of the superior nuchal line [2].

Occipital condyles

The paired occipital condyles are the biconvex cranial structures which articulate with the superior surface of the atlas. As such, they support the nearly 10-lb weight of the head at rest. They are proportionally large structures, with a mean length, width, and height of 23.4 mm, 10.6 mm, and 9.2 mm respectively. The distance between the condyles tapers from back to front, with mean intracondylar distances of 41.6 mm and 21.0 mm, respectively [3]. The hypoglossal nerves traverse the occipital condyles anterior laterally through the hypoglossal foramen. The nerve enters the foramen a mean of 12.2 mm from the posterior margin of the condyle [4].

Atlas (C1)

The atlas is a roughly ring-shaped vertebra with large paired lateral masses. It is unique among cervical vertebrae in that it is not associated with an intervertebral disc. The posterior portion of the anterior arch incorporates an articular surface which contacts the anterior surface of the dens. The posterior arch incorporates an abbreviated spinous process. The atlas is the widest of the cervical vertebrae, with mean external width, height, and anterior posterior dimensions of 78.6 mm, 15.4 mm, and 45.8 mm, respectively. The generous mean inside dimensions of 31.7 mm (anteroposterior) and 32.2 mm (width) accommodate the spinal cord, dens, and an approximately equivalent amount of extra space. The thickness of the anterior and posterior cortices average 6.4 mm and 8.0 mm, respectively [5].

The lateral masses articulate with the occipital condyles superiorly and the axis inferiorly. These structures have mean width, height, and anterior posterior dimensions of 15.47 mm, 14.09 mm, and 17.21 mm, respectively [6].

Axis (C2)

The upper portion of the axis incorporates broad articular surfaces for interaction with the inferior surface of C1, as well as the dominant feature of the axis, the superiorly projecting odontoid process. The lower portion of the axis, which articulates with C3, is associated with an intervertebral disc and paired facets, similar to the subaxial vertebrae.

The mean surface area of the superior facet is 211.3 mm^2 (right) [7]. The mean body height, not including the odontoid, is 23.3 mm. Including the odontoid, it is 39.9 mm in height. The mean anterior posterior diameter of the C2 body is 16.2 mm, while that of the odontoid is 11.2 mm at the widest part, the tip. The odontoid is angled posteriorly a mean of 13 degrees [8].

The inferior end plate of C2 slopes upward in the sagittal plane a mean of 4.2 degrees [9], and has a mean surface area of 194.4 mm^2. The left C2 pedicle, which tends to be slightly larger than that of the right, has a mean width of 8.3 mm and a mean height of 11.1 mm [9].

Articulations and normal movements

The craniocervical junction is comprised of two motion segments with very different mechanical properties. The mechanical properties of the occiput–C1 segment are determined largely by bony elements, whereas those of C1–C2 are determined largely by ligamentous elements. For the purposes of this discussion, the Cartesian coordinate system will be used to describe movement at these segments. Table 1 lists terms and equivalents.

Occiput–C1

The primary movement of the occiput–C1 segment is X-plane rotation. Mean rotational movement is 23–24.5 degrees, limited by impingement of tip of dens on foramen magnum in flexion and the tectorial membrane in extension. Z-plane rotation averages 3.4–5.5 degrees per side and is resisted by anatomy of the occipital–C1 articulation as well as by the alar ligaments [10,11]. Y-plane rotation is 2.4–7.2 degrees per side [10,11] and is likewise restricted by anatomy of the occipital–C1 articulation as well as by the alar ligaments. The instantaneous axis of Y-plane rotation has been observed to be anterior to the foramen magnum [12].

Table 1
Terms and equivalents

Cartesian coordinate system	Alternate nomenclature
X-plane rotation	Flexion Extension
Y-plane rotation	Axial rotation
Z-plane rotation	Lateral bending
X-plane translation	Lateral translation
Y-plane translation	Stretch/Compression/Settling
Z-plane translation	Sagittal plane translation

X, Y, and Z plane translation under normal circumstances is minimal [13], and is constrained by the bony anatomy of the occipital–C1 articulation (Z,–Y), tectorial membrane (Z, +Y), alar (Z, X,+Y), and (minimally) apical ligaments (+Y) [14].

C1–C2

The primary movement of the C1–C2 segment is Y-plane rotation. Mean rotational movement is 23.3–38.9 degrees per side [10,11]. This movement is constrained by the atlantoaxial joints, transverse ligament (ipsilateral), alar ligaments (contralateral) [15], and capsular ligaments [12]. Y-plane rotation at C1–C2 is negatively coupled to Y-plane rotation at occiput–C1, in that increases in Y-plane rotation at C1–C2 induce Y-plane rotation in the opposite direction (of a lesser magnitude) at occiput–C1. The instantaneous axis of Y-plane rotation at C1–C2 has been observed to be in the central portion of the dens [12]. X-plane rotation is 10.1–22.4 degrees total [10,11] and is resisted by the transverse ligament (flexion) [16], tectorial membrane, and joint anatomy [14]. The instantaneous axis of X-plane rotation at C1–C2 has been observed to lie near the posterior cortex of the odontoid, mid way between the base and tip [17]. Z-plane rotation is limited to 6.7 degrees [11], primarily by the alar ligament [15].

Z plane translation as defined by the atlantodental interval is normally held to less than or equal to 3 mm in the presence of an intact transverse ligament [18,19]. Anterior translation is resisted by the transverse ligament [19] > alar ligaments [15] >accessory atlantoaxial ligaments and capsular ligaments [14]. Posterior translation is resisted by abutment of dens on arch of C1. X-plane and Y-plane translation is minimal under normal circumstances.

Craniocervical junction instrumentation

Because of the complexity of the craniocervical junction, the diversity of craniocervical junction pathology, and the lack of a technique which can be universally applied to fulfill all of the requirements of occipitocervical instrumentation, numerous techniques for immobilizing the occipital–C1-C2 region have been developed. In order to systematize discussion, the topic of *instrumentation* is divided into two subtopics: *points of fixation* and *constructs*.

Points of fixation

Points of fixation include those areas used to connect spinal instrumentation to the occiput, atlas, or axis. In order to systematize the discussion, the topic of *points of fixation* has been divided into two subtopics: *elemental* and *motion segment*. *Elemental* points of fixation include those points that involve fixation to only one element of the craniocervical junction, the occiput, C1, or C2. Stabilization is achieved by connecting elemental points of fixation together with a rod, plate, or other longitudinal element. *Motion segment* points of fixation include those points that involve fixation to two or more elements of the craniocervical junction. Some stabilization is achieved between the elements fixated, though in most cases options exist to connect motion segment points of fixation to other elemental points of fixation. An overview can be found in Table 2.

Elemental points of fixation

Occiput. Current methods of fixation to the occiput all include some type of purchase in the bone of the suboccipital region. As has been discussed previously, this bone varies greatly in its thickness dependent on location and individual patient anatomy. In the clinically relevant areas, between the superior and inferior nuchal line, bone thickness increases from lateral to medial and from inferior to superior. In general, strength of fixation is positively correlated to bone thickness, indicating that, whenever possible, fixation should be carried out nearer to the superior nuchal line and the midline [2,20,21].

Options for fixation to the suboccipital bone include wires (cables), unicortical and bicortical screws, and ‘‘inside outside’’ screws. The latter involves ‘‘a flat-headed screw or stud placed through a burr hole in the calvaria with the flat head of the screw in the epidural space and the threads facing outwards’’ [22,23]. Direct biomechanical comparison of wires, unicortical screws, and bicortical screws has been performed in human cadavers yielding

Table 2
Points of fixation

Type*	Level(s)	Fixation point
Elemental	Occiput	Biocortical wire
		Unicortical screw
		Biocortical screw
		‘‘Inside-outside screw’’
	C1	Sublaminar wire
		Lateral mass screw
		‘‘Pedicle’’ screw
	C2	Sublaminar wire
		Lateral mass screw
		Pedicle screw
		Intralaminar screw
Motion segment	Occiput–C1	Bone and wire (Cable)
		Oc–C1 Transarticular screw
	C1–C2	C1–C2 Transarticular screw

* See text.

a pullout strength for bicortical screws 50% higher than either wires or unicortical screws [21]. However, with screw insertion depth of >7 mm, using a 3.5-mm screw, screw fracture and pullout occur with equal frequency, suggesting that an increase in screw diameter may be beneficial with >7 mm insertion depth [2]. ‘‘Inside-outside’’ screws have been compared with cables and bone screws in a synthetic bone model, yielding favorable load to failure results [24].

Potential concerns, aside from pullout strength, regarding each of these techniques have been raised. Both wires and ‘‘inside-outside’’ screws require making burr holes for placement, raising concerns of cerebrospinal fluid leakage if the dura is inadvertently violated. All techniques, with the exception of unicortical screws, carry a potential for intracranial hemorrhage or injury. Unicortical screws may be impossible to place in the more inferior and lateral suboccipital regions, secondary to insufficient bone thickness.

C1. Options for fixation to C1 include sublaminar wiring techniques as well as newer screw-based techniques. The broad and robust lamina of C1 allows the placement of one or more sublaminar wires or cables with relative simplicity. The primary drawback of sublaminar wires at C1 is the frequency with which the lamina is congenitally absent, fractured, or surgically removed at the time of operation in individuals undergoing occipitocervical fusion. For this reason, recent efforts have led to alternative screw-based techniques which allow rigid fixation to C1.

C1 screws may be placed directly into the lateral mass, with an entry point above the C2 nerve root, at the junction of the C1 posterior arch and the midpoint of the posterior inferior part of the C1 lateral mass [25]. Partially threaded screws are placed with a medial angulation of 9.8–21.6 degrees and a superior angulation of 17.8–28.8 degrees, depending on patient anatomy. Using this technique, a screw thread length of 19.1–25.9 mm can be accommodated within the lateral mass [26]. The unthreaded portion of screw incorporates a smooth section which abuts the C2 nerve root and elevates a connector above the C1–C2 foramen.

C1 ‘‘pedicle’’ screws are placed using a variant technique though the lateral laminar arch of the atlas into the lateral mass. The more superior screw entry point used in this technique allows for a longer interface between the bone and the screw, with less dissection of the venous structures in the C1–C2 foramen [27]. A potential drawback to this technique is the difficulty of identifying an appropriate screw entry point without the use of intraoperative navigation techniques, though use of the lateral mass of C2 as a landmark appears to hold promise in this regard [28].

C2. As with C1, sublaminar wiring techniques may be employed as a point of fixation to C2. Although the lamina of C2 is perhaps less frequently deficient, it is also larger in a rostral-caudal direction, making placement of sublaminar wires more challenging. A complication rate of up to 7% has been reported for sublaminar wiring of cervical vertebrae [29].

A variety of screw-based techniques have been developed which draw upon established techniques in the subaxial cervical spine and lumbar spine. As will be discussed later, screw-based techniques have as a distinct advantage the ability to rigidly couple with the axis as well as with modern systems for posterior segmental instrumentation.

Lateral mass screws may be placed at C2 using a modification of the technique used for the subaxial cervical spine. Using an entry point at the junction of the inferior border of the lamina and the midpoint of the inferior facet process of C2, a screw may be placed using a 35-degree superior and 15-degree medial trajectory into the usually generous lateral mass of C2 [30]. Bicortical screw purchase is not used in the lateral mass of C2. Screw length may be tailored to avoid even the most aberrant vertebral artery.

Pedicle screws may be placed at C2 using a modification of the technique used in the lumbar spine. With the assistance of intraoperative navigation techniques, the pedicle of C2 may be cannulated using a medial trajectory (mean 39 degrees) which is parallel to the inferior end plate [31]. Using this technique, approximately 91% of C2 pedicles can be safely cannulated with a 4-mm screw to a mean maximum length of 24.2 mm [27]. A potential reward for the increased complexity of placing pedicle screws at C2 rather than lateral mass screws is a significant increase in the mean pure pullout strength (650 Newtons vs. 371 Newtons) which is not correlated with bone density [31].

A more recently described technique is that of the intralaminar C2 screw. This technique may be conceptualized as a variation of the lumbar translaminar facet screw, though the tip of the screw, in this instance, does not cross a joint. Using a starting point at the base of the C2 spinous process, a pilot hole is drilled anterior laterally into the contralateral lamina, through which a bone screw is introduced. Initial biomechanical data comparing C1–C2 constructs using intralaminar C2 screw to constructs using C2 pedicle screws yielded no significant differences [32].

Motion segment points of fixation

Occiput–C1. Bone and wire techniques have been developed to immobilize and simultaneously bone graft the occiput–C1 segment [33]. These elegant techniques may be used when instability is isolated to this segment. Although these techniques have the relative advantage of simplicity, they are not well suited to incorporation into a multisegment construct. However, in certain situations, they may be useful adjuncts to other instrumentation techniques, particularly the occiput–C1 transarticular screw technique described below.

More recently, a technique for craniovertebral junction fixation with transarticular screws has been described [34,35]. As above, this technique is best utilized when instability is isolated to the occiput–C1 segment, as it is difficult to incorporate into a multisegment construct. A screw entry point is designed above the C2 nerve root, at the junction of the C1 posterior arch and the midpoint of the posterior inferior part of the C1 lateral mass (similar to that used in placement of C1 lateral mass screws). Using intraoperative navigation, a pilot hole is made using the middle aspect of the occipital condyle as a target, with a 10-degree to 20-degree medial angulation, until the drill point is 1 cm rostral to the tip of the odontoid. A self-tapping lag screw with a length of 28–32 mm is placed. Biomechanical testing of this fixation technique in destabilized human cadaveric specimens revealed reduction in X-, Y-, and Z-plane rotation to below that of intact specimens. Performance was poorest in X-plane rotation, suggesting that a supplemental bone and wire fixation technique (above) may be of utility in this situation [35].

C1–C2. While numerous bone and wire techniques have been developed as motion segment points of fixation for C1–C2, their primary utility remains the treatment of instability isolated to this segment. As with bone and wire techniques at occiput–C1, none are well suited to incorporation into a multisegment construct. The interested reader is referred to the excellent review of this topic by McDonnell and Harrison [36].

In contrast, the development of the C1–C2 transarticular screw technique has done much to enhance the surgeon's ability to perform rigid occipitocervical instrumentation. Not only does this technique provide rigid fixation to both C1 and C2 while adding substantial stability to the segment, it is relatively easily incorporated into a multisegment construct (Fig. 1). A screw entry point is designed at the level of the inferior border of the C2 lamina and the midpoint of the ipsilateral pars interarticularis of C2. Using intraoperative navigation, a pilot hole is drilled with a slightly medial trajectory through the lateral mass of C2, across the C1–C2 articulation, and into the lateral mass of C1. The anterior arch of C1 is used as a target [37]. Two fully threaded screws are placed or, alternatively, one lag screw followed by a fully threaded screw on the contralateral side.

A number of authors have called attention to the fact that not all patients are suitable candidates for bilateral or even unilateral C1–C2 transarticular screws [38,39]. An anomalous (high-riding) position of the vertebral artery in these patients places the artery at risk. Based on analysis of patient radiographic data, 18–23% of patients may be unsuitable for C1–C2 transarticular screw placement on at least one side, of which 3% may be unsuitable for screw placement on either side [38]. Fortunately, excellent clinical results have been achieved with C1–C2 fixation using a single screw [40].

Most investigations of the biomechanical properties of C1–C2 transarticular screws have been done in the context of their use as internal fixators to treat instability isolated to this segment, rather than as points of fixation for a larger construct [41]. However, the finite analysis investigation of Puttlitz et al. suggests that, when used in an occiput–C1–C2 construct, C1–C2 transarticular screws confer occiput–C1 stability which is equivalent to C2 pedicle screw when used bilaterally. When either is used unilaterally, C1–C2 transarticular screws confer occiput–C1 stability which is superior to C2 pedicle screws [42].

Fig. 1. Lateral radiograph. Posterior occipitocervical fusion and instrumentation in a patient with rheumatoid craniocervical instability, 23 months postoperatively. This construct incorporates suboccipital screws, C1 sublaminar wires (cables), and C1–C2 transarticular screws.

Constructs

The occipital–C1–C2 region remains difficult to immobilize secondary to a number of interrelated factors. The two segments are highly mobile, particularly in X-plane rotation at occiput–C1 and Y-plane rotation at C1–C2. Pathologic states add additional movements, particularly Z-plane translation at C1–C2. Y-plane translation across the two segments (cranial settling) is particularly difficult to control. Operations that involve decompression may introduce additional instability [43] or remove options for fixation points (ie, transoral odontoidectomy or C1 laminectomy).

Occipitocervical instrumentation constructs consist of, at a minimum, points of fixation and some type of longitudinal element. The interface between the two cannot be overlooked. Constructs incorporating wiring techniques coupled to rods are particularly susceptible to loosening with cyclic loading. As this occurs, the wires slide on the rods, resulting in loss of immobilization and reduction,

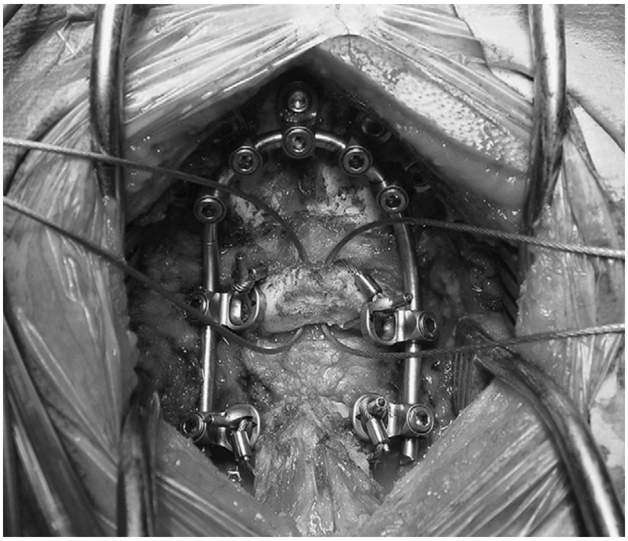

Fig. 2. Intraoperative photograph. Posterior occipitocervical instrumentation construct, in a patient with traumatic craniocervical instability, who was not a candidate for placement of C2 pedicle screws or C1–C2 transarticular screws. The use of wire (cable) to rod connectors is illustrated.

particularly in Y-plane translation (settling) [44]. While this may be ameliorated somewhat by the use of dedicated wire to rod couplers (unpublished observation) (Fig. 2), screw-based points of fixation are more resistant to this phenomenon [44]. Screws with constrained heads, generally interfacing with a rod, spread loads more evenly among points of fixation. Screws with nonconstrained heads, generally interfacing with plates, are subject to screw backout and uneven loading of fixation points.

There currently exist many choices for longitudinal elements in occipitocervical instrumentation constructs. From the perspective of building an effective construct, an ideal longitudinal element would have the following characteristics:

- Able to interface with all types of fixation points;
- Multiple locations for interfacing with points of fixation craniocaudally;
- Provision for interfacing with points of fixation in the thickest regions of bone in the suboccipital region;
- Ability to be crosslinked (or internally crosslinked, as with loops).

Current types of longitudinal elements include structural bone graft, stainless steel rectangles, reconstruction plates, rods with specialized connectors, and hybrid devices which combine plates and rods in preformed shapes. All have advantages and disadvantages, summarized in Table 3. It is important to tailor the type of longitudinal element to the individual needs of a given patient.

Having discussed the elements that make up an occipitocervical instrumentation construct, it is useful to consider how they may be assembled to make an effective internal fixator. It would seem intuitive that a construct including the most robust points of fixation, including screws with constrained heads, and rod-based or hybrid longitudinal elements would produce the strongest construct.

The primary movement at occiput–C1 is X-plane rotation (flexion/extension). In order to best control this movement, a construct incorporating screw-based points of fixation at the occiput and C2 is necessary. In the study of Hurlbert et al., only constructs with these characteristics exhibited greater stiffness in X-plane rotation than uninjured segments [42].

The primary movement at C1–C2 is Y-plane rotation (axial rotation). In order to best control this movement, an occipitocervical instrumentation construct, incorporation of C2 pedicle screws or C1–C2 transarticular screws is necessary [45].

A common failure mode of occipitocervical instrumentation constructs is failure of C2 fixation in flexion [46,47]. Therefore, because a C1 lateral mass screw coupled to a C2 pedicle screw may offer greater stability in X-plane rotation than a C1–C2 transarticular screw [48], there may be an advantage to the former. Biomechanical testing of a construct incorporating suboccipital screws, C1 lateral mass screws, and C2 pedicle screws, however, revealed similar reduction in motion when compared with a construct incorporating suboccipital screws and C1–C2 transarticular screws [49]. It is theoretically possible to incorporate a C1–C2 transarticular screw and a C1 lateral mass screw into the same construct (Fig. 3). This has not been investigated biomechanically.

Table 3
Longitudinal elements

	Structural bone graft	Stainless steel rectangle	Reconstruction plate	Rods with specialized connectors	Hybrid plate/Rods
Types of fixation points	Wire	Wire	Wire/Non constrained screws	All*	All*
Multiple locations for fixation points?	Yes	Yes	No	Yes	Yes*
Interfaces with midline suboccipital bone?	Yes	Yes	No	Yes*	Yes*
Crosslink	Not applicable	Internal	No	Yes*	Internal*

* Some but not all systems.

Fig. 3. Anatomical model, photograph. A proposed posterior occipitocervical instrumentation construct incorporating suboccipital screws, C1 lateral mass screws, and C1–C2 transarticular screws.

Two other points bear emphasis with regard to occipitocervical instrumentation constructs. The first, and most obvious, is that all of the constructs described above, with the exception of those using structural bone as a longitudinal element, require supplemental bone grafting. Achieving a solid arthrodesis is essential to the long-term success of the procedure. The second is that the occipitoaxial angle after instrumentation must be maintained in the neutral or positive range. An excessively negative (chin-down) angle appears to predispose the patient to the premature development of subaxial subluxation [50].

Conclusion

Construction of the optimal posterior occipitocervical instrumentation construct for a given patient is dependent on a number of factors, including the individual patient's anatomy before and after decompression. A thorough study of the anatomy determines what options are available for points of fixation. Analysis of the anatomy, available points of fixation, and the movements to be controlled leads to the choice of a longitudinal element which can control movement by incorporating the strongest points of fixation. By going through this process for each patient, an informed decision may be made regarding the optimal occipitocervical instrumentation construct.

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