Atlantoaxial fixation using C1 posterior arch screws: feasibility study, morphometric data, and biomechanical analysis

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OBJECTIVE C1–2 is a highly mobile complex that presents unique surgical challenges to achieving biomechanical rigidity and fusion. Posterior wiring methods have been largely replaced with segmental constructs using the C1 lateral mass, C1 pedicle, C2 pars, and C2 pedicle. Modifications to reduce surgical morbidity led to the development of C2 laminar screws. The C1 posterior arch has been utilized mostly as a salvage technique, but recent data indicate that this method provides significant rigidity in flexion-extension and axial rotation. The authors performed biomechanical testing of a C1 posterior arch screw (PAS)/C2 pars screw construct, collected morphometric data from a population of 150 CT scans, and performed a feasibility study of a freehand C1 PAS technique in 45 cadaveric specimens.

METHODS Cervical spine CT scans from 150 patients were analyzed to determine the average C1 posterior tubercle thickness and size of C1 posterior arches. Eight cadavers were used to compare biomechanical stability of intact specimens, C1 lateral mass/C2 pars screw, and C1 PAS/C2 pars screw constructs. Paired comparisons were made using repeated-measures ANOVA and Holm-Sidak tests. Forty-five cadaveric specimens were used to demonstrate the feasibility and safety of the C1 PAS freehand technique.

RESULTS Morphometric data showed the average craniocaudal thickness of the C1 posterior tubercle was 12.3 ± 1.94 mm. Eight percent (12/150) of cases showed thin posterior tubercles or midline defects. Average posterior arch thickness was 6.1 ± 1.1 mm and right and left average posterior arch length was $28.7 \text{ mm} \pm 2.53 \text{ mm}$ and $28.9 \pm 2.29 \text{ mm}$, respectively. Biomechanical testing demonstrated C1 lateral mass/C2 pars and C1 PAS/C2 pars constructs significantly reduced motion in flexion-extension and axial rotation compared with intact specimens ($p < 0.05$). The C1 lateral mass/C2 pars screw construct provided significant rigidity in lateral bending ($p < 0.05$). There was no statistically significant difference between the two constructs in flexion-extension, lateral bending, or axial rotation. Of the C1 posterior arches, 91.3% were successfully cannulated using a freehand technique with a low incidence of cortical breach (4.4%).

CONCLUSIONS This biomechanical analysis indicates equivalent stability of the C1 PAS/C2 pars screw construct compared with a traditional C1 lateral mass/C2 pars screw construct. Both provide significant rigidity in flexion-extension and axial rotation. Feasibility testing in 45 cadaveric specimens indicates a high degree of accuracy with low incidence of cortical breach. These findings are supported by a separate radiographic morphometric analysis.

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KEYWORDS C1 screw; atlantoaxial fixation; atlantoaxial instability; C1 posterior arch screw; C1–2 instrumentation; biomechanical analysis; cervical

ATLANTOAXIAL fixation presents a unique challenge due to the inherent mobility of the C1–2 joint, horizontal articular surfaces, and the complex and often variable vascular anatomy. Half of axial rotation and 12% of flexion-extension in the cervical spine occurs at C1–2.¹

In an effort to avoid potential morbidity with exposure of this area, posterior wiring techniques with structural bone grafts were developed.^{3,6,11} Posterior wiring methods alone are technically simple but have demonstrated low fusion rates and less rigidity in axial rotation and lateral bend-

ABBREVIATIONS PAS = posterior arch screw; ROM = range of motion.

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FIG. 1. C1 morphometric measurements obtained from 150 cervical spine CT scans. **A:** C1 posterior tubercle craniocaudal thickness shown in the midsagittal plane. **B:** Parasagittal cut demonstrating C1 posterior arch anteroposterior diameter. **C:** Axial CT scan through the atlas demonstrating trajectory of C1 PASs and maximal posterior arch length.

ing.⁴⁴ Consequently, C1–2 transarticular screw fixation was developed.²² Although it provides superior rigidity with high fusion rates, this method is technically challenging because of the proximity to the vertebral artery and the

acute angle of approach necessary for proper screw placement.^{22,27,33,39} Goel and Laheri described C1–2 fixation utilizing the C1 lateral mass and C2 pars construct, which was later modified by Harms and Melcher.^{13,19,34,35,40} C1–2 fixation using this technique has been shown to have good biomechanical stability, but places the vertebral artery at risk. Wright described C2 translaminar screw fixation in 2004 as an alternative method of fixation to mitigate the risk of vertebral artery injury in cases of anomalous course or unfavorable anatomy.^{7,42}

While various options exist for C2 fixation, few exist for the atlas. In contrast to the literature supporting the C2 lamina as a viable point of fixation,^{26,43} few studies have rigorously evaluated the C1 posterior arch as a viable alternative for C1 fixation.^{2,10,23} The primary advantages of C1 posterior arch fixation mirror those seen with C2 translaminar screw fixation. Advantages include reduction in blood loss by avoiding exposure of the perivertebral artery venous plexus, reducing C2 neuralgia and numbness by avoiding manipulation of the C2 nerve roots, and avoidance of anterior structures such as the cervical internal carotid artery and hypoglossal nerve. C1 posterior arch fixation has been described primarily as a salvage technique in the case of lateral mass destruction by tumor or arthritic conditions.^{2,10} However, recent evidence shows that a C1 posterior arch/C2 pedicle screw construct provides similar biomechanical strength to a traditional C1 lateral mass/C2 pedicle screw construct.^{2,23}

C1 fixation options have been limited, although reports of constructs using the C1 posterior arch have been described.^{2,10,23,32} In this paper we describe the results of biomechanical testing of a C1 posterior arch screw (PAS)/C2 pars screw construct, morphometric analysis from a random population sample of 150 cervical spine CT scans, proof of concept data to support freehand placement of C1 PASs in a sample of 45 cadaveric specimens, and a brief case illustration.

Methods

C1 Posterior Arch Morphometric Data

Data Collection

Cervical spine CT scans were obtained from a sample of 150 consecutive trauma patients admitted to the University of California, Davis, Medical Center. Exclusion criteria were fractures involving the atlas. Morphometric data were obtained by measuring the following radiographic parameters: 1) C1 posterior tubercle craniocaudal thickness; 2) C1 posterior arch anteroposterior diameter; and 3) C1 posterior arch length.

C1 posterior tubercle thickness was measured as the craniocaudal length in the midsagittal plane (Fig. 1A). C1 posterior arch thickness was measured independently for each side as the largest anterior-posterior distance using parasagittal cuts (Fig. 1B). Unilateral posterior arch length was estimated by a line drawn from the contralateral posterior tubercle–arch junction through the posterior arch in an axial plane, ending at the dense cortical bone on the contralateral arch where the sulcus arteriosus resides (Fig. 1C). Averages and standard deviations were calculated for each of the above measurements (Table 1).

TABLE 1. C1 posterior arch morphometric analysis generated from 150 consecutive CT scans of the cervical spine

Group	No. of Pts	Posterior Tubercle Thickness	Posterior Arch Thickness		Posterior Arch Max Length	
			Rt	Lt	Rt	Lt
Total	150	12.3 ± 1.94	6.1 ± 1.10	6.1 ± 1.16	28.7 ± 2.53	28.9 ± 2.29
Males	91	12.8 ± 1.96	6. ± 1.14	6.3 ± 1.26	29.4 ± 2.33	29.5 ± 2.13
Females	59	11.5 ± 1.64	5.7 ± 0.93	5.7 ± 0.89	27.6 ± 2.41	28.0 ± 2.24

Pts = patients.

Data reported as mean ± standard deviation (mm) unless otherwise indicated.

Proof of Concept for Freehand C1 PAS Placement

Freehand C1 PAS Technique

Forty-five fresh-frozen cadaver upper cervical spines (C0 [occiput]–C4) were used to determine the feasibility and safety of freehand C1 PAS placement. This yielded a total of 90 possible screw placements. The C1 PAS entry point was identified using the posterior tubercle–lamina junction on each side (Fig. 2A). Entry points were selected on the superior and inferior halves of the tubercle with each screw directed slightly inferior and superior along the direction of the contralateral posterior arch, respectively. Pilot holes were drilled with a 2-mm high-speed drill at the cranial tubercle–lamina junction on one side and the caudal half of the tubercle–lamina junction on the contralateral side. A handheld power drill was used to cannulate each posterior arch to a predetermined depth of 16 mm in an oblique superior or inferior direction, remaining roughly parallel to the contralateral superior and inferior corti-

cal posterior arch margins, respectively. Screw holes were tapped with a 2.5-mm threaded tap (Fig. 2B), followed by cannulation with 3.5 × 16-mm polyaxial screws (Fig. 2C and D) in a crossing fashion to avoid tulip head interference. Following screw placement in all specimens, each C1 vertebra was dissected en bloc to evaluate for evidence of cortical breach, violation of the vertebral artery sulcus, and canal violation. Breach was defined as grossly visible violation of any cortical surface of the C1 posterior arch.

In Vitro Biomechanical Testing

Spinal Constructs

Eight fresh-frozen upper cervical spines (C0–4) were harvested from donated human cadavers. Specimens were stripped of all musculature, taking care to preserve the ligamentous structures. Anterior-posterior and lateral fluoroscopic images were used to assess bone quality prior to screw implantation and biomechanical testing. The poste-

FIG. 2. Cadaveric specimen demonstrating freehand C1 PAS placement. **A:** Starting point for placement of left C1 PAS. **B:** Tapping the left posterior arch. **C:** Final placement of left 3.5 × 16-mm C1 PAS. **D:** Final bilateral C1 PAS placement. Figure is available in color online only.

rior arch of C1 was exposed in the usual subperiosteal fashion. Two constructs were created. C1 lateral mass screws and C2 pars screws were placed according to the method described by Goel and Laheri¹³ and C1 PASs were placed using the technique described above. Each construct was connected independently via 3.5-mm rods to yield two separate constructs (C1 lateral mass/C2 pars screw and C1 PAS/C2 pars screw) for biomechanical testing (Fig. 3A).

Biomechanical Testing

Specimens were secured in a neutral position to test fixtures at C0 and C4 and mounted onto a custom-built LabView (NuVasive, Inc.) biomechanical testing system with 6 degrees of freedom. Kinematic data were obtained via an optoelectronic motion system (Optotrak, NDI) with infrared light-emitting diode marker arrays attached to the C1 and C2 vertebral bodies. Pure-moment flexibility testing was performed using 2 N·m moments in each axis (flexion, extension, axial rotation, lateral bending) for 3 cycles in each direction.

Testing Conditions

C1–2 flexibility and construct rigidity was evaluated in the following three conditions. The initial sequence of testing the second and third conditions was alternated to minimize any potential bias favoring one construct over the other. In the first condition, intact specimens without rod constructs were tested to generate baseline values in flexion-extension, lateral bending, and axial rotation. For the second condition, C1 lateral mass/C2 pars screw constructs were tested by attaching 3.5-mm rods to the C1 lateral mass and C2 pars screws (Fig. 3B). Flexibility testing was repeated in flexion-extension, lateral bending, and axial rotation. In the third condition, C1 PAS/C2 pars screw constructs were tested according to conditions described in condition two above (Fig. 3C).

Statistical Analysis

Means and standard deviations were calculated for each test condition and loading direction. Paired comparisons were made using repeated measures ANOVA and Holm-Sidak tests. Statistical significance was set at $p < 0.05$.

Case Illustration

A 19-year-old man was struck by a vehicle, sustaining a type II odontoid fracture without significant displacement or angulation (Fig. 4A). He was neurologically intact on presentation. Due to age and favorable anatomy, odontoid screw placement was chosen as the initial surgical treatment. He presented to our institution 3 months later with severe neck pain secondary to nonunion with C1–2 subluxation (Fig. 4B), although he remained neurologically intact. A decision was made to proceed with posterior C1–2 fusion. Significant venous bleeding was encountered with exposure of the C1 lateral mass bilaterally, despite the use of various hemostatic agents. His anatomy was deemed unsuitable for placement of a C1 lateral mass screw at an alternative entry point just inferior to the C1 arch/lateral mass junction. Thus, we elected to place two

FIG. 3. A: Biomechanical construct prior to testing with implanted C1 lateral mass screws, C1 PAS screws, and C2 pars screws. B: Testing of C1 lateral mass/C2 pars screw construct. C: Testing of C1 PAS/C2 pars screw construct. Figure is available in color online only.

posterior arch screws utilizing the technique described above. Two 3.5×12 -mm polyaxial screws were placed into the posterior arches of C1, followed by cannulation of the C2 pars bilaterally. Rods were cut and sized appropriately. Due to nonunion with C1–2 instability, the construct was further supported with sublaminar wires and a tricortical iliac crest allograft wedged between the C1 posterior arch and C2 lamina. The C1 posterior arch and C2 lamina were decorticated and a mixture of cancellous allograft with demineralized bone matrix was placed over the decorticated surfaces (Fig. 4C and D).

FIG. 4. **A:** Initial CT scan demonstrating traumatic type II odontoid fracture. **B:** CT scan 3 months after odontoid screw placement demonstrating screw pullout and nonunion. **C:** Postoperative sagittal radiograph showing C1 PAS/C2 pars screw construct with sublamina wires and allograft. **D:** 3D postoperative CT scan demonstrating final construct and allograft placement over decorticated surfaces. Figure is available in color online only.

Results

C1 Posterior Arch Morphometric Data

One hundred fifty consecutive cervical spine CT scans obtained for trauma were used to generate C1 posterior arch morphometric data. There were 91 male and 59 female patients. The mean age was 42 years (range 18–96 years, Table 1). The average C1 posterior tubercle cranio-caudal thickness was 12.3 ± 1.94 mm. There were 6 instances in which the midline posterior arch was absent. There were an additional 6 cases in which the posterior tubercle was extremely thin and unable to accommodate a posterior arch screw. Due to these anomalies, 8.0% (12/150) of C1 posterior arches were unsuitable for C1 posterior arch screw placement. In 6 specimens, the posterior tubercle was large enough to accommodate entry points for 2 crossing PASs. However, 1 or both posterior arches were 3.5 mm or smaller in each of these patients. The average posterior arch thickness was 6.1 ± 1.1 mm (range 3.5–9.3 mm and 3.2–9.6 mm for right and left posterior arches, respectively). Right and left average posterior arch length was 28.7 ± 2.53 mm and 28.9 ± 2.29 mm, respectively.

Proof of Concept for Freehand C1 Posterior Arch Screw Placement

Forty-five fresh-frozen cadaveric specimens were used

FIG. 5. Biomechanical testing of intact specimens compared with C1 lateral mass/C2 pars (C1 Lat Mass) and C1 PAS/C2 pars screw (C1 PAS) constructs in flexion-extension, lateral bending, and axial rotation. ROM in flexion-extension and axial rotation was significantly reduced in both C1–2 constructs as compared with the intact spine. The C1 lateral mass/C2 pars screw construct reduced lateral bending ROM significantly (* $p < 0.05$).

for freehand placement of C1 PASs utilizing the technique described above. Of 90 individual posterior arches cannulated for C1 PAS placement, 3.5×16 -mm polyaxial screws were successfully placed via freehand technique in 91.3% of specimens. Seven arches that were short, thin, or had posterior midline defects were cannulated with shorter 3.5-mm screws. En bloc dissection revealed 4 cortical breaches (4.4%), all of which occurred through the posterior cortical margin. There was no identifiable evidence of canal breach or injury to the horizontal portion of the vertebral artery.

In Vitro Biomechanical Testing

Biomechanical testing was conducted for three separate testing conditions. Both C1 lateral mass/C2 pars and C1 PAS/C2 pars screw constructs significantly reduced range of motion (ROM) in flexion and extension compared with intact specimens ($p < 0.05$, Fig. 5). A significant reduction in axial rotation was noted when each construct was compared with intact specimens ($p < 0.05$). ROM in lateral bending was reduced in both constructs compared with the intact spine. The C1 lateral mass/C2 pars construct provided significant rigidity in lateral bending compared with the intact spine ($p < 0.05$). There was no statistically significant difference seen in flexion-extension, lateral bending, or axial rotation when the two constructs were compared directly (Fig. 6).

Discussion

Atlantoaxial instability presents a unique challenge to spine surgeons given the inherent high degree of mobility of this complex. Techniques for atlantoaxial fixation have evolved since Mixter and Osgood's original description in 1910.³⁰ Gallie later popularized the posterior wiring technique in 1939.¹¹ Posterior wiring techniques^{3,6,11} were

FIG. 6. C1 lateral mass/C2 pars construct provides greater, but nonsignificant rigidity in flexion-extension, lateral bending, and axial rotation, as compared with the C1 PAS/C2 pars screw construct.

widely utilized but found to have poor rigidity in axial rotation⁴⁴ and translation^{5,14,31} and posed a significant risk of spinal cord injury due to wire passage.

Although technically simple, wiring techniques suffered from high rates of pseudarthrosis and nonunion. Transarticular screw fixation was introduced in 1992 by Magerl²² and has demonstrated more rigidity than posterior wiring techniques.^{15,18,29,31} Despite providing optimal rigidity, inherent problems with the approach include a difficult screw angle, need for C1–2 reduction, and anatomical variability of the vertebral artery. The technique is technically demanding and vertebral artery injury rates range from 2.2% to 4%.^{20,45} Anatomical studies have shown up to 23% of patients may have a vertebral artery course that precludes safe transarticular screw placement.^{27,33}

Due to the anatomical limitations for transarticular screw placement, C1–2 segmental fixation techniques using the C1 lateral mass, C1 pedicle, C2 pars, and C2 pedicle have been developed. Independent C1 and C2 screws are connected either by rigid plates^{12,13} or rods.^{19,34} The C2 pars screw trajectory allows for less risk to the vertebral artery,^{16,19} making this approach feasible for more patients, although pullout strength has been shown to be less than C2 pedicle screws.⁴¹ Segmental C1–2 screw placement also permits intraoperative reduction of atlantoaxial subluxation.^{19,24} Biomechanical analyses have demonstrated equivalent to superior stability when the C1 lateral mass–C2 pars/pedicle screw construct is compared to the transarticular screw construct.^{4,25,28} Furthermore, fusion rates greater than 98% have been reported when supplemented with intraarticular bone grafts.^{1,12}

C2 pedicle screw placement, although technically simpler than transarticular screw placement, still incurs some degree of risk to the vertebral artery. Cadaveric studies have shown a variable course of the vertebral artery in as many as 22% of specimens²⁷ and a significant rate of transverse foramen violation during C2 pedicle screw placement,⁸ although a recent meta-analysis indicates clinically significant injury remains less than 1%.⁹ To avoid vertebral artery injury, the C2 intralaminar screw technique has

been described.^{21,26,42} Biomechanical testing shows equivalent stability of atlantoaxial constructs using C2 translaminar screws as compared with C2 pedicle screws and no statistically significant difference in pullout strength between C2 translaminar and C2 pedicle screws.^{17,37,38}

Many viable alternatives to transarticular and C2 pedicle screw placement now exist that reduce vascular injury while still providing satisfactory biomechanical stability. C1 fixation is still largely limited to the lateral mass. Entry point modifications via the posterior arch were developed to reduce C2 neuropathy and blood loss from exposure of the traditional C1 lateral mass screw entry point, even in the setting of ponticulus posticus.^{34,46} Occipital neuralgia from retraction and/or irritation of the C2 nerve root by C1 lateral mass screw placement, although uncommon, has been described.^{16,36} Utilization of the C1 posterior arch has largely been limited to case reports of its use as a salvage technique when the C1 lateral mass cannot be used.^{2,10,23,32} More recent reports have detailed encouraging biomechanical results, although pullout strength remains less than C1 lateral mass screws.^{17,23,38} Jin et al. have recently reported good biomechanical stability of C1 PAS–C2 pedicle screw constructs as compared with traditional C1–2 lateral mass/pedicle screw constructs.²³ They report significant reduction in flexion, extension, and axial rotation and nonsignificant reduction in lateral bending. Shen et al. developed a unique hybrid construct consisting of unilateral C1–2 pedicle screws with ipsilateral parallel and ipsilateral crossed C1 posterior arch/C2 laminar screw construct.³⁸ Their results showed no statistically significant difference between the hybrid constructs and traditional bilateral C1–2 pedicle screw construct. Similar results were found in another biomechanical analysis of a hybrid C1 PAS/C2 laminar screw construct.¹⁷ In that analysis, there were no significant differences in flexion-extension and rotational stability. Bilateral C1–2 pedicle screw constructs were significantly more rigid in right lateral bending compared with hybrid constructs with a contralaterally placed C1 PAS and C2 laminar screws.

Our method of atlantoaxial fixation involves a C1 PAS and C2 pars screw construct. C2 pars screw placement is technically similar to C2 pedicle screws, but with a potentially broader range of applications in patients that have either small C2 pedicles or an anomalous vertebral artery course. We initially used the C1 PAS technique as a salvage option when profuse bleeding precluded placement of C1 lateral mass screws in a patient with type II odontoid fracture nonunion (Fig. 4B). In our clinical scenario, the construct was reinforced with a tricortical iliac crest allograft and sublaminar wires. Importantly, this illustrates several points. Our screw-rod construct does not preclude placement of a structural graft, still allows for supplemental wiring techniques, and provides a suitable bony surface for decortication and allograft placement (Fig. 4C and D). While exposure of the C1–2 joint provides a potential fusion surface, we feel that the bony surfaces of the C1 arch, C2 lamina, and medial C1–2 joint surfaces are sufficient.

Exposure for placement of bilateral C1 posterior arch screws is safe and relatively quick, avoiding blood loss associated with exposure of the C1 lateral mass entry point, risk to the vertebral artery, and risk of C2 neuralgia. Re-

sults of our biomechanical analysis indicate that this method compares favorably with traditional C1 lateral mass/C2 pars screw constructs and provides significant reduction in flexion-extension and axial rotation as compared with intact specimens (Fig. 5). There was a trend toward greater rigidity of the C1 lateral mass/C2 pars screw construct when directly compared with the C1 PAS/C2 pars screw construct, although results did not reach statistical significance. Prior studies have also shown the biomechanical stability and utility of this type of unilateral construct when combined with C1–2 pedicle screws. This can be extremely valuable in the case of patients who have anatomy that precludes safe C2 pedicle screw placement or in patients who have a unilateral dominant vertebral artery that needs to be protected. Biomechanically, different rod lengths generate different moment arms, which can impact axial rotational stability. While our data indicate less axial rotational stability in the C1 PAS/C2 pars construct (Fig. 6), results did not reach statistical significance when compared with a traditional C1 lateral mass/C2 pars construct, although small sample size may have limited this evaluation. Additional support can be provided to the construct via sublaminar wiring and placement of a structural graft, as shown in our case example (Fig. 4).

Morphometric data from our population sample demonstrated favorable conditions for C1 PAS placement. Average diameter of the C1 posterior arch was 6.1 ± 1.1 mm in our sample of 150 patients with average posterior tubercle craniocaudal diameter measuring 12.3 ± 1.94 mm. Eight percent of our sample did not have radiographically suitable anatomy for placement of a C1 posterior arch screw. This number is nearly identical to what we found in our feasibility study using a freehand technique in 45 cadavers (90 single posterior arches). Results of this study indicated successful placement in 91.3% of specimens with a very low incidence of cortical breach (4.4%). Importantly, no instances of canal breach or vertebral artery violation were observed in any of the specimens. Seven C1 arches in our cadaveric series were either small or had midline defects, features that would have indicated poor radiographic suitability for C1 PAS placement. The same anatomical constraints were identified in the 12 radiographically “unsuitable” specimens; 6 of these cases had C1 posterior arches that were thinner than 3.5 mm and would theoretically not accommodate our smallest available screw. The remaining 6 cases each had varying degrees of midline defects. Importantly, the same midline anatomical defects were encountered in 7 of the 45 cadaveric specimens. In spite of this, we were able to successfully cannulate these 7 arches with shorter 3.5-mm screws. Although screw placement was technically feasible, placing a viable construct in these cases may be limited by the tulip heads being in close proximity to one another. In addition to congenital midline defects, traumatic C1 fractures are commonly seen. While we did not specifically encounter any of these examples in our CT population or cadaveric study, we postulate that C1 PASs can safely be placed in cases of isolated C1 anterior arch fracture, while fractures involving the posterior arch or posterior arch/lateral mass junction would be contraindicated.

There were notable differences in our morphometric

data compared with results reported by Jin et al.,²³ though most variability was due to differences in measuring technique. Importantly, we found our C1 posterior arch length to be 10 mm greater on average than that reported by Jin et al. Our measurement was performed in an oblique orientation from the arch–tubercle junction to the posterior cortical margin of the contralateral vertebral artery sulcus (Fig. 1C), as opposed to measuring from the midline of the atlas to the dense cortical bone at the medial margin of the arterial sulcus. Despite differences in measuring technique, practical application in our cadaveric feasibility testing demonstrated that 3.5×16 -mm polyaxial screws could be safely placed free-hand in the majority of specimens.

Conclusions

To our knowledge, this is the largest study demonstrating both the feasibility and safety of freehand C1 PAS placement. Cortical breach was 4.4% and even smaller arches were successfully cannulated with shorter screws. Limitations of the study include lack of a destabilized biomechanical model, although we felt it unlikely that our construct would not have provided significant reduction in ROM in this model as compared with an intact specimen. One limitation of biomechanical analyses has been the lack of standardization of moment arms, what constitutes a “destabilized spine,” minimum number of cadaveric specimens needed, and number of testing conditions to prove or disprove a theory of biomechanical stability. While our preliminary data and those of others support the biomechanical strength of this technique both alone or as a hybrid construct, more clinical studies are needed to validate its use and long-term effectiveness at achieving successful fusion in a variety of real-world scenarios. For now, we can confidently say that this construct appears to be a safe, viable, and generally applicable salvage technique in the atlantoaxial fixation armamentarium.

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