Original Article

Biomechanical comparison of a novel C1 posterior U-construct with four other techniques in a C1–C2 fixation model[☆]Joshua P. Herzog^{a,d}, Nicholas J. Zarkadis^{b,d}, Gautham Prabhakar^{c,d,*}, Nicholas A. Kusnezov^{b,d}^a Orthopaedic Spine Center, Massachusetts General Hospital, Boston, MA, United States^b Department of Orthopaedic Surgery and Rehabilitation, William Beaumont Army Medical Center, El Paso, TX, United States^c Paul L. Foster School of Medicine at Texas Tech University Health Sciences Center El Paso, El Paso, TX, United States

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ABSTRACT

Background: Compare the biomechanical stability of a novel “U” posterior cervical fixation construct to four other posterior cervical atlantoaxial fixation constructs.**Methods:** Eight fresh frozen human cadaver spines were tested after a simulated odontoid fracture, and following stabilization with each construct.**Results:** All constructs significantly decreased flexion-extension and axial rotation compared to the destabilized spine. The U construct provided significantly more axial stability than the Brooks wire technique.**Conclusion:** The novel U construct demonstrated comparable biomechanical stability to the existing constructs in all three planes of motion with the exception of axial rotation, in which it was inferior to TAS.

1. Introduction

Atlantoaxial stabilization is frequently indicated in the setting of instability.¹ A number of fixation constructs have been described for this purpose, each with varying degrees of surgical risk and clinical success.^{2–22} The universal goals of these techniques are to maximize the likelihood of achieving a stable fusion while limiting the surgical risk to the patient.

Early sublaminar wiring techniques required a more limited exposure and were less technically demanding but provided only moderate stability and were associated with considerable rates of non-union.^{2,3,5–7,10,13,21} Later constructs utilizing screw fixation resulted in increased biomechanical stability and often obviated the requirement for an intact posterior arch of C1. However these were more technically complex and posed a great risk to the delicate local neurovascular structures.^{4,8,9,11,14–16,18–20,22} Presently, axial (C2) fixation is most often achieved via either pedicle screws^{9–11} or less commonly crossing translaminar screws.^{23–25} Conversely, modern atlantal (C1) fixation techniques typically rely on carefully placed lateral mass screws.^{9–11} Dissection and placement of C1 lateral mass screws however is not trivial and may be complicated by significant blood loss from the posterior cervical venous plexus or neurovascular injury to the greater occipital nerve or vertebral artery.⁴ To avoid the risks associated with

placement of lateral mass screws, the author has introduced a unique “U construct”, utilizing C2 pedicle screws connected to one another via a 3.5 mm rod contoured into an inverted “U” shape, which is subsequently fixed to the C1 arch with sublaminar cables.

In this investigation, we described the novel U construct for atlantoaxial fixation and conduct a biomechanical comparison to existing commonly implemented constructs.

We hypothesized that the U construct would offer at least comparable biomechanical stability to the other constructs in each plane of motion.

2. Materials and methods

2.1. Specimen preparation

Eight fresh frozen human cadaver C0–C4 spines with intact ligaments were obtained. The specimens were kept frozen at -20°C. The spines were thawed, and the tissue around the spine with the exception of the ligaments and disc were removed. C0 and C3 were potted using Bondo auto body filler. During mounting the specimens were oriented in the neutral position. L-shaped Plexiglass plates, each having 3 infrared light emitting diodes (LEDs) were attached to C0, C1, C2, and C3. Three-dimensional spatial locations of the LEDs were recorded in

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Fig. 1. Standard three degrees of freedom spine simulator with cadaveric specimen.

response to applied loads, using a motion measurement system (Optotrak; Northern Digital, Waterloo, Ontario, Canada). The root mean square accuracy and the resolution of Optotrak are 0.1 mm and 0.01 mm, respectively.

2.2. Motion measurement

The prepared specimens were attached to the rigid bases of the three degrees of freedom machine (Fig. 1). A load control protocol with an unconstrained pure moment of ± 2 Nm was used in flexion-extension, lateral bending, and axial rotation. A total of three load-unload cycles were performed for each specimen.

2.3. Constructs and testing sequence

The intact spines were first tested for load displacement behavior after preparation but prior to instrumentation. This generated baseline values that were used for statistical comparison. The specimens were then tested after a simulated type II odontoid fracture was created, effectively destabilizing the atlantoaxial articulation. Finally, each spine was then stabilized and serially tested with each of five constructs including (1) the Brooks wire technique (B), (2) C1 lateral mass and C2 pedicle screws (LMS + PS), (3) C1 lateral mass and C2 translaminar screws C2 (LMS + TLS), (4) C1-C2 transarticular screws (TAS), and (5) the novel U construct. The U construct utilizes C2 pedicle screws placed in standard fashion connected to one another via a 3.5 mm rod contoured into an inverted U-shape, which is subsequently affixed to the C1 arch with sublaminar cables (Figs. 2, 3). Testing order was randomized for each specimen, except for TAS which was always tested last.

2.4. Surgical techniques

The sublaminar cable/graft construct was created as described by Brooks.² Instead of bone, peak interbody spacers (Globus Medical, Philadelphia, PA) were used. To tension the braided titanium cable a standard tension device (Globus Medical, Philadelphia, PA) was used. After applying tension of at least 30 N, a separate crimping tool was used to secure the cable. Posterior fixation for the two rod-and-screw

constructs were performed using 3.5 x 20 mm screws for C1 lateral mass screw (LM), as described by Harms and Melcher,¹¹ and 3.5 x 25 mm screws for C2 translaminar (TLS) or pedicle screw (PS) fixation as described by Wright²⁴ and Harms.¹¹ The technique described by Margerl and Seeman¹⁶ was used for TAS fixation with 3.5 x 40 mm screws.

3. Statistical methods

The spatial locations of the LEDs fixed to the vertebral bodies were tracked with the use of the Optotrak motion measurement system. The intersegmental motion across C1-C2 segment for each of the intact and stabilized specimens was calculated. The intact versus destabilized versus stabilized spine for each of the five constructs were compared using the SPSS statistical analysis software. The raw data was analyzed for any outliers using Box plots. No outliers were found. The raw data was observed to be non-parametric and hence log transformation was applied to make it parametric data. The data was normalized for the intact spine. Single factor Analysis of Variance (ANOVA) was performed for over all significance and Tukey post hoc was performed for individual comparisons with significance at $p < 0.05$.

4. Results

4.1. Flexion extension

All the instrumented constructs reduced the range of motion (ROM) for flexion-extension compared to intact spine but only the Brooks Wire, U construct, and LMS + PS techniques were statistically significant. Destabilizing the specimens increased the ROM by 101.7% but was statistically insignificant compared to intact spine. The B, U, LMS + PS, LMS + TLS, and TAS instrumented constructs reduced ROM by 175.05%, 171.12%, 174.55%, 159.54%, and 157.84% respectively and were all statistically significant compared to the destabilized spine (Table 1). No statically significant differences were observed between the instrumented constructs.

4.2. Lateral bending

All the instrumented constructs reduced the range of motion compared to intact spine but none of them were statistically significant. Destabilizing the specimens increased the ROM in intact spine by 62% but was statically insignificant. The instrumented constructs B, U, LMS + PS, LMS + TLS, and TAS reduced range of motion by 103.89%, 96.06%, 125.51%, 87.83%, 144.54% and only LMS + PS, and TAS were statistically significant compared to the destabilized spine (Table 1). No statically significant differences were observed between the instrumented constructs.

4.3. Axial rotation

All the instrumented constructs reduced the range of motion compared to intact spine and were statistically significant. Destabilizing the specimens increased the range of motion of the intact spine by 4.02% and was statically insignificant. The instrumented constructs B, U, LMS + PS, LMS + TLS, TAS reduced range of motion by 70.41%, 96.30%, 98.80%, 97.93%, 102.62% and were statistically significant compared to destabilized spine (Fig. 4). All the constructs U, LMS + PS, LMS + TLS, TAS were significantly more stable than the Brooks wiring. Specifically the U construct decreased axial rotation by 96%. This was significantly more than the Brooks wiring at 70% reduction. The TAS construct was significantly more stable in axial rotation than all other instrumented constructs.

5. Discussion

The local anatomy and physiologic movement of the atlantoaxial

Fig. 2. (A) Posterior and (B) lateral views of novel U construct on sawbones model.

joint is complex. As a result, treatment of atlantoaxial instability represents one of the most challenging clinical problems for the modern spine surgeon as it involves working intimately among complicated and variable vital anatomical structures. Literature and clinical practice is replete with a variety of techniques that have been developed over the past century to restore biomechanical stability and allow reliable fusion at this level.^{2–22}

In the current study, we compare the stability of five different atlantoaxial constructs in a cadaveric spine model. The novel U construct significantly decreased flexion-extension and lateral rotation compared to the destabilized spine and was not significantly different than the other standard constructs in regard to stability in flexion-extension or lateral bending. While the U construct provided significantly more axial stability than the Brooks wire technique (70%), TAS were found to limit axial rotation significantly more so than any other construct. The U construct otherwise showed no significant difference in any of the 6 degrees of motion tested when compared to the LMS + PS and LMS + TLS techniques.

The U construct was developed to mitigate complications associated with existing techniques while still affording the stability necessary to produce a fusion. Wiring techniques initially used for posterior cervical spine fixation have largely fallen out of favor due to the suboptimal stability profile and less reliable resulting union rates (75%–93%).^{2, 3, 5, 10} To obviate the need for an intact posterior arch of C1, screw-based constructs were developed.^{8, 9, 11, 16} The earlier trans-articular lateral mass fixation technique (TAS) originally described by Magerl provided enhanced rigidity, particularly in rotation, when compared to wired fusions.^{16, 18} While TAS offered increased fusion rates (90%–98%)^{10, 15, 16, 22} and lower complications than sublaminar wires, this technique is associated with a well-documented risk to the vertebral artery and is additionally limited by the need for a complete reduction of C1 on C2.¹⁹ Careful preoperative planning is required,⁴ as an aberrant course of the vertebral artery precludes TAS fixation entirely in as many as 6–23% of cases.^{14, 15, 20}

Atlantal (C1) lateral mass screws with segmental axial (C2) fixation (LMS + TLS and LMS + PS techniques) evolved to address limitations

Fig. 3. Standard constructs in situ in cadaveric specimens (A) the Brooks wire technique (B), (B) C1 lateral mass and C2 pedicle screws (LMS + PS), (C) C1 lateral mass and C2 translaminar screws C2 (LMS + TLS), (D) C1–C2 transarticular screws (TAS), and (E) the novel U construct. The U construct utilizes C2 pedicle screws placed in standard fashion connected to one another via a 3.5 mm rod contoured into an inverted U-shape, which is subsequently affixed to the C1 arch with sublaminar cables.

Table 1

Normalized multidirectional range of motion at C1–C2 as measured on three degrees of freedom spine simulator with intact, destabilized, and stabilized spine with each of the five constructs depicted in Fig. 3.

and morbidity associated with TAS fixation.^{11, 24, 26, 27} Similar to our investigation, previous biomechanical and clinical studies have demonstrated no significant differences in the stability or fusion rates (88.2%–100%)^{26, 28} afforded by these constructs as compared to TAS.^{29–31} However C1 lateral mass screw misplacement risks injury to the internal carotid artery and hypoglossal nerve anteriorly and to the dura and spinal cord with medial breach.^{8, 9} The U construct obviates the risks of anterior penetration as well as dissection about the greater occipital nerve, but potentially maintains a similar risk to the dura and cord. However this technique avoids risks associated with sublamina wire passage at C2 as well as dissection around the posterior venous plexus, potentially limiting significant venous bleeding. Given the comparable stability among the four screw-based constructs in our study, utilization of the novel U construct would likely result in similarly high union rates while boasting these several potential surgical advantages. Axial (C2) pedicle screw placement nevertheless remains technically demanding and cannot be used in patients possessing a narrow C2 pars or medially located foramen transversarium.^{9, 11, 12}

The translamina method of axial (C2) screw fixation was most recently developed as an alternative to LMS + PS and TAS in the setting of a hypoplastic C2 pedicle, high-riding vertebral artery, bone loss secondary to a pathological lesion, or as a salvage option.^{17, 26, 32} Although not analyzed in the current study, translamina fixation may offer an additional option over C2 pedicle screws to be incorporated into the U construct. There were a number of additional limitations to this study. Foremost, fusion cannot be inferred strictly from construct stability and is largely dependent on surgical technique. However, given the well-characterized fusion rates of the other techniques in this analysis as well as similar soft tissue dissection and fixation techniques, it stands to reason that the U construct should provide similar results. This remains to be demonstrated in the clinical setting. Additionally, by the cadaveric nature of the study, muscle forces could not be accounted for. However, the study was conducted under pure moments of 2 N m, which fall well within the physiologic range of 1.5–3 N m recommended and previously validated by Goel.³³ Lastly, this study focused chiefly on ROM measurements and did not assess fatigue properties of the constructs. Further biomechanical analysis and clinical application of the U

construct is warranted given the promising findings of this investigation.

The proposed novel U construct demonstrated comparable biomechanical stability to the existing constructs in all three planes of motion with the exception of axial rotation, in which it was inferior to TAS. Though limited by the need for an intact posterior C1 arch, the U construct provides a viable treatment option with adequate stability while potentially incurring less risk of arterial injury and epidural bleeding than other more popular screw stabilization techniques.

Disclaimers

The authors are employees of the U.S. Federal Government and the United States Army. The opinions or assertions contained herein are the private views of the authors and are not to be construed as official or reflecting the views of William Beaumont Army Medical Center, the Department of Defense, or United States government.

Conflict of Interest

The authors have no conflict of interest. We do not have any financial or personal relationships to disclose.

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