Biomechanical evaluation of two alternative techniques to the Goel-Harms technique for atlantoaxial fixation: C1 lateral mass–C2 bicortical translaminal screw fixation and C1 lateral mass–C2/3 transarticular screw fixation

*Yue-Qi Du, MD,¹ Teng Li, MD,¹ Chao Ma, PhD,² Guang-Yu Qiao, MD,¹ Yi-Heng Yin, MD,¹ and Xin-Guang Yu, MD, PhD¹

¹Department of Neurosurgery, Chinese PLA General Hospital, Beijing; and ²Key Laboratory of Modern Measurement and Control Technology, Ministry of Education, Beijing Information Science and Technology University, Beijing, China

OBJECTIVE The authors conducted a study to investigate the biomechanical feasibility and stability of C1 lateral mass–C2 bicortical translaminal screw (C1LM–C2TL) fixation, C1 lateral mass–C2/3 transarticular screw (C1LM–C2/3TA) fixation, and C1LM–C2/3TA fixation with transverse cross-links (C1LM–C2/3TACL) as alternative techniques to the Goel-Harms technique (C1 lateral mass–C2 pedicle screw [C1LM–C2PS] fixation) for atlantoaxial fixation.

METHODS Eight human cadaveric cervical spines (occiput–C7) were tested using an industrial robot. Pure moments that were a maximum of 1.5 Nm were applied in flexion-extension (FE), lateral bending (LB), and axial rotation (AR). The specimens were first tested in the intact state and followed by destabilization (a type II odontoid fracture) and fixation as follows: C1LM–C2PS, C1LM–C2TL, C1LM–C2/3TA, and C1LM–C2/3TACL. For each condition, the authors evaluated the range of motion and neutral zone across C1 and C2 in all directions.

RESULTS Compared with the intact spine, each instrumented spine significantly increased in stability at the C1–2 segment. C1LM–C2TL fixation demonstrated similar stability in FE and LB and greater stability in AR than C1LM–C2PS fixation. C1LM–C2/3TA fixation was equivalent in LB and superior in FE to those of C1LM–C2PS and C1LM–C2TL fixation. During AR, the C1LM–C2/3TA–instrumented spine failed to maintain segmental stability. After adding a cross-link, the rotational stability was significantly increased in the C1LM–C2/3TACL–instrumented spine compared with the C1LM–C2/3TA–instrumented spine. Although inferior to C1LM–C2TL fixation, the C1LM–C2/3TACL–instrumented spine showed equivalent rotational stability to the C1LM–C2PS–instrumented spine.

CONCLUSIONS On the basis of our biomechanical study, C1LM–C2TL and C1LM–C2/3TACL fixation resulted in satisfactory atlantoaxial stabilization compared with C1LM–C2PS. Therefore, the authors believe that the C1LM–C2TL and C1LM–C2/3TACL fixation may serve as alternative procedures when the Goel-Harms technique (C1LM–C2PS) is not feasible due to anatomical constraints.

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KEYWORDS atlantoaxial instability; screw-rod fixation; biomechanics; alternative technique; pedicle screw; translaminal screw; transarticular screw; cervical

THE atlantoaxial complex is the most mobile section in the cervical spine owing to its unique anatomical structure. The horizontal morphology of the atlantoaxial articular surface and the absence of an intervertebral disc, with stability mainly provided by capsuloligamentous structures, make the atlantoaxial joint prone to instability.²⁰ Atlantoaxial instability or dislocation, which can result from trauma, congenital malformation, and in-

flammation, may cause potentially life-threatening neurological deterioration and require C1–2 stabilization.^{8,12}

Presently, fixation with a C1 lateral mass and C2 pedicle screw and rod, also known as the Goel-Harms technique, has been widely used for atlantoaxial fixation with optimal stability, high fusion rates, and excellent clinical outcomes compared with the posterior wiring technique or the C1–2 transarticular technique.^{8,10} The placement of C2 pedicle

ABBREVIATIONS AR = axial rotation; C1LM–C2PS = C1 lateral mass–C2 pedicle screw; C1LM–C2TL = C1 lateral mass–C2 bicortical translaminal screw; C1LM–C2/3TA = C1 lateral mass–C2/3 transarticular screw; C1LM–C2/3TACL = C1LM–C2/3TA fixation with transverse cross-links; FE = flexion-extension; LB = lateral bending; NZ = neutral zone; ROM = range of motion.

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* Y.Q.D. and T.L. contributed equally to this work.

screws, however, still carries the risk of neurovascular injury, especially when vertebral artery variations and unfavorable pedicle anatomy are identified.^{6,19} C2 intralaminar screws and C2 short pedicle/pars screws have been used as alternative strategies when C2 pedicle screw placement is prohibited, which could avoid the aforementioned limitations regarding C2 pedicle screws.^{23,24} Nevertheless, intralaminar and short pedicle screws have been shown, during *in vitro* testing, to produce inferior biomechanical stability compared to standard pedicle screws.^{5,16,18} Therefore, an ideal alternative atlantoaxial construct that could provide rigid immobilization while minimizing the risk of vascular violation is needed. More recently, C2 bicortical translaminal screw fixation and C2–3 transarticular screw fixation, used as salvage techniques in atlantoaxial fixation, have shown satisfactory fusion rates and clinical outcomes with low complication rates.^{15,21,26} However, the biomechanical properties of C2 bicortical translaminal screws have not been well investigated, and, to our knowledge, there are no studies concerning the biomechanical stability of C2–3 transarticular screws.

The objective of the present study was to evaluate the biomechanical stability of the C2 bicortical translaminal screw fixation and C2–3 transarticular screw fixation as alternatives to the Goel-Harms technique for the management of atlantoaxial instability in a type II odontoid fracture model.

Methods

Specimen Preparation

Eight fresh-frozen human cadaveric spinal specimens (occiput–C7) were obtained (mean age at death 57.3 years; 5 males and 3 females). All specimens were examined with radiographs to exclude those with marked, advanced degenerative changes, autofusion, previous surgery, deformity, and congenital bony anomalies. Specimens were sealed in double plastic bags and kept frozen at -20°C , thawed overnight at room temperature, and kept moist during all procedures. The attached soft tissues and paraspinal musculature were removed, with care taken to preserve the ligaments, intervertebral discs, joint capsules, and bony structures. The occiput and C7 vertebra were then mounted with polymethylmethacrylate. The transverse plane of the C1–2 junction was kept at a horizontal orientation while potting the specimens.

Biomechanical Testing and Protocol

An industrial robot (AUBO; AUBO Robotics) capable of motion in 6 axes was used as the spine-testing apparatus for multidirectional flexibility tests. Each specimen was secured onto the robotic testing system via custom-designed spinal fixtures (Fig. 1). The robot was programmed using its custom software to apply loading and unloading cycles of pure moments in 3 orthogonal directions (maximum moment 1.5 Nm) to induce flexion-extension (FE), lateral bending (LB), and axial rotation (AR). A 6-axis, force-moment sensor (OnRobot) connected to the cranial fixture was used to measure the applied forces and provide feedback for the robot to ensure pure moments. To eliminate any viscoelastic effects, the specimens were loaded

3 times, and data were taken from the third loading cycle for each specimen.

Specimens were tested in the following configurations:

1. Intact specimen
2. Destabilized specimen: destabilization was achieved by creating a type II odontoid fracture model
3. Destabilized + C1 lateral mass (C1LM) and C2 pedicle screw (C2PS) fixation (Fig. 2A)
4. Destabilized + C1LM and C2 bicortical translaminal screw (C2TL) fixation (Fig. 2B)
5. Destabilized + C1LM and C2–3 transarticular screw (C2/3TA) fixation (Fig. 2C)
6. Destabilized + C1LM and C2/3TA fixation with transverse cross-link (C2/3TACL) (Fig. 2D)

Three-dimensional atlantoaxial motion was tracked stereophotogrammetrically using a high-speed and high-resolution camera system (VSTARS D5; Geodetic Systems) by measuring the 3D displacement of reflective markers rigidly inserted in each vertebra. The range of motion (ROM), defined as the angular deformation at the maximum load across C1 and C2, and the neutral zone (NZ), defined as the difference at zero loads between the angular positions in all directions of the loading and unloading phase, were evaluated.

Destabilization and Fixation Technique

Atlantoaxial instability was achieved by creating a type II odontoid fracture. Using a bone drill, the base of the dens was sectioned off without disrupting the lateral facet joints. After destabilization, 4 different atlantoaxial fixation methods were performed.

Instrumentation was performed using the Vertex Select posterior cervical reconstruction system (Medtronic). The placement of C1 lateral mass screws (diameter 3.5 mm; length 28–30 mm) and C2 pedicle screws (diameter 3.5 mm; length 26–28 mm) was performed unicortically as described by Harms and Melcher.¹⁰

For C2 translaminal screws, screw insertion was performed in a bicortical fashion using a modified method described by Wright.²⁴ A high-speed drill was used to open a small cortical window on either side of the junction of the C2 spinous process and lamina. Using a hand drill, the contralateral lamina was carefully drilled. The trajectory was kept more divergent than the downslope of the lamina. When the outer cortex of the lamina at the junction of the C2 facet and lamina was penetrated, a screw (diameter 3.5 mm; length 24–28 mm) was carefully inserted to achieve bicortical screw purchase (Fig. 3A).

Using the method as described by Zong et al., C2–3 transarticular screws were placed.²⁶ The screw entry point was located at the midpoint of the posterior wall of the C2 inferior articular process. The screw trajectory was drilled approximately 45° caudally and 10° laterally, perpendicular to the C2 inferior articular facet joint. When the anterior cortex of the C3 superior articular process was penetrated, a ball probe was used to palpate the length of the trajectory. Then a quadricortical screw (diameter 3.5 mm; length 12–16 mm) was inserted along the prearranged hole (Fig. 3B). A transverse cross-link device was used to further enhance the stiffness of the C1 lateral mass and C2–3 transarticular screw construct.

FIG. 1. Robotic spine testing system. Photograph of the AUBO industrial robot with a cervical specimen mounted. Figure is available in color online only.

Statistical Analysis

Statistical analysis was performed using the SPSS 22.0 software (IBM Corp.). All data are presented as mean ± SD. Comparisons of the ROM and NZ between various

groups were made using the repeated-measures ANOVA. After assessing the significance using the ANOVA, pair-wise comparisons with a Tukey’s post hoc test were performed. $p < 0.05$ was considered significant.

Results

The mean ROM and NZ values for all tested specimens in different loading modes, including FE, LB, and AR, are summarized in Table 1. The results of statistical comparisons of the ROM and NZ in different fixation groups are summarized in Table 2. After destabilization, the ROM and NZ in all 3 loading modes increased significantly compared with those of the intact specimens ($p < 0.01$). All instrumented conditions demonstrated significantly decreased ROM and NZ values in the 3 loading modes compared with those values for the destabilized specimens.

FE

During flexion and extension, there were no statistically significant differences in ROM and NZ between the C1LM-C2PS and C1LM-C2TL constructs ($p = 0.994$). For the C1LM-C2/3TA construct with or without a cross-link device, significantly decreased ROM and NZ were identified in comparison with the C1LM-C2PS or C1LM-C2TL constructs (all $p < 0.001$). The addition of a cross-link device to the C1LM-C2/3TA construct appeared to improve stability over fixation without a cross-link; however, the decrease in ROM and NZ did not reach statistical significance ($p = 0.518$; $p = 0.514$) (Figs. 4 and 5).

LB

For LB, no statistical differences in ROM or NZ were observed between any of the fixation techniques (all $p > 0.05$). Although no significant differences were found, cross-linked C1LM-C2/3TA fixation appeared to provide marginally improved stability over fixations without a cross-link, and C1LM-C2TL fixation seemed to be less resistant to LB than other constructs (Figs. 4 and 5).

FIG. 2. Posterior view of different atlantoaxial screw-rod constructs. **A:** The C1LM-C2PS construct. **B:** The C1LM-C2TL construct. **C:** The C1LM-C2/3TA construct. **D:** The C1LM-C2/3TAACL construct. Figure is available in color online only.

FIG. 3. A: Illustration of the C2TL construct. B: Illustration of the C1LM-C2/3TA construct. Figure is available in color online only.

AR

During axial rotation, the C1PS-C2TL construct showed the greatest stability, and the ROM and NZ were significantly decreased compared with other 3 constructs (all $p < 0.001$). The C1LM-C2/3TA construct showed stability inferior to that of the C1LM-C2PS construct, with significantly increased ROM and NZ ($p = 0.022$; $p = 0.015$). After placement of a cross-link on the C1LM-C2/3TA construct, however, axial stability increased, and there was a significant decrease in ROM and NZ ($p = 0.002$; $p < 0.001$). There were no statistically significant differences in ROM and NZ when the C1LM-C2/3TACL and C1LM-C2PS constructs were compared ($p = 0.867$; $p = 0.410$) (Figs. 4 and 5).

Discussion

Over the last few decades, atlantoaxial fixation has evolved from simple posterior wiring techniques to a multitude of rigid screw and rod fixation constructs, which provide effective immobilization while reducing the risk of neurovascular injury. Presently, C1LM-C2PS fixation, introduced by Goel and Laheri⁹ and subsequently popularized by Harms and Melcher,¹⁰ has been widely utilized for atlantoaxial stabilization. Although it provides superior rigidity with high fusion rates and avoids the risk of vertebral artery injury, this technique is not feasible in cases involving a narrow C2 pedicle and a high-riding or

medialized vertebral artery. It is therefore essential to consider alternatives to the Goel-Harms technique.

In 2004, Wright²⁴ introduced C2 translaminar screw fixation as an alternative method, which essentially avoids the risk of vertebral artery injury during placement. However, in biomechanical studies, it has been shown to confer inferior stability when compared with that of C2 pedicle screw fixation. Dmitriev et al.⁴ and Sim et al.²² have found that C2 translaminar screw constructs are significantly less resistant to LB than C2 pedicle screw constructs. Similarly, Claybrooks et al.,³ using a type II odontoid fracture model, found that C2 pedicle screw fixation outperformed C2 translaminar screw constructs in both LB and AR, with no significant difference in FE. The biomechanical differences can be explained by the fact that the screw may toggle within the cancellous lamina bone due to a lack of bicortical purchase.

Jea et al.¹⁵ modified C2 translaminar screws, using the “exit” window in the dorsal lamina cortex to achieve bicortical purchase. The inclination of the trajectory is not as acute as it is in Wright’s technique, which could minimize the risk of inner lamina breakthrough during screw placement. Moreover, it seems that bicortical translaminar screws could augment the stiffness, reduce the potential of early instrumentation failure, and be an ideal alternative for atlantoaxial fixation. However, relevant biomechanical studies are still limited. In a recent study, Liu et al.¹⁷ found that the C1LM-C2TL fixation is the biomechanical equivalent to C1LM-C2PS fixation and superior to C2 unicortical translaminar screw fixation. Similarly, satisfied biomechanical results were found in the present study with the use of C2 bicortical translaminar screws. During AR, the C1LM-C2TL construct provided significantly greater stabilization than the C1LM-C2PS construct. During FE and LB, there was no statistically difference between the 2 constructs, though greater ROM and NZ were seen in the C1LM-C2TL construct. These findings demonstrated that the bicortical translaminar screw with 2 anchor points could significantly reduce the toggle effect and increase stability. Moreover, C1LM-C2TL fixation could form a crossed screw-rod construct, resulting in a better horizontal compressive force than C1LM-C2PS fixation, which may account for the increased stability in AR.²

More recently, C2–3 transarticular screws penetrating the C2 and C3 articular process were used as salvage options for atlantoaxial stabilization. The trajectory of the

TABLE 1. Summary of ROM and NZ values for all tested groups under a 1.5-Nm load

Spinal Condition/Construct	FE		LB		AR	
	ROM (°)	NZ (°)	ROM (°)	NZ (°)	ROM (°)	NZ (°)
Intact	21.47 ± 2.76	10.80 ± 1.69	3.98 ± 2.76	1.64 ± 1.28	34.81 ± 3.77	20.58 ± 3.81
Destabilized	33.09 ± 2.21*	19.79 ± 1.98*	8.72 ± 1.59*	3.81 ± 1.01*	61.34 ± 1.97*	39.24 ± 1.63*
C2PS	1.88 ± 0.11	0.74 ± 0.04	1.14 ± 0.75	0.43 ± 0.28	2.73 ± 0.84	1.20 ± 0.37
C2TL	1.92 ± 0.33	0.87 ± 0.15	1.29 ± 0.51	0.47 ± 0.19	1.40 ± 0.33	0.53 ± 0.12
C2/3TA	0.74 ± 0.36	0.31 ± 0.15	1.15 ± 0.68	0.39 ± 0.24	3.27 ± 0.48	1.47 ± 0.21
C2/3TACL	0.52 ± 0.38	0.22 ± 0.14	1.08 ± 0.73	0.37 ± 0.24	2.58 ± 0.22	1.06 ± 0.42

Values are presented as the mean ± SD.

* Compared with intact condition ($p < 0.01$).

TABLE 2. Summary of p values from statistical comparisons of ROM and NZ in different fixation groups

Construct	FE		LB		AR	
	ROM	NZ	ROM	NZ	ROM	NZ
C2PS vs C2TL	0.994	0.228	0.926	0.968	<0.001	<0.001
C2PS vs C2/3TA	<0.001	<0.001	1.000	0.979	0.022	0.015
C2PS vs C2/3TACL	<0.001	<0.001	0.993	0.832	0.867	0.410
C2TL vs C2/3TA	<0.001	<0.001	0.938	0.829	<0.001	<0.001
C2TL vs C2/3TACL	<0.001	<0.001	0.811	0.564	<0.001	<0.001
C2/3TA vs C2/3TACL	0.518	0.514	0.990	0.969	0.002	<0.001

C2/3TA screws is in a mediolateral and craniocaudal direction, which could largely eliminate the risk of vertebral artery injury. Several studies have shown satisfied outcomes using C2/3TA screws as a salvage alternative when conventional pedicle screws were not available or feasible. Goel⁷ first elaborately demonstrated the technical nuances and long-term outcomes of C2/3TA fixation. In his study, C2/3TA fixation was done for C1–3 fixation in 12 patients. The follow-up duration ranged from 6 to 18 months and successful bone fusion was achieved in all cases with no implant failure, neurovascular injury, facet-related pain, or any other complications. Senturk et al.²¹ reported on one case of os odontoideum and atlantoaxial dislocation in a patient who was successfully treated with C1LM-C2/3TA fixation. Clinical studies from our institution have also showed good results. Yin et al.²⁵ reported 174 surgical cases with atlantoaxial dislocation and basilar invagination. Eight cases were successfully managed via C2/3TA fixation. Zong et al.²⁶ reported 19 patients treated with C1 lateral mass and C2–3 transarticular fixation that involved a cross-link device; all patients had solid bone fusion at the most recent follow-up, and no vertebral artery injury, neurological deficits, or facet-related pain occurred. Therefore, C2/3TA fixation is a simple, easy, and safe technique with promising clinical results, but the biomechanical properties of the C1LM-C2/3TA construct with or without a cross-link device still remain unknown.

In the present study, for the first time, we evaluated the biomechanical stability of the C1LM-C2/3TA constructs. C1LM-C2/3TA fixation was equivalent in LB and superior in FE to the C1LM-C2PS and C1LM-C2TL constructs. This is because the cortical nature of facet joints provided a firm and lasting grip for the screws. Therefore, the quadricortical C2/3TA fixation could achieve a rigid purchase, though the trajectory is short. During AR, C1LM-C2/3TA fixation failed to maintain segmental stability. A few factors can contribute to these results. The trajectory of C2/3TA screws is more vertical than other constructs. The construct can offer greater pullout strength in the vertical direction with a quadricortical purchase, but the torque in the horizontal direction is correspondingly decreased. Furthermore, quadrilateral shifting of the parallel rods also impairs the rotational stiffness. In previous studies, cross-link devices have been reported to improve rotational stability in screw-rod constructs,^{11,16} and the same biomechanical effect was found in our study. The rotational stability was significantly increased in the C1LM-C2/3TACL constructs compared with the C1LM-C2/3TA constructs. Although inferior to the C1LM-C2TL fixation, C1LM-C2/3TACL fixation showed equivalent rotational stability to the C1LM-C2PS construct.

However, compared with C1LM-C2PS or C1LM-C2TL fixation, there is still a concern for the C1LM-C2/3TACL construct that the C2–3 segment is involved and its motion

FIG. 4. Comparison of the ROM at C1–2 in different loading modes after fixation.

FIG. 5. Comparison of the NZ at C1–2 in different loading modes after fixation.

will be lost after fixation. Several kinematic studies evaluating the C2–3 segment's contribution to cervical motion have found that the movement was less than 5° at C2–3.^{1,13,14} Therefore, we believe that the safety benefits and good biomechanical stability of the C2/3TA construct outweigh the C2–3 immobilization. However, the additional C2–3 fixation may increase stress on the adjacent segment and lower cervical spine, and the impact has not been well investigated. Therefore, further study is needed to explore long-term effects of this additional C2–3 fixation and its stress on the adjacent level and subaxial cervical spine.

Since this was a cadaveric study, there are some limitations. First, the sample size was limited; however, we believe this should not restrict the interpretation of our results. Another limitation is that the contribution of the paraspinal muscle to segmental stability could not be measured, and therefore it is possible that differences could be offset by muscular loading. Furthermore, our study assessed only the immediate stability after fixation; additional fatigue studies need to be conducted in these constructs. We used unicortical screws in C1LM–C2PS constructs rather than bicortical screws, which is different from some of the previous studies but would not influence the biomechanical comparison among the groups. Despite these limitations, our study demonstrated that C1LM–C2TL and C1LM–C2/3TACL fixation resulted in satisfactory atlantoaxial stabilization compared with C1LM–C2PS fixation. Therefore, we believe that the C1LM–C2TL and C1LM–C2/3TACL fixation may serve as alternative procedures when other techniques are not suitable or feasible.

Conclusions

On the basis of our biomechanical study, C1LM–C2TL fixation demonstrated similar stability in FE and LB and greater stability in AR than C1LM–C2PS fixation. C1LM–C2/3TACL fixation demonstrated similar stability in LB and AR and greater stability in FE than C1LM–C2PS fixation. Therefore, the C1LM–C2TL and C1LM–C2/3TACL fixations may serve as suitable and safer alternatives in at-

lantoaxial stabilization when C1LM–C2PS fixation is not feasible due to anatomical constraints.

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Disclosures

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions

Conception and design: all authors. Acquisition of data: Du, Li, Ma, Yu. Analysis and interpretation of data: Du. Drafting the article: Du. Critically revising the article: Du. Reviewed submitted version of manuscript: Du. Statistical analysis: Du. Administrative/technical/material support: Yin, Du, Yu. Study supervision: Yin, Qiao, Yu.

Correspondence

Yi-Heng Yin: Chinese PLA General Hospital, Beijing, China. yihengyin@aliyun.com.