Novel posterior artificial atlanto-odontoid joint for atlantoaxial instability: a biomechanical study

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OBJECTIVE Atlantoaxial instability is usually corrected by anterior and/or posterior C1–2 fusion. However, fusion can lead to considerable loss of movement at the C1–2 level, which can adversely impact a patient’s quality of life. In this study, the authors investigated the stability and function of a novel posterior artificial atlanto-odontoid joint (NPAAJ) by using cadaveric cervical spines.

METHODS The Oc–C7 regions from 10 cadaveric spines were used for anteroposterior (AP) translation and range of motion (ROM) tests while intact and after destabilization, NPAAJ implantation, and double-rod fixation.

RESULTS The mean AP C1–2 translational distances in the intact, destabilization, and double-rod groups were 6.53 ± 1.07 mm, 11.54 ± 1.59 mm, and 3.24 ± 0.99 mm, respectively, and the AP translational distance in the NPAAJ group was significantly different from that in the intact group (p < 0.05). The AP translational distance in the NPAAJ group was not significantly different from that in the double-rod group (p = 0.24). The mean flexion, extension, and axial rotation ROM values of the NPAAJ group were 9.87° ± 0.91°, 8.75° ± 0.99°, and 61.93° ± 2.93°, respectively, and these were lower than the corresponding values in the intact group (p < 0.05). The mean lateral bending ROM in the NPAAJ group (9.26° ± 0.86°) was not significantly different from that in the intact group (p = 0.23), and the flexion, extension, and rotation ranges in the NPAAJ group were 79.5%, 85.2%, and 82.3%, respectively, of those in the intact group.

CONCLUSIONS Use of NPAAJ for correction of atlantoaxial instability disorders caused by congenital odontoid dysplasia, odontoid fracture nonunion, and C-1 transverse ligament disruption (IA, IB, and IIB) may restore the stability and preserve most of the ROM of C1–2. Additionally, the NPAAJ may prevent soft tissue from embedding within the joint. However, additional studies should be performed before the NPAAJ is used clinically.

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KEY WORDS artificial atlanto-odontoid joint; atlantoaxial instability; posterior approach; biomechanical; cervical
periments by using cadaveric cervical spines to compare the stability and function of the NPAAJ with those of the intact state and a rod fixation system.

**Methods**

**Design of the NPAAJ**

We randomly selected 60 cervical CT and 3D reconstruction images obtained in outpatients and hospitalized patients (30 men and 30 women, 18–60 years of age) from the Chongqing General Hospital database for inclusion in this investigation (examples shown in Fig. 1). Patients with a current or prior history of cervical trauma, cervical cancer, cervical infections, cervical deformities, or cervical surgery were excluded from the study. The C1–2 bone sizes and peripheral space sizes were measured by an imaging software program and were ultimately used to design the NPAAJ. All procedures performed were in accordance with the ethical standards of the institutional ethics committee and with the 1964 Helsinki declaration.

The NPAAJ was designed to stabilize the C1–2 joint and preserve all of its characteristic movements. The NPAAJ consisted of an atlas component, an axis component, an outer-sleeve component, and 4 cervical polyaxial pedicle screws (diameter 3.6 mm, length 22.0 mm) (Fig. 2). The metal structures were composed of titanium alloy materials, and the outer-sleeve component was composed of nontoxic silicone materials. The atlas component included an arc-shaped track groove (inner diameter 4.3 mm, outer diameter 11.0 mm, longitudinal depth 8.5 mm, radians $72^\circ$, arc length 52.8 mm) and an arc-shaped connecting rod (diameter 3.3 mm). The axis component contained an ellipsoidal rolling body (long axis 6.0 mm, short axis 4.0 mm) and a V-shaped connecting rod (diameter 3.3 mm). The outer-sleeve component (inner diameter 11.0 mm, outer diameter 13.5 mm, radians $72^\circ$, arc length 52.8 mm)

**FIG. 1.** Cervical CT and 3D reconstruction images obtained in patients with AAI showing lines (L1–L5) and angles (a–c) characteristic of the C1–2 vertebrae. **A:** The vertical distance from the superior margin of the posterior tubercle of the atlas to the superior margin of the axis lamina (L1). **B:** The horizontal distance from the posterior margin of the posterior tubercle of the atlas to the posterior margin of the axis lamina (L2) and the angle between L3 and the perpendicular bisector of L2 (angle a). **C:** The distance from the intersection of the L2 bisector and the upper edge of the lamina to the entry point of the axis pedicle screw (L3) and the angle between the 2 sides of L3 (angle b). **D:** The distance from the center of the odontoid process to the entry point of the atlas pedicle screw (L4). The distance from the center of the odontoid process to the posterior margin of the posterior tubercle of the atlas (L5) and the angle between the 2 sides of L4 (angle c). Figure is available in color online only.
consisted of an arc-shaped hollow tube with an opening in the sidewall and with an arc-shaped track groove. The ellipsoidal rolling body could be inserted into the arc-shaped track groove through the open end and held in place with 2 small screws and 1 shell. A track groove with external arc-shaped and internal U-shaped structures facilitated free movement of the ellipsoidal rolling body in the arc-shaped track groove and enabled flexion-extension, lateral bending, and axial rotation of the C1–2 joint. The inner diameter (4 mm) of the arc-shaped track groove was longer than the length (2.8 mm) of the lower edge of the U-type opening; thus, the groove prevented the rolling body from falling off its lower end. Moreover, when the connecting rod of the rolling body was freely sliding along the sidewall of the outer-sleeve component, the closed state of the opening in the sidewall prevented soft tissues from embedding within the arc-shaped track groove. Finally, the NPAAJ was fixed on the rear of the atlas and axis by using a rod that connected the atlas and axis components and 4 cervical polyaxial pedicle screws.

Cadaveric Specimens

After the protocol was approved by the appropriate institutional review board, we selected 10 fresh-frozen cadaveric cervical spines (C0–7) with a mean donor age of 67 years for the biomechanical study. Specimens exhibiting signs of soft-tissue injury or bone abnormalities were excluded by gross observation and radiographic examination. The specimens were wrapped in saline-soaked gauze and double plastic bags and then stored at –20°C. After thawing the specimens at room temperature (20°C–25°C) for 8–12 hours, we prepared them by dissecting the surrounding tissue and muscle while carefully preserving the cervical discs, ligaments, and joint capsules. The C-0 and C-7 vertebrae of each specimen were subsequently embedded in a metal mold containing polymethylmethacrylate. We sprayed the specimens with normal saline to keep them moist throughout the entire experiment.

Biomechanical Experiments

The Anteroposterior Translation Test

The cervical specimens were placed in a material testing machine (ELF-3510AT; Bose, Inc.) (Fig. 3), and a 50 N preload was placed along the anterior and posterior directions of each specimen. Based on a previous experimental study design,21 we performed 3 separate load tests, in which each specimen was placed under an anteroposterior (AP) load of ± 100 N at a speed of 0.25 mm/second, and measured the C1–2 AP translational distance. The third measurement was used for analysis.

The ROM Test

After testing the AP translational distance, we tested the ROM of the cervical specimens with an MTS 858 Mini Bionix II Test System (MTS Systems Corp.). The specimens were loaded using a testing system comprising cables and pulleys that applied pure moments and induced the flexion-extension, lateral bending, and axial rotation of C1–2.25 Each moment was applied in 3 load-unload cycles to achieve a maximum torque of 1.5 Nm at a rate of 0.1 Nm/second.14 The torque of 1.5 Nm was held constant for 10 seconds to stabilize the mechanical response. In this case, the occipital-cervical specimens could undergo the maximum amount of physiological movement without suffering any damage. Each specimen was loaded 3 times to minimize the viscoelastic effect. After each load-unload cycle, the specimen was held stable for 30 seconds to allow creep movement of the cervical spine, and stable experimental results were obtained. The data from the third cycle were recorded with a computer. A 3D spine motion measurement system (co.6Eagle system; Motion Analysis) was used to process the resulting images to identify, locate, and calculate markers of positions of the C-1 and C-2 vertebrae in space and to reconstruct the 3D motion of the spinal segments.

Each cervical specimen was tested under the following conditions: 1) while intact (the structural integrity of the cervical spine, which was without wounds or abnormalities, was intact); 2) after destabilization (the cervical transverse ligament, anterior longitudinal ligament, alar ligament, apical dental ligament, and odontoid process were cut off); 3) after NPAAJ implantation (destabilization...
TABLE 1. Measurements of the bone and peripheral space sizes of C1–2 vertebrae in 60 patients with AAIs

<table>
<thead>
<tr>
<th>Variable</th>
<th>Measured Values</th>
<th>Mean ± SD</th>
</tr>
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<tbody>
<tr>
<td>Line 1</td>
<td>8.62–17.47 mm</td>
<td>14.59 ± 2.26 mm</td>
</tr>
<tr>
<td>Line 2</td>
<td>5.13–13.82 mm</td>
<td>9.53 ± 1.92 mm</td>
</tr>
<tr>
<td>Line 3</td>
<td>21.53–27.57 mm</td>
<td>24.52 ± 1.67 mm</td>
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<tr>
<td>Line 4</td>
<td>25.14–35.25 mm</td>
<td>29.17 ± 1.97 mm</td>
</tr>
<tr>
<td>Line 5</td>
<td>26.23–41.78 mm</td>
<td>31.91 ± 2.63 mm</td>
</tr>
<tr>
<td>Angle a</td>
<td>95.17–117.28°</td>
<td>108.67 ± 3.63°</td>
</tr>
<tr>
<td>Angle b</td>
<td>78.12–102.37°</td>
<td>87.87 ± 4.88°</td>
</tr>
<tr>
<td>Angle c</td>
<td>69.23–97.56°</td>
<td>84.62 ± 5.93°</td>
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* See Fig. 1 for illustrations and descriptions of lines and angles.

with NPAAJ implantation; and 4) after double-rod fixation (destabilization with screw rod implantation—screw diameter 3.6 mm, screw length 22 mm, rod diameter 3.3 mm, rod length 40 mm).

Statistical Analysis

The results are presented as the mean ± SD. Statistical analysis was performed with 1-way ANOVA for independent samples, followed by Fisher’s protected least significant difference test for multiple comparisons. Statistically significant differences were defined at the 95% confidence level. Analyses were performed with SPSS Statistics for Windows, version 17.0 (SPSS Inc.).

Results

Table 1 shows the data for the lines (L1–L5) and angles (a–c) characteristic of the C1–2 vertebrae for 60 cervical CT and 3D reconstruction images. The mean AP C1–2 translational distances in the intact, destabilization, and double-rod groups were 6.53 ± 1.07 mm, 11.54 ± 1.59 mm, and 3.24 ± 0.99 mm, respectively (Table 2). The AP translational distance in the NPAAJ group (3.75 ± 0.87 mm) was significantly different from that in the intact group (6.53 ± 1.07 mm) (p < 0.05). However, the AP translational distance in the NPAAJ group (3.75 ± 0.87 mm) was not significantly different from that in the double-rod group (3.24 ± 0.99 mm) (p = 0.24), but was significantly different from the distance in the destabilization group (11.54 ± 1.59 mm) (p < 0.05).

Table 3 and Figs. 4 and 5 show the ROMs of the specimens while intact and after destabilization, double-rod fixation, and NPAAJ implantation. Motion was elicited by a maximum applied moment of 1.5 Nm. The mean ROM in the intact group was 12.42° ± 1.96° in flexion, 10.27° ± 1.20° in extension, 9.82° ± 1.17° in lateral bending, and 75.17° ± 4.76° in axial rotation, and the ROM in the destabilization group was significantly increased in all directions compared with that in the intact group (p < 0.05). However, the ROM in the double-rod group was significantly decreased in all directions compared with that in the destabilization group (p < 0.05). The ROM in the NPAAJ group was significantly increased in all directions compared with that in the double-rod group (p < 0.05). However, the mean flexion, extension, and axial rotation ranges in the NPAAJ group were 9.87° ± 0.91°, 8.75° ± 0.99°, and 61.93° ± 2.93°, respectively, and were lower than the corresponding values in the intact group (p < 0.05). The flexion, extension, and rotation ranges in the NPAAJ group were 79.5%, 85.2%, and 82.3%, respectively, of those in the intact group. However, the mean lateral bending ROM in the NPAAJ group (9.26° ± 0.86°) was not significantly different from that in the intact group (p = 0.23).

Discussion

The C1–2 joint, which constitutes the occipitocervical transitional region, is an essential structure. Currently, the common causes of AAI include trauma, congenital malformations, rheumatoid arthritis, and tumors. Only a small portion of affected patients can be treated with nonsurgical methods, and surgical intervention is usually necessary in cases in which AAI poses a risk of spinal cord injury. The purpose of surgery is to relieve nerve compression and restore the stability of the C1–2 joint. However, surgical decompression can aggravate AAI, which is commonly treated with standard posterior wires, transarticular C1–2 screws, C-1 lateral mass screws, and plate internal fixation. All of these operations can improve the stability of C1–2; however, C1–2 fusion may result in loss of ROM in all directions and adversely impact patient quality of life.

Researchers have recently developed several devices and techniques intended to restore C1–2 stability while simultaneously preserving C1–2 movement in all directions. Some of these studies have focused on artificial atlanto-odontoid joints. For example, Hu et al. and Lu et al. designed 2 types of artificial atlanto-odontoid joints that restored C1–2 stability and preserved C1–2 rotation function but did not preserve flexion, extension, and lateral bending function. Moreover, Cai et al. developed a new type of artificial atlanto-odontoid joint for which the ball-in-trough articulation enables it to preserve motion in all directions. However, placing these 3 types of artificial atlanto-odontoid joints requires resecting the odontoid process via a transoral approach, which could lead to serious perioperative complications such as infection, vertebral artery injury, CSF leaks, and velopharyngeal incompetence. The posterior C1–2 approach provides surgeons with a larger operative field of view without putting important nerves.
and blood vessels at risk. Kato et al.12 designed a novel motion preservation device that preserves 50% of the motion at C1–2; however, the extremely large size of the device caused several problems. Chen et al.5 designed a posterior C1–2 restricted nonfusion fixation device that retains C1–2 rotation and lateral flexion motion but cannot preserve flexion-extension. Gradual improvements in anterior and posterior artificial joints have largely facilitated the preservation of ROM in the C1–2 joint in all directions. Nevertheless, all of these options involve the use of open joints, which will probably result in soft tissues embedding in the joint, causing functional joint failure.

To overcome the shortcomings of the previous implants, we designed the NPAAJ and performed biomechanical experiments to test its function. The NPAAJ can be fixed to the posterior aspect of C1–2 via screws after C1–2 joint reduction. In cases in which the intraoperative reduction is suboptimal, the NPAAJ may be fixed in the wrong position, resulting in functional joint failure and increased spinal cord compression. We used the unicortical C-1 pedicle screw fixation technique to place the C-1 screw at its corresponding screw point for the following 4 reasons. First, the pullout strength of a C-1 pedicle screw is greater than that of a C-1 lateral mass screw.1,17,26 Second, the C-1 lateral mass screw fixation technique is associated with a high risk of venous sinus and C-2 nerve root injury.17,22 Third, C-1 pedicle screw fixation avoids causing internal carotid artery damage and hypoglossal nerve injury. Last, the C-1 pedicle screw point is higher than the C-1 lateral mass screw point, and placing the NPAAJ along the posterior aspect of the C-1 posterior arch is easier than placing it at another position. We chose the unicortical C-2 pedicle screw fixation technique (the drill was directed 20°–30° medially and in a cephalad trajectory along the C-2 pedicle) to place the C-2 screw at its corresponding screw point. This technique is generally considered an ideal method for fixing the C-2 screw during C1–2 fusion procedures because of its excellent pullout strength.2 In addition, the axis component of the NPAAJ is placed in C-2 with cervical screws based on the technique of the C-2 pedicle screw instrumentation. The entry point of the C-2 pars screw is different from that of C-2 pedicle screw. Therefore, fixing the axis component with a C-2 pars screw may lead to unsatisfactory binding of the atlas and axis components (leading to a failed surgery). Considering the aforementioned points, the C-2 pedicle screw is the preferred choice as opposed to C-2 pars screws.

After NPAAJ implantation, the ellipsoidal rolling body of the NPAAJ can move freely in the arc-shaped track groove to support the ROM of the C1–2 in all directions.
The longitudinal depth of the arc-shaped track groove (8.5 mm) is longer than the short axis of the ellipsoidal rolling body (4.0 mm). Therefore, the ellipsoidal rolling body can move up and down in the arc-shaped track groove to facilitate flexion-extension movements at C-1. The NPAAJ ROM test showed that there was a significant difference in the extent of flexion and extension between the NPAAJ group and the intact group (p < 0.05), but the flexion and extension ranges of the NPAAJ group were 79.5% and 85.2%, respectively, of those in the intact group.

The ellipsoidal rolling body can swing up and down in the arc-shaped track groove to facilitate lateral bending movements at C-1. The ROM test results showed that the difference in the range of lateral bending motion between the NPAAJ and the intact groups was not statistically significant (p > 0.05). The ellipsoidal rolling body can move left and right in the arc-shaped track groove to facilitate axial rotation movements at C-1. We noted a significant difference (p < 0.05) between the NPAAJ group and destabilization groups with respect to axial rotation range, as well as a significant difference between the NPAAJ and intact groups with respect to the same parameter (p < 0.05). The axial rotation range in the NPAAJ group was 82.3% of that in the intact group. We attributed this result to the insufficient length of the arc-shaped track groove. However, a longer arc-shaped track groove would have occupied more space and blocked the access points at which the double-sided screws were placed.

Due to the compression of the spinal cord, mainly from the front and rear, the anterior and posterior stability of the C1–2 joint is very important for the decompression of the spinal cord. In our study, the AP translation test results were not significantly different between the NPAAJ and the double-rod groups (p = 0.24). It is noteworthy that the mean AP translational distance in the NPAAJ group (3.75 ± 0.87 mm) was significantly different from that in the intact group (6.53 ± 1.07 mm) (p < 0.05). However, this does not prevent the movement of the NPAAJ in all directions.

To avoid soft-tissue incarceration, we designed a unique outer-sleeve component. The ellipsoidal rolling element connecting rod can slide freely within the sidewall, and the opening of the outer cover could prevent the soft tissues from embedding into the curved track groove (Fig. 6).

In our study, to simulate AAI, we cut off the cervical transverse ligament, anterior longitudinal ligament, alar ligament, apical dental ligament, and odontoid process. We think that the NPAAJ may be useful for treating AAI.
disorders caused by congenital odontoid dysplasia, odontoid fracture nonunion, and C-1 transverse ligament disruption (IA, IB, and IIB). Moreover, the NPAAJ is based on the technique of C1–2 pedicle screw instrumentation, so it is not suitable for patients with osteoporosis, atlas and/or axis bone structure abnormalities, peripheral vascular and/or nerve abnormalities, or mental disorders. Because the NPAAJ requires a normal lateral C1–2 joint to achieve motor function, we think that it is not suitable for lateral C1–2 joint disorders, such as rheumatoid arthritis, tumor, or fracture of the lateral C1–2 joint. In addition, patients can also easily undergo revision or fusion surgery by using previous C1–2 pedicle screws if the joint fails. Problems of pedicle screw implantation surgery, such as screw–bone interface loosening, may also occur in our surgery. Screw loosening of C-1 could be revised with surgery performed using posterior arch screws for instrumentation and C1–2 fusion. If screw loosening occurs at C-2, revision surgery of the C-2 lamina screw implantation and C1–2 fusion could be applied. Moreover, another option for revision surgery is anterior fusion and internal fixation with plate and screws.

The limitations of this study must be acknowledged. The NPAAJ is still in the preclinical phase of testing. The cadaver model results may signify only the short-term in vitro effects of NPAAJ implantation. The long-term in vivo results of NPAAJ implantation remain unknown. Titanium alloy is a safe material for implantation. However, we think that it is possible that after wear and tear, metal particles may lead to inflammation, and this response cannot be observed in the cadaver experiment. The effects of implantation should be verified with in vivo animal experiments. In future studies, we also intend to increase the ROM of the C1–2 with respect to flexion, extension, and rotation, and to improve the articular surfaces of the NPAAJ such that they are more wear resistant. It is also worth noting that the NPAAJ is prone to fatigue fracture at the connecting rod of the ellipsoidal rolling body; thus, the NPAAJ should be modified to enhance its antifatigue properties, and additional studies should be performed before it is used clinically.

Conclusions

The NPAAJ can be used to correct AAI disorders caused by congenital odontoid dysplasia, odontoid fracture nonunion, and C-1 transverse ligament disruption (IA, IB, and IIB) by using a posterior approach. The NPAAJ may restore C1–2 stability, and it preserves most C1–2 movements. In addition, the NPAAJ may also prevent soft tissue from embedding in the joint. However, additional studies should be performed before the NPAAJ is used clinically.

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References


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

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