Biomechanical comparison of anterior and posterior stabilization methods in atlantoaxial instability

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Object. The authors compared the biomechanical stability of two anterior fixation procedures—anterior C1–2 Harms plate/screw (AHPS) fixation and the anterior C1–2 transarticular screw (ATS) fixation; and two posterior fixation procedures—the posterior C-1 lateral mass combined with C-2 pedicle screw/rod (PLM/APSR) fixation and the posterior C1–2 transarticular screw (PTS) fixation after destabilization.

Methods. Sixteen human cervical spine specimens (Oc–C3) were tested in three-dimensional flexion–extension, axial rotation, and lateral bending motions after destabilization by using an atlantoaxial C1–2 instability model. In each loading mode, moments were applied to a maximum of 1.5 Nm, and the range of motion (ROM), neutral zone (NZ), and elastic zone (EZ) were determined and values compared using the intact spine, the destabilized spine, and the postfixation spine.

The AHPS method produced inferior biomechanical results in flexion–extension and lateral bending modes compared with the intact spine. The lateral bending NZ and ROM for this method differed significantly from the other three fixation techniques (p < 0.05), although statistically significant differences were not obtained for all other values of ROM and NZ for the other three procedures. The remaining three methods restored biomechanical stability and improved it over that of the intact spine.

Conclusions. The PLM/APSR fixation method was found to have the highest biomechanical stiffness followed by PTS, ATS, and AHPS fixation. The PLM/APSR fixation and AATS methods can be considered good procedures for stabilizing the atlantoaxial joints, although specific fixation methods are determined by the proper clinical and radiological characteristics in each patient.

KEY WORDS • atlantoaxial instability • biomechanical testing • transarticular screw fixation • cervical spine • spinal fusion

ANY disorders can cause atlantoaxial instability, such as fractures, malignancy, rheumatoid arthritis, congenital anomalies, or infectious diseases. Atlantoaxial instability disrupts bones and ligaments and causes local pain, limitation of ROM, C-2 rhizopathy, or myelopathy. The goals of surgical management in cases of atlantoaxial instability are to provide neural decompression, restoration of occipitocervical spinal alignment, and stabilization of unstable segments to allow for successful osseous fusion.

Since Gallie introduced the posterior wiring technique in 1939, various posterior fixation methods for C1–2 stabilization have been reported. In 1979, Margel and Seeman introduced bilateral PATS fixation that, in combination with C1–2 posterior wiring, provides a three-point fixation and resulted in a high fusion rate. Currently, this technique is considered the gold standard for C1–2 posterior fusion for atlantoaxial instability. The PTS method, however, is technically demanding because of the risk of VA injury. It also poses a problem of accessibility in patients with pronounced thoracic kyphosis, in that the screw must be inserted at such an angle that it intersects with adjacent vertebrae. In 2001, Harms and Melcher introduced the PLM/APSR fixation technique. After screw fixation to the C-1 lateral mass and C-2 pedicle, the screws are fixed by attaching bilateral rods. Although the risk of vascular or neural injury during C-2 pedicle screw fixation remains, it has been found to be safe and advantageous because the degree of thoracic kyphosis does not affect the fixation.

The ATS method via the prevascular retropharyngeal approach has been reported to be an effective alternate for stabilization of the atlantoaxial joint and osseous fusion. The advantage of this approach is that it provides single-stage odontoid decompression and stabilization.
while avoiding posterior surgery. It also permits release of locked C1–2 joints and decortication of the articular cartilages at the atlantoaxial joints to enable fusion. One possible disadvantage is that the anterior device may not provide as much stability as would posterior instrumentation; however, no studies have been conducted to assess the biomechanical characteristics of the ATS method relative to other atlantoaxial fixation methods. Various anterior atlantoaxial plate fixators have been developed and used clinically after transoral odontoid resection. Nevertheless, there have been very few biomechanical studies conducted to evaluate this procedure.

The purpose of this study was to compare two anterior and two posterior atlantoaxial transarticular screw fixation (AHPS, ATS, PLM/APSR, and PTS) methods for restoring biomechanical stability after atlantoaxial destabilization in cadaveric human spines.

Materials and Methods

Cadaveric Specimen Preparation and Fixation

Sixteen human cadaveric cervical spines with the occiput attached (Oc–C4) were obtained from Science Care Anatomical (Phoenix, AZ). The mean age of the eight men and eight women was 65.1 ± 13.2 years (range 38–94 years) at the time of death. Anteroposterior and lateral radiographs were acquired to exclude oseous abnormalities, and BMD measurements were also obtained using dual-energy x-ray absorptiometry (Hologic QDR 4500A; Hologic, Inc., Waltham, MA). The mean BMD (± SD) of the atlantoaxial area was 0.72 ± 0.09 g/cm² (range 0.56–0.84 g/cm²). The mean BMD values (± SD) of the ATS, PTS, AHPS, and PLM/APSR groups were 0.71 ± 0.12, 0.72 ± 0.05, 0.72 ± 0.13, and 0.71 ± 0.09 g/cm², respectively. There were no significant differences among groups with regard to age, sex, or BMD. En bloc specimens for biomechanical testing were stored at −20°C, were thawed at room temperature overnight, and were kept moist during all procedures. The attached musculature was removed, with care taken to preserve the joint capsules, ligaments, discs, and oseous structures. After completion of the specimen preparation, several screws were drilled into C-4 and the occiput and movement between C-3 and C-4 was eliminated by screwing through both levels. The occiput and C-4 were primarily potted in PMMA (COE Tray Plastic; GC America, Alsip, IL) and then the PMMA was secondarily potted into the polyester resin (Bondo; Atlanta, GA). During PMMA and polyester curing, the midsagittal plane of the C3–4 disc was kept in a horizontal orientation with the anterior surface of the C-3 VB in the normal lordotic 15 to 20° anterior inclination. The potting fixtures for the occiput and C3–4 were attached to the upper and lower spine fixtures, respectively, of the loading frame (858 Minibionix; MTS, Eden Prairie, MN). In this fixation, the motions between Oc–C1, C1–2, and C2–3 were preserved.

Biomechanical Testing and Protocol

The Oc–C3 specimen was loaded nondestructively and three-dimensional segmental motion was measured using the MTS machine (Fig. 1). Six modes of loading (right/left axial rotation, right/left lateral bending, and flexion and extension) were applied to the Oc–C3 junction. In each loading mode, moments were applied from 0 Nm to a maximum of 1.5 Nm with a loading rate of 0.05 Nm/second. In the loading modes of flexion–extension and right/left lateral bending, relative intervertebral rotations (C1–2) were determined using extensometers, and those of Oc–C3 were determined using the rotatory sensor of the MTS. In the loading mode of rotation, it is assumed that most of the relative Oc–C3 rotation occurs at C1–2, and, as such, extensometers were not used. Thus, relative Oc–C3 axial rotation can be approximated by this axial rotation between C-1 and C-2. After each step, the torque was held constant for 10 seconds to let the viscoelastic effect stabilize.

To stabilize the mechanical response, the loading steps were repeated three times, and only the data from the third loading was taken. Range of motion, NZ, and EZ values were then determined. Range of motion was defined as the angular deformation in all directions at maximum load, NZ as the difference at zero load between the angular positions in all directions of the loading and unloading phases, and EZ as ROM minus NZ. Intact specimens were tested initially, and then the four aforementioned fixation methods were tested after destabilization by using a known C1–2 instability model (Fig. 2). All loadings were performed three times in the following sequence: 1) intact control group (16 specimens); 2) destabilized group after odontoidectomy and detachment of the C1–2 isthmus (16 specimens); 3) the ATS group (four specimens); 4) the PTS group (four specimens); 5) the AH group (four specimens); and 6) the PLM/APSR group (four specimens). In each mode of loading, NZ, EZ, and ROM values were compared among methods and were analyzed relative to the intact spine and the destabilized spine.

Instability Model and Fixation Techniques

Atlantoaxial instability was created using the method described by Kandziora, et al. For an odontoidectomy, the atlantal anterior tubercle was marked, and two vertical osteotomies of the anterior neural arch, each 5 mm lateral to the tubercle, were made. The bone block was removed and the odontoid was exposed. The apical part of the odontoid was removed using a high-speed drill. Additionally, the transverse ligament, tectorial membrane, and C1–2 joint capsules were resected.

Four different reconstruction methods of the atlantoaxial complex were performed under fluoroscopic guidance. Anterior transarticular screw fixation was conducted as follows: a single 4-mm-diameter screw was placed in each facet via an anterior approach through the anterior surface of the C-2 VB. The entry point was 4 mm above the inferior edge of the lateral border of the C-2 VB, and the ideal trajectory ranged from 5 to 20° of lateral angulation relative to the sagittal plane and 10 to 25° of posterior angulation relative to the coronal plane. Cortical self-tapping 25- to 30-mm cancellous screws (Aesculap, San Francisco, CA) were used (Fig. 2A).

For the posterior transarticular screw approach, after drilling into the posterior C-2 cortex 2 to 3 mm above the C-2 inferior facet joint and 3 mm lateral to the medial border of the C2–3 facet, a posterior or 4-mm-diameter transarticular screw was placed through the C-2 pedicle, the C1–2 facet, and into each atlantal lateral mass. Screws were placed toward the posterior cortex of the anterior C-1 arch to 10° medially, relative to the sagittal plane in the posteroanterior direction, and 4-mm cortical screws were used (Fig. 2B); this procedure was performed while using lateral radiography.

For the AHPS procedure involving the Harms system (DePuy AcroMed, Cleveland, OH), 30-mm-wide titanium transoral plates and 4-mm-diameter screws were used. Atlantal screws were inserted in a cranialolateral direction starting at the lateral aspect of the atlantal plate. Three axial screws were inserted in the midline. After the screw length was measured using fluoroscopic monitoring, 4-mm cortical screws were inserted bicortically (Fig. 2C).

The PLM/APSR fixation technique was performed using the SUMMIT fixation system (DePuy AcroMed) with polyaxial 3.5-mm-diameter screws. The entry point for C-1 lateral mass screw was located in the middle of confluence of the posterior arch and C-1 inferior lateral masses. They were inserted bilaterally into the C-1 lateral masses. The trajectory of the C-1 screw was straight or slightly convergent in a posteroanterior direction, with the tip of the drill directed toward the anterior arch of C-1, parallel to the plane of the C-1 posterior arch in the sagittal direction. Polyaxial 3.5-mm screws were inserted bicortically at the C-1 lateral mass. The entry point of the C-2 pedicle screw was in the cranial and medial quadrant of the C-2 isthmus surface. Polyaxial screws 3.5 mm in diameter were inserted unicortically, 20 to 30° in a convergent and cephalad direction, guided by the superior and medial surface of the C-2 isthmus. The atlantal and axial screws and 3-mm-diameter rods were then connected (Fig. 2D).
Comparing stabilization methods in atlantoaxial instability

Statistical Analysis

The comparison of ROM and NZ for the Oc–C3 and C1–2 motions for the different fixation methods was performed using a multiple comparisons analysis of variance test. The level of significant difference was defined as a probability value equal to 0.05, and values are presented as the mean ± SD.

Results

Range of Motion, NZ, and EZ Values

The range denotes one SD among all specimens for the ROM, NZ, and EZ of the different loading modes. In the cases of flexion–extension and right/left lateral bending, the atlantoaxial ROM, NZ, and EZ values were determined by the extensometer placed across C-1 and C-2 (Table 1).

After destabilizations of both the C1–2 and Oc–C3 motion segments, there were significantly increased ROM values for all test modes in the destabilized group compared with the baseline ROM values in the intact spine group (p < 0.05). Marked increments in NZ values without changes in those of EZ during flexion–extension and right/left axial rotation were reflected as increased ROM measurements in the destabilized group for both the C1–2 and Oc–C3 motion segments (p < 0.05). During lateral bending, the increments in the values of ROM showed some changes in both values of NZ and EZ (p < 0.05).

Compared with measurements obtained in the destabilized group, each fixation method significantly decreased the ROM values in all test modes except for lateral bending in the AHPS specimens for the C1–2 and Oc–C3 motion segments (p < 0.05). In the other three groups of specimens, there were significant decreases in the ROM and NZ values (p < 0.05). In the AHPS group, however, there were no significant reductions in the ROM and NZ values during lateral bending of either the Oc–C3 or C1–2 motion segments.

To compare the effectiveness of stabilization when using different fixation methods, the ROM and NZ values of the destabilized and instrumented Oc–C3 motions were also normalized with those of the intact specimens—that is, the ROM and NZ values were each divided by the intact spine values (Figs. 3 and 4). The normalized ROM and NZ data obtained during atlantoaxial motions were compared with those of the intact specimens. For both the C1–2 and Oc–C3 motions, it was determined that the lateral bending NZ for the AHPS method was significantly different from those associated with the other fixation methods (p < 0.05). The lateral bending ROM for the AHPS-related C1–2 motions was also significantly different from those for the ATS and PLM/APSR methods (p < 0.05). Otherwise, there were no intergroup statistical differences found for any values of ROM and NZ (Table 1).

Unlike AHPS fixation, the other three techniques restored the biomechanical stability to close to or better than that of the intact specimens. There were no statistically significant differences among the other three fixation methods. Although not statistically significant, the PLM/APSR was associated with greater decreases in the values of ROM, NZ, and EZ in the axial rotational mode than the ATS and PTS methods for both C1–2 and Oc–C3 segments.

Discussion

Several fixation techniques have been reported to produce atlantoaxial stability after odontoidectomy and resection of bilateral C1–2 joint capsules. The bilateral PTS method has been demonstrated to result in a higher fusion rate than the traditional posterior wiring.
techniques such as the Brooks- and Gallie-type methods. \textsuperscript{3,5,6,12} In a biomechanical in vitro study, PTS fixation was shown to be efficacious in limiting the motion of the atlantoaxial segment after transoral odontoidectomy. In other biomechanical studies, wiring techniques have been associated with significant graft displacement and wire loosening under fatigue conditions. \textsuperscript{4} The PTS procedure was also found to provide greater resistance to translational and rotational forces than the atlantoaxial wiring methods. \textsuperscript{5,11,12} Although PTS fixation has been found to be a superior technique, it has not yet completely replaced the atlantoaxial wiring procedures because of several limitations such as the following. 1) For safe and accurate insertion of transarticular screws bilaterally, accurate reduction of C1–2 subluxation is required. \textsuperscript{5} 2) The procedure is technically demanding. 3) The risk of VA injury is significant (2.2% per screw). \textsuperscript{21,30} 4) The presence of an anomalous VA prevents a safe insertion of transarticular screws in 15 to 20% of the population. \textsuperscript{1,5,12} 5) Access to the C-2 insertion point in patients with pronounced thoracic kyphosis can be difficult and may require a wide operative exposure. \textsuperscript{23}

The posterior approach also requires repositioning of the patient after an anterior decompressive procedure while he or she is in a most unstable condition. Repositioning at this time is potentially deleterious to the spinal cord. If anterior decompression and stabilization procedures were necessary, as in cases involving synovial pannus formation around the odontoid, basilar artery invagination, and irreducible atlantoaxial disease, ATS or AHPS fixation would be relatively satisfactory procedures that avoid the aforementioned risks. The AHPS method was originally used after transoral odontoid resection. \textsuperscript{14} According to our biomechanical analyses, however, this method alone does not provide adequate stability for a successful atlantoaxial fusion. It was found that the lateral bending NZ and ROM values associated with AAHPS-treated specimens were significantly higher than for the other three methods in terms of both the Oc–C3 and C1–2 motion segments. The AHPS method could not restore the biomechanical stability of flexion–extension and lateral bending to the level of the intact spine. It has also been reported clinically that AHPS fixation was associated with a high rate of screw loosening. \textsuperscript{16} Additional posterior fusion procedures such as the Brooks, or Gallie-type, or the interspinous methods would be required to induce effective bone fusion and additional fixation for stability.

The ATS fixation is an effective means of stabilizing the atlantoaxial joint in patients in whom anterior decompression or odontoidectomy is mandatory. \textsuperscript{20} This has been an uncommon procedure for C1–2 instability and has been conducted when posterior C1–2 fixation is not possible. It is performed via the anterior prevascular retropharyngeal approach, \textsuperscript{19} in which the high cervical vertebrae are widely exposed and internal fixation can be facilitated. The ATS procedure is also a technically demanding procedure and requires intact atlantoaxial lateral masses for fixation. It allows direct visualization of the atlantoaxial joints, confirmation of C1–2 alignment, removal of joint cartilage, and direct cancellous iliac bone graft insertion for fusion of the atlantoaxial joint. The ATS technique has been reported to be suitable for Type II odontoid fracture nonunion, irreducible atlantoaxial dislocation, odontoidectomy, or C-1 anterior arch and C-2 VB tumors. \textsuperscript{20} In our study we showed that this fixation method resulted in lower ROM and NZ values than those obtained in the intact spine group for all six modes of motion and that similar results were comparable to the PTS or PLM/APSR methods. This ATS method provides a safer and more effective atlantoaxial fixation than the APHS method. Thus, if anterior decompression and stabilization procedures are necessary, the latter procedure can be considered from biomechanical, positional, and surgical points of view more favorably than the other stabilization techniques.
Comparing stabilization methods in atlantoaxial instability

### Summary of biomechanical testing results*

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<th>Types of Mode</th>
<th>Intact</th>
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<th>ATS</th>
<th>PTS</th>
<th>AHPS</th>
<th>PLM/APSR</th>
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<tr>
<td>ROM</td>
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* For Oc–C3 rotation, it is assumed that most of the rotary motion occurred at C1–2. All data are presented as the means ± SD of the angle.
† Significant difference compared with intact spine (p < 0.05).
‡ Significant difference compared with destabilized spine (p < 0.05).
§ Significant difference compared with other fixation methods (p < 0.05).
‖ Significant difference compared with ATS and PLM/APSR methods (p < 0.05).

The PLM/APSR method requires direct polyaxial screw placement into the C-1 lateral mass and C-2 pedicle with bilateral longitudinal rods. Atlantoaxial instability often results in subluxation or displacement requiring reduction maneuvers. The reduction procedure in the other three fixation methods precedes screw insertion, and thus accurate reduction must be maintained during the screw placement. The PLM/APSR method, however, is not dependent on a reduction maneuver. Instead, this technique facilitates reduction after screw placement and easy extension of the fixation system to the occiput or subaxial cervical spine. Our results indicate that PLM/APSR fixation is as effective as ATS and PTS fixation. We also found a greater decrease in ROM, NZ, and EZ values for the axial rotation mode were obtained by using the ATS and PTS techniques.

Destabilization of the C1–2 motion segment produced significantly greater ROM values for all test modes in the intact spine. During flexion–extension and axial rotation, a higher ROM had an accompanying increase in EZ with intact spine. During flexion–extension and axial rotation, we also found a greater decrease as ATS and PTS fixation. We also found a greater decrease with intact spine. During flexion–extension and axial rotation, a higher ROM had an accompanying increase in EZ with intact spine. During flexion–extension and axial rotation, we also found a greater decrease as ATS and PTS fixation. We also found a greater decrease

![Fig. 3. Bar graphs demonstrating normalized Oc–C3 motion data of the destabilized and the instrumented spine. Left: Normalized ROM. Right: Normalized NZ. AH = AHPS fixation; AT = ATS fixation; PP = PLM/APSR fixation; PT = PTS fixation. Error bar denotes one SD.](image-url)
Panjabi’s NZ hypothesis in that the NZ appears to be a clinically important measure of spinal stability. The change in the NZ, then, is more sensitive than that in the corresponding ROM, and in fact the NZ is the most sensitive indicator of instability.

Like all cadaveric studies, ours has certain limitations. Most of the cadaveric specimens were obtained from elderly individuals. Our results possibly reveal lower stability values than those that would be demonstrated in a young healthy population because the BMD influences the primary stability of screw fixation. Most of the patients needed anterior decompression and fusion for rheumatoid arthritis and irreducible anterior compressive lesions, which are diseases found in the elderly. Therefore, our results seem to be appropriate for this patient group. It should be also considered that motion could not be evaluated with the typically attendant muscle response, and our data resulted from pure moments applied to Oc–C3.

The destabilized specimens showed higher values of ROM and NZ in all loading modes. The Oc–C3 ROM values for flexion–extension and right/left lateral bending were approximately twofold that of the intact specimens. For the ROM of Oc–C3 axial rotation, most specimens were significantly destabilized such that the MTS loading frame had achieved its mechanical limit before reaching 1.5 Nm; hence, the apparent axial rotation destabilization is only approximately 1.5-fold that of the intact spine. Actual axial rotation destabilization data would be higher if the specimens were allowed to be loaded up to 1.5 Nm.

Although the small number of specimens in each group (four spines) limited the results of the statistical analysis, the ROM and NZ values for each stabilization method were compared with those of the intact spine, which serves as a baseline measurement of the biomechanical stability. Consequently, this limitation does not appear to negate the main findings of this study. Long-term biomechanical data are also not known because this study was only undertaken to test acute stability.

We reported on total Oc–C3 motion rather than C1–2 alone. Because the ligaments and tissues at the atlantoaxial junction were destroyed, the motion between the occiput and C-1 and that between C-2 and C-3 would potentially be affected. It is believed that the analysis of overall Oc–C3 motion better reflects the movement at the upper cervical spine as a whole. Motion between C-1 and C-2 as well as the occiput and C-3, however, show a similar trend for all the respective biomechanical variables following each of the fixation methods.

Conclusions

The anterior Harms system–augmented fixation did not restore biomechanical stability in flexion–extension and lateral bending modes to the level of the intact spine. The PLM/APSR fixation was found to confer the greatest biomechanical stiffness followed by the PTS procedure, the ATS, and the AHPS fixation. No statistically significant differences, however, were found between the PLM/APSR, PTS, and ATS fixation techniques. Although biomechanically the ATS fixation and the PLM/APSR fixation methods provided effective alternatives to the PATS method, determination of the proper fixation technique requires careful assessment of clinical and radiological characteristics of individual patients.

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