Traumatic spondylolisthesis of the axis: a biomechanical comparison of clinically relevant anterior and posterior fusion techniques

Laboratory investigation

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Object. Surgical management of unstable traumatic spondylolisthesis of the axis includes both posterior and anterior fusion methods. The authors performed a biomechanical study to evaluate the relative stability of anterior fixation at C2-3 and posterior fixation of C-1 through C-3 in hangman's fractures.

Methods. Fresh-frozen cadaveric spine specimens (occipital level to T-2) were subjected to stepwise destabilization of the C1–2 complex, replicating a Type II hangman’s fracture. Intact specimens, fractured specimens, and fractured specimens with either anterior screw and plate or posterior screw and rod fixation were each tested for stability. Each spine was subjected to separate right and left rotation, bending, flexion, and extension testing.

Results. Anterior fixation restored stiffness in flexion and extension movements to values greater than those for intact specimens. For other movement parameters, the values approximated those for intact specimens. Posterior fixation increased the stiffness to above those values seen for anterior fixation specimens.

Conclusions. In cadaveric spine specimens subjected to a Type II hangman’s fracture, both anterior fixation at C2–3 and posterior fixation with C-1 lateral mass screws and C-2 and C-3 pedicle screws resulted in a consistent increase in stiffness, and hence in stability, over intact specimens. (DOI: 10.3171/2009.4.SPINE08S16)

KEY WORDS • hangman’s fracture • C-2 fracture • surgical fixation • biomechanical testing

Hangman’s fracture, or TSA, is a well-characterized injury of the upper cervical spine. The fracture pattern was first described in relation to judicial hangings.26 Over the years, distinctions have been made between the commonly occurring TSA and the classic hangman’s fracture.14,20,21 The fracture has been classified by Pepin and Hawkins19 and Effendi et al.9 The cervico-cranial concept of the hangman’s fracture was described by Effendi, wherein the cephalad element consists of the skull, the atlas, the dens, and the body of the axis. The caudal element consists of the arch of the atlas, the third cervical vertebra, and the remaining cervical spine. It has been postulated that posterior C2–3 fusion may be inadequate, whereas C1–3 fusion would be an overtreatment. Anterior C2–3 fusion has been proposed to be adequate in this model.2 In the present study we used this proposal as a starting point for our study design. A review of the clinical data revealed that a comparison of anterior C2–3 fixation and posterior C1–3 fixation was most relevant from a clinical point of view. In clinical practice, the Effendi system is commonly used to describe the severity of the fracture.

Effendi et al.9 classified hangman’s fractures based on appearance (and the putative mechanism) as follows: Type I, isolated hairline fractures of the ring of the atlas with minimal displacement of the body of C-2 (axial loading and hyperextension); Type II, displacement of the anterior fragment with disc disruption (hyperextension and rebound flexion); and Type III, fixed displacement and angulation of the anterior segment with locked facets. Due to a flexion-distraction type of injury, Levine and Edwards15 modified the classification scheme to introduce the Type IIA hangman’s fracture. The management of Effendi Type I hangman’s fractures usually consists of external immobilization with a hard cervical

Abbreviation used in this paper: TSA = traumatic spondylolisthesis of the axis.
orthosis. Management of Type II and Type III fractures includes rigid external immobilization using a halo vest and/or surgery. Verhegen and Jansen have argued in favor of surgical fixation of Type IIa and Type III fractures. A review of evidence-based management strategies generated Level 3 recommendations for the treatment of the various subtypes of TSA. In cases of severe angulation of C-2 on C-3 (Effendi Type II), disruption of the C2–3 disc space, or nonunion, surgery should be considered. Options include anterior or posterior fusion and/or fixation techniques: C2–3 anterior cervical discectomy with fusion, or C1–3 or C2–4 posterior fusion with screw-rod fixation.

The purpose of this biomechanical study was to investigate the stiffness afforded by anterior and posterior fixation in cadaveric cervical spine specimens with spondylolisthesis of the axis. The study hypothesis (H₀) was that there is no difference in the increase in stiffness after anterior or posterior fixation of a hangman's fracture. Such a study may help surgeons determine the best course of action when choosing fixation techniques for unstable TSAs.

Methods

Study Model

A clinically relevant injury model has been described by Arand et al. It consists of stepwise destabilization of the C1–2 complex, replicating the injuries seen in hangman's fractures. The original model, as described in the earlier biomechanical study, consists of 4 stepwise defects created in the intact C1–3 cadaveric segments. In our study, Defect 1 consisted of bilateral osteotomies of the pedicles of the axis (Fig. 1). Defect 2 involved division of the anterior longitudinal ligament, division of the posterior longitudinal ligament, and disruption of the C1–2 disc space. A No. 10 scalpel blade was used to disrupt the annulus fibrosis anteriorly and the disc space posteriorly. A discectomy was not performed at this level to prevent excessive kyphosis.

For anterior fixation, we used an anterior H-shaped plate (42.4 mm) and 4.0 × 14-mm nonconstrained screws (Fig. 2). Insertion of a bone graft would have prevented us from alternating anterior and posterior fixation in the specimens. Such a protocol would have forced us to test all specimens with posterior fixation first, followed by discectomy and insertion of a bone graft to perform anterior fixation. A similar sentiment has been expressed by Duggal et al. The posterior fixation technique utilized C1 lateral mass screws, C-2 pars and C-3 pedicle screws, and rod fixation (Fig. 3). For the C-1 lateral mass screws, 3.5 × 18-mm screws were used. For the C-2 pars and C-3 pedicle, 3.5 × 14-mm screws were used. The screws were inserted under direct vision by using techniques that have been described in the literature. Bicortical purchase was not achieved in any of the C-1 screws. We did not attempt to cross the fractured segment with the C-2 screws. Such a fixation technique would require precise anatomical reduction of the fractured segments and the possible use of lag screws that extend to the body of C-2.

The placement of pedicle screws at C-3 under direct vision prevented cortical breach. Pedicle screws at C-3, as opposed to the obvious choice of lateral mass screws, allowed us to keep the screw heads from C1–3 in the approximate sagittal plane, which permitted us to connect the screw heads without contorting the connecting rod excessively. Instrumentation for both fixation techniques was provided by Medtronic.

Cadaveric Specimens

Six occipital through cervical specimens were harvested from unembalmed cadavers, 4 men and 2 women. The average age at death was 70 years with a range of 51–85 years. After harvesting, the specimens were visually examined; none showed signs of defects, anomalies, or surgeries. The specimens were frozen until they were prepared for testing.

Study Procedures

Preparation began by allowing the specimen to thaw in a refrigerator for 24 hours. The thawed specimens were carefully cleaned of soft tissue except for the joint capsules of the facet joints and the longitudinal ligaments. The spinal segment was reduced to C-1 through C-6. Levels C-3 through C-6 were fused together using wood screws 3.5 mm in diameter and 30 mm long. The distally fused segments were encased in automotive body filler (Bondo, Bondo Corp.). A major component of the laxity
in the C1–4 spinal cadaveric specimen could be ascribed to the rotational movement between C-1 and C-2. Wood screws 3.5 mm in diameter and 30 mm long were used to perform C1–2 transfixation bilaterally. The screws immobilized C-1 and the part of C-2 anterior to the proposed fracture defect. We based our model for the stepwise creation of a hangman’s fracture on that described by Arand et al.3 These authors described bilateral screw transfixation to eliminate rotation between C-1 and C-2. Replicating this model allowed us to conduct the study within the limited range permitted by our testing apparatus. In the original description of the cervicocranial model of the hangman’s fracture, Effendi et al.4 described 2 distinct segments separated by the fracture. The ventrocranial part is formed by the cranium, atlas, and body of the axis anterior to the fracture; and the dorso-caudal part is formed by the posterior element of the axis and C-3. Transfixation of C1–2 did not alter the relationship of the ventrocranial and dorso-caudal parts (see Fig. 7). Another unrelated but somewhat more important reason for C1–2 transfixation was to isolate the C2–3 level for biomechanical testing. The transfixation was performed between C-1 and the anterior fracture fragment of C-2 and did not affect the stability at the C2–3 disc space. Aluminum rods 9.6 mm in diameter were cut to custom length and attached to the C-1 facets by using Bondo. To allow the Bondo to properly cure, the specimens were placed in a refrigerator overnight.

Biomechanical Testing

All biomechanical testing was conducted in an Instron 8874 servohydraulic testing frame (Instron Corp.). Data were collected using Instron’s MAX software on a

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**Fig. 2.** Sagittal reconstruction of a CT scan demonstrating anterior C2–3 fixation with an H-shaped plate and screws. Despite disruption of the disc space at C2–3, there is no appreciable loss of disc height. The specimen has been fixed in an anatomical position.

**Fig. 3.** Reconstructed CT scan showing posterior C1–3 fixation with C-1 lateral mass screws and C-2 pars and C-3 pedicle screws. The screw heads of the screws posterior to C-1, C-2, and C-3 are visible in this image.

Dimension 4100 personal computer (Dell Corp.). Collected data were evaluated and plotted using Excel (Microsoft Corp.). Custom-built vices were used to grip the specimen during rotational testing, and a custom fixture was used to translate the specimen in the flexion, extension, and bending modes. Randomization of testing was only partially achieved because of difficulties in switching the clamps and vices from rotation to bending modes. However, the testing sequence either originated or terminated with rotation, and the bending, flexion, and extension modes were randomized. Rotation was conducted with the specimen vertically mounted in the testing frame with vices used to grip the aluminum bar at C-1 and the distal mass of Bondo. The rotation sequence was the first mode of testing and the bending sequences were subsequently performed randomly. For right and left bending, flexion, and extension testing, the specimen was rotated 90° from the vertical and rigidly clamped in the vice to allow for a cantilever form of testing in the corresponding direction.

Each spine specimen was first evaluated as intact followed by Defect 1, Defect 2, anterior fixation, and posterior fixation. The orders of both fixation techniques were randomized. Each of these scenarios involved 6 modes of testing and consisted of flexion (1 mm), extension (1 mm), separate left and right lateral bending (1 mm), and sepa-
rate left and right rotation (5°). Testing in the Instron 8874 was conducted under displacement control. This method was chosen to protect the specimens from possible fractures inherent to load control protocols. Furthermore, displacement control allowed an adequate and standardized movement to be applied to each specimen and a recording of the response. The stiffness values were calculated as the slope of the load versus the displacement curve, and the data were normalized with respect to the intact value.

The testing parameters are shown in Table 1. SigmaStat software (Systat Software, Inc.) was used to perform t-tests on the data obtained in the study.

Results

Data from 6 cervical spine specimens were used in the study. Normalized values (procedure divided by intact values) were obtained from all specimens (Table 2). The neutral zones could be estimated in the rotational mode only; because of the cantilever form of testing, neutral zones could not be estimated for bending and flexion and extension modes. One-way repeated measures ANOVA using the SigmaStat software revealed that the neutral zone values in both left and right rotations were not significantly different among the intact, Defect 1, Defect 2, anterior fixation, and posterior fixation specimens (p = 0.05 at a power of 0.05). The calculated p value for the left rotation was 0.77, and for the right rotation 0.12. The relatively low power value was attributable to the high degree of variability (Table 3).

Defects 1 and 2

Defect 1 resulted in apparent stiffening of some specimens because of increased laxity and bone-on-bone contact. The normalized moments for flexion ranged from 0.84 to 1.6 with a mean value of 1.12 ± 0.27 (mean ± SD). For extension, Defect 1 resulted in normalized moments ranging from 0.6 to 2.16 with a mean of 1.17 ± 0.53. For Defect 2, the mean normalized value for flexion was 0.89 ± 0.37, and for extension 1.41 ± 1.11. For rotation and lateral bending, the specimens showed a uniform decrease in stiffness. The normalized moments for Defect 1 were 0.48, 0.46, 0.6, and 0.73 for rotation in positive and negative directions and left and right lateral bending, respectively. The corresponding normalized moments for Defect 2 were 0.32, 0.25, 0.59, and 0.70 (Table 4).

The laxity created by the defects resulted in deflection of bony anatomical landmarks. This deflection was observable even with specimens under no tension in the direction of measurement. In some cases, because of the extent of deflection, direct bone-to-bone contact was noticeable. In flexion, the deflections ranged from 1.05 to 2.85 mm. In extension, the result was more dramatic, with deflections ranging from 3.57 to 5.92 mm.

Anterior Fixation

Specimens with anterior fixation showed a uniform increase in flexion and extension moments. The mean normalized value for flexion was 1.45 ± 0.42 (range 1.03–2.27). The mean normalized value for extension was 2.41 ± 1.91 (range 0.89–5.72). Anterior fixation increased the stiffness to above normal values in flexion and extension movements.

In bending moments, anterior fixation resulted in an increase in stiffness over the defects, but the fixed specimens were not any more rigid than intact specimens. The mean normalized value for left bending was 0.86 ± 0.32 (range 0.47–1.17), and for right bending the value was 1.22 ± 0.73 (range 0.46–2.59). For rotational movement, an increase in stiffness was seen over Defect 2, but again the fixed specimens were not stiffer than intact specimens. The mean normalized value for positive rotation was 0.70 ± 0.15 (range 0.55–0.90), and for negative rotation the value was 0.69 ± 0.23 (range 0.42–1.01; Table 5 and Figs. 4–6). Although anterior fixation revealed an increase in stiffness over intact specimens in flexion and extension, the increase was not as pronounced as with anterior fixation in the sagittal plane.
Traumatic spondylololisthesis of the axis

### TABLE 3: Calculated neutral zones in the rotational testing mode*

<table>
<thead>
<tr>
<th>Testing Mode</th>
<th>Intact</th>
<th>Defect 1</th>
<th>Defect 2</th>
<th>Ant Fixation</th>
<th>Pst Fixation</th>
</tr>
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<tbody>
<tr>
<td>lt rotation</td>
<td>0.78 ± 0.58</td>
<td>0.53 ± 0.63</td>
<td>0.69 ± 0.39</td>
<td>0.86 ± 0.20</td>
<td>0.76 ± 0.56</td>
</tr>
<tr>
<td>rt rotation</td>
<td>1.01 ± 0.50</td>
<td>0.77 ± 0.27</td>
<td>0.62 ± 0.56</td>
<td>0.55 ± 0.81</td>
<td>0.94 ± 0.96</td>
</tr>
</tbody>
</table>

* Values are presented as the means ± SDs in degrees. Abbreviations: Ant = anterior; Pst = posterior.

extension movements, such an increase was not seen in lateral bending and rotation.

**Posterior Fixation**

Posterior fixation resulted in a uniform increase in stiffness over intact specimens in all testing parameters. For flexion, the mean normalized value was 2.15 ± 0.55 (range 1.35–3.02). The greatest increase in stiffness was seen in extension with the mean normalized value at 2.56 ± 1.05 (range 1.40–4.13). The rotational moments were increased to slightly above normal values. The mean normalized value for positive rotation was 1.00 ± 0.47 (range 0.5–1.79), and for negative rotation it was similar at 1.16 ± 0.46 (range 0.58–1.78), as seen in Table 5. An increase in bending moments above intact values was also observed in posteriorly fixed specimens. The mean normalized value for left bending was 1.78 ± 0.71 (range 1.61–3.15), and for right bending 2.23 ± 0.86 (range 1.04–3.37; Figs. 4–6).

Statistically significant differences were seen in 1 mode of rotation, flexion, and lateral bending. Posterior fixation resulted in a statistically significant stiffening of the specimens when compared with anterior fixation. In extension and 1 mode of rotation, the differences were not statistically significant (Table 6).

**Discussion**

Effendi et al.9 described surgical treatment options that included anterior C2–3 fixation and posterior C1–3 fixation. Similarly, Francis et al.10 reported surgical options that also included a patient who underwent posterior C2–4 fixation. Although usually described in clinical settings with excellent functional results, transfacetal screw fixation has not gained wide clinical usage.2,4 Other techniques of posterior fixation have been reported, including posterior interlaminar wiring and screw fixation of the arch of the axis.13,17,18,24 A review to identify evidence-based management strategies of traumatic fractures of the axis led the authors to conclude that surgical options for hangman’s fractures include anterior C2–3 fixation and posterior C1–3 fixation.2 Our study design reflects the clinically relevant surgical options available to surgeons when considering the treatment of unstable hangman’s fractures (Fig. 7).11

Arand et al.3 compared the stabilizing capabilities of anterior and posterior fusion techniques after stepwise destabilization. They compared 2 anterior plating systems with posterior pedicle screw fixation. The hangman’s fracture model used in their study replicated the instabilities seen in clinically observed fractures. Such stepwise destabilization replicated the possible defects along the Effendi classification of the fractures. Their model used a C1–3 specimen with bilateral screw fixation of C-1 and C-2. They concluded that anterior fusion is mandatory in hangman’s fractures with additional segmental damage at C2–3. Arand and colleagues used a clinically relevant model to compare the stabilization properties of anterior C2–3 fixation and posterior transfacetal screw fixation at C-2.

Kim et al.14 used a C1–2 instability model to investigate the biomechanical stability of 2 anterior and 2 posterior fixation techniques. The model used in that study included disruption of the anterior arch of C-1 and removal of the dens. The fusion techniques compared were as follows: anterior C1–2 Harms plate/screw, anterior C1–2 transarticular screw, posterior C-1 lateral mass screw combined with C-2 pedicle screw/rod, and posterior C1–2 transarticular screw. These authors concluded that a posterior C-1 lateral mass screw combined with a C-2 rod/screw provided the highest stability in their model.14 Thus, it is not surprising that the posterior fixation of C-1 through C-3 utilizing the transarticular screws yielded a stiffer construct in our study as well. In a recent biomechanical study authors compared the stability of

### TABLE 4: Normalized stiffness values (procedure/intact) for Defects 1 and 2

<table>
<thead>
<tr>
<th>Testing Mode</th>
<th>Defect 1</th>
<th>Defect 2</th>
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<tbody>
<tr>
<td>lt rotation</td>
<td>0.48 ± 0.14</td>
<td>0.32 ± 0.17</td>
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<tr>
<td>rt rotation</td>
<td>0.48 ± 0.14</td>
<td>0.25 ± 0.10</td>
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<tr>
<td>flexion</td>
<td>1.12 ± 0.27</td>
<td>0.89 ± 0.37</td>
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<tr>
<td>extension</td>
<td>1.17 ± 0.53</td>
<td>1.41 ± 1.11</td>
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<tr>
<td>lt bending</td>
<td>0.60 ± 0.17</td>
<td>0.59 ± 0.16</td>
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<tr>
<td>rt bending</td>
<td>0.73 ± 0.23</td>
<td>0.70 ± 0.27</td>
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### TABLE 5: Mean normalized values for anterior and posterior fixation

<table>
<thead>
<tr>
<th>Testing Mode</th>
<th>Ant Fixation</th>
<th>Pst Fixation</th>
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<tbody>
<tr>
<td>lt rotation</td>
<td>0.7 ± 0.15</td>
<td>1 ± 0.47</td>
</tr>
<tr>
<td>rt rotation</td>
<td>0.69 ± 0.23</td>
<td>1.16 ± 0.46</td>
</tr>
<tr>
<td>flexion</td>
<td>1.45 ± 0.42</td>
<td>2.15 ± 0.55</td>
</tr>
<tr>
<td>extension</td>
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<td>2.56 ± 1.05</td>
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</tr>
<tr>
<td>rt bending</td>
<td>1.22 ± 0.73</td>
<td>2.23 ± 0.86</td>
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Fig. 4. Bar graph showing averaged normalized values from rotational data. The x-axis represents the stiffness of the specimens when compared with intact specimens. The bold lines on each side of the plot (1.0 and -1.0) represent the averaged normal values for the specimens. Defects cause a significant reduction in stiffness. Anterior fixation results in an increase in the stiffness toward normal, and posterior fixation results in stiffness values approximating intact specimens.

Fig. 5. Bar graph demonstrating averaged normalized values from flexion and extension data. Both anterior and posterior fixations result in a large increase in stiffness of the specimens.
specimens after anterior fixation and a novel technique consisting of posterior C2–3 fixation. Based on this study, Duggal et al.7 concluded that C2–3 fixation with C-2 pars screws offered more stability than anterior cervical plating for unstable hangman’s fractures.14 The inclusion of C-1 in the posterior fixation in our model was based on current clinical practice. The aim of our study was to compare commonly used techniques for the surgical management of hangman’s fractures.13 Based on the findings of Duggal et al.7 it would appear that C-1 fixation in the model is redundant, as even C-2 pars screw and C-3 screw fixation afford greater stiffness as well. The pars screw fixation of a hangman’s fracture at the level of injury has been described in a technical case report.6,13 The addition of C-3 screws and rod fixation affords stability in Type III fractures with disruption of the disc at C2–3. This technique may prevent a reduction in the range of motion by excluding C-1 in the construct. This novel method of fixation with bilateral screws engaging the fractured segments was not within the scope of our study as we intended to investigate the stiffness provided by techniques commonly used by surgeons in clinical practice.

Study Weaknesses

Our study did not include a disc space bone graft as is used in most clinical situations. One could argue that the addition of a disc space graft would increase the stability of specimens in all parameters. Some other weaknesses of our study are inherent to biomechanical studies of the spine, such as the viability of properties of cadaveric specimens and the use of specimens fixed at both ends. A peculiar effect of disc disruption was the introduction of bone-on-bone contact in specimens with Defect 2. We accounted for the lax zone by measuring deflection of specimens with Defects 1 and 2 under gravity. Lax zone measurements were performed for rotational modes (Table 1).

Conclusions

In our study, the posterior fixation technique increased the stiffness in all tested parameters to levels above the intact values, with significant differences in

<table>
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<th>TABLE 6: Statistical analysis of normalized values using the t-test</th>
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<td>rt rotation</td>
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<tr>
<td>lt rotation</td>
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<tr>
<td>flexion</td>
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<tr>
<td>extension</td>
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<tr>
<td>lt lat bending</td>
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<td>rt lat bending</td>
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more than one-half of the tested parameters. Posterior fixation involves a clinically significant reduction in the range of motion by fixing C-1 to C-2, as well as a higher incidence of dorsal pain. However, the posterior fixation technique is technically challenging, with a narrow margin of error for the placement of hardware. The anterior fixation technique was adequate in restoring the stiffness of specimens in the anterior-posterior movement to values that approximated intact specimens. Clinically, high stiffness offered by posterior fixation may not translate into additional fusion rates. It may be reasonable to conclude that anterior C2–3 fixation is a biomechanically viable surgical option for unstable hangman’s fractures.

Fig. 7. Schematic depicting hangman’s fractures and approaches to surgical fixation. The atlas, axis, and C-3 are pictured in a midsagittal view. A hangman’s fracture results in 2 distinct segments. The ventrocranial part is formed by the atlas (A) and the body of the axis anterior to the fracture (B). The dorsocaudal part is formed by the posterior element of the axis (C) and C-3 (D). a: Defect 1 is created with bilateral osteotomies of the pedicles of the axis. b: Defect 2 results in significant mobility of the ventrocranial part. Although C is attached to D at the facet joint, the movement between the 2 bony elements was quite significant. c: An Effendi Type III fracture would result in detachment of C from D in addition to other defects. An adequate surgical fixation technique would require fixation of the ventrocranial segment to the dorsocaudal segment. d: This procedure may be performed anteriorly by fixing B to D. e: An adequate posterior fixation technique would necessarily involve A, C, and D. In posterior fixation, the fixation of A to C may not be sufficient treatment given the detachment or mobility of C on D. An alternative posterior fixation technique would involve fixation of B, C, and D, a procedure beyond the scope of our study.

Disclaimer

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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Traumatic spondylolisthesis of the axis


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Results from this study were presented as an electronic poster at the 2008 American Association of Neurological Surgeons Annual Meeting in Chicago, where it was awarded Third Place in the Spine and Peripheral Nerve Category.
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