The C2 isthmus screw provided sufficient biomechanical stability in the setting of atlantoaxial dislocation

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Abstract

Background. The emerging of the C2 isthmus screw fixation technique is gaining popularity in the setting of atlantoaxial dislocation or other conditions requiring fixation of C2. However, the biomechanical stability of this fixation is poorly understood.

Purpose. To compare and elucidate the biomechanical stability of C2 pedicle screw (C2PS), C2 isthmus screw (C2IS) and C2 short isthmus screw (C2SIS) fixation techniques in atlantoaxial dislocation (AAD).

Method. A three-dimensional finite element model (FEM) from occiput to C3 was established and validated from a healthy male volunteer. Three FEMs, C1 pedicle screw (PS)-C2PS, C1PS-C2IS, C1PS-C2SIS were also constructed. The range of motion (ROM) and the maximum von Mises under flexion, extension, lateral bending and axial rotation loading were analysed and compared. The pullout strength of the three fixations for C2 were also evaluated.

Result. C1PS-C2IS showed the greatest decrease in ROM with flexion, extension, lateral bending and axial rotation. C1PS-C2PS showed the least ROM reduction under all loading condition than both C2IS and C2SIS. The C1PS-C2PS model had the largest von Mises under all directions followed by C1PS-C2SIS, and lastly the C1PS-C2IS. Under axial rotation and lateral bending loading, the three models showed the largest and least von Mises stress respectively. The stress of the three models was mainly located in the connection of the screw and rod. Overall, the maximum pullout strength for C2PS, C2IS and C2SIS were 729.41N, 816.62N, 640.54N respectively.

Conclusion. In patients with atlantoaxial dislocations, the C2IS fixation provided comparable stability, with no significant stress concentrations. Furthermore, the C2IS had sufficient pullout strength when compared with C2PS and C2SIS. C2IS is an effective and safe fixation modality in the treatment of atlantoaxial dislocations.

Introduction

Atlantoaxial dislocation (AAD) can resulting in joint dysfunction, nerve compression or even devastating consequence due to trauma, degeneration, congenital deformity, inflammation and other factors. The aim of surgical treatment is to relieve the nerve compression thus to prevent progressive neurological dysfunction and to restore the stability of the atlantoaxial joint [1]. Currently, the mainstream surgical approach is the posterior atlantoaxial screw and rod fixation technique (i.e., Harms' technique) which was modified by Harms et al [2] on the basis of Goel et al [3] in 2001. Since the C2 pedicle screw penetrates through the posterior, middle and anterior columns of the spine, it has showed excellent biomechanical stability and became the most preferred choice for posterior fixation in the setting of atlantoaxial dislocation [4, 5]. However, C2 pedicle screw is not indicated in cases of developmental defects of the pedicle, small pedicle or high riding vertebral arteries (HRVA) [6, 7]. Also, the incidence of vertebral artery injury with pedicle screw is as high as 8.5% [8]. In the meantime, there are some other disadvantages to the insertion of pedicle screw as well. For one thing, as the entry point of the C2 pedicle screw was the
cranial and medial quadrant of the isthmus surface of C2, with the trajectory 20 to 30 cranially and medially, surgeons have to perform a wider dissection of the paraspinal muscles eventually leading to soft tissue retraction to achieving a certain mediolateral angle. For another, in facing of vertical and angulated dislocation, the short anteroposterior and vertical distance between the heads of the C1 and C2 screw can result in a lack of space for reduction [9].

In 2005, Bristol et al [10] firstly presented a case of Effendi II cervical fracture treated with isthmus/pars interarticularis screw, which not only resulted in satisfactory reduction of the fracture but also sacrificed no spinal motion, with both excellent fracture healing and solid fixation at the 6-month postoperative follow-up. Since then, an increasing number of scholars have been applying this technique in a variety of diseases requiring fixation of C2 in the craniocervical junction area, and achieved satisfactory outcomes [11-13]. However, to the best of our knowledge, there have been no biomechanical studies of this approach. In view of this, the author conducted a finite element study to investigate the biomechanical performance differences in terms of stability, internal fixation stress and pullout strength among the three types of fixation, namely C1PS-C2PS, C1PS-C2IS and C1PS-C2SIS, to provide more details for clinical decision making.

Materials and methods

This study have been performed in accordance with the ethical standards in the 1964 Declaration of Helsinki. This study was approved by our institutional review board (approval number: 2017SL015). The requirement for informed consent from the participants was waived because of its retrospective nature. For the construction of the finite element model, a healthy male volunteer (38 years old, height 173 cm, weight 74 kg), with no history of cervical spine trauma or surgery, imaging examination ruled out cervical spine fracture, inflammation, tumour, deformity and degenerative disease. A 64-row spiral CT scanner (GE, USA) was used at the Imaging Medicine Centre, with scanning conditions set at 140 kV and 200 mA, and a slice thickness of 0.625 mm. The DICOM data was imported into Mimics21.0 (Materialise Company, Belgium) and a three-dimensional model was generated. Subsequently, the spine model was imported to Geomagic Studio 2014 (Raindrop Company, America) and to generate a finite element model (FEM) for analysis. To mesh the model and construct the main ligaments, HyperMesh 2019 (Altair Engineering, Inc., Troy, Michigan, USA) was utilized. Finally, MSCPatan2019 NASA Company, America was used for model assembly, material property definition and finite element analysis. The intact model is consisted of the occiput, cervical vertebrae, intervertebral disc, facet joints and ligaments attached to the craniocervical junction area (Table. 1). The thicknesses of the cortical bone and cartilage endplate were 1 mm and 0.5 mm respectively. The intervertebral disc was composed of the nucleus pulposus, annulus fibrosus and annulus ground substance. The analysis of the parameters was in accordance with the suggestions of a previous study [14, 15]. Bone, disc and cartilage structures were assigned linear elasticity. The assignment of the properties for all elements was as follows (Table. 2).

Establishment of unstable and three fixed FEMs
The unstable model due to the removal of transverse ligament was constructed based on the normal model. Then, we created three additional unstable FEMs to simulate the three different atlantoaxial posterior screw fixation techniques. Finally, five models were analysed and compared: (i) stable, (ii) unstable, (iii) C1PS-C2PS, (iv) C1PS-C2IS and (v) C1PS-C2SIS. To construct the fixed model, the parameters of the screw, rod and nut were referring from Shao et al [16]. The curvature of the corresponding rods was constructed according to the anatomical morphology of the patient's upper cervical spine. To simplify the model, post-fixation bone grafts were not modelled.

**Surgical procedures**

The entry point and trajectory of C2PS was inserted as described in the literature [4]. The entry point for C2IS was 2–3 mm lateral to the junction of the midline of the C2 lamina and lateral mass, which is more inferior and inward compared with the pedicle screw. The trajectory is placed along the isthmus, and the screw is placed as long as possible into C2 without exceeding the upper articular surface of the C2 at the exiting point. The C2SIS has the same entry point and trajectory with C2IS, which just stopped in the posterior wall of the vertebral artery foramen. In our study, all the screws of C2 were fixed with unicortical. The length of the three types of screw (C2PS, C2IS and C2SIS) was 26mm, 24mm and 16mm respectively with 3.5mm in diameter (Fig. 1).

**Boundary and loading conditions**

The lower surface of the C3 vertebra was constrained in all directions. A pure load of 50N and a torque of 1.5Nm were applied to C0 to simulate the loading conditions of the cervical spine according to studies that had been established in other C0-C2 FE models [17, 18]. To reach the target moment, 10 load steps were applied. The ROM calculated at the end point of the loading cycle was compared with that reported in a human study [19, 20]. Frictional contact interaction for the facet joints was defined as using a coefficient of friction of 0.5 [21]. The interaction between bone and screw was defined as using a coefficient of friction of 0.3 [22]. To only investigate the impact of the fixation methods, we assumed all models shared the same boundary and loading conditions.

**Pullout strength**

The load is applied along the longitudinal axis of the screw at the end of the screw. A sudden increase in the displacement of the screw head, i.e. a sudden increase in the slope of the curve, indicates that the screw is loosening and the corresponding loading value is the maximum pullout strength.

**Results**

**Validation of the intact FEM model**

The ROM of the intact models were 15.8°, 13.1°, 6.0° and 33.1° under flexion, extension, lateral bending and axial rotation loading condition respectively, which were 3.9°, 2.9°, 4.85° and 5.95° lower than the
unstable model. Our results are in accordance with those of previous both cadaveric and FEM simulation studies [19, 20, 23–25] (Table.3).

**ROM of the three fixed FEMs**

The ROM of the C1PS-C2PS, C1PS-C2IS and C1PS-C2SIS models under flexion, extension, lateral bending and axial rotation loading conditions were 2.1°, 1.7°, 0.55°, 0.85° and 1.8°, 1.5°, 0.45°, 0.75°, as well as 1.9°, 1.6°, 0.45°, 0.8° respectively. The ROM of the C1PS-C2PS, C1PS-C2IS and C1PS-C2SIS models in flexion, extension, lateral bending and axial rotation conditions were reduced by 86.7%, 87.0%, 90.8%, 97.4% and 88.6%, 88.5%, 92.5%, 97.7%, as well as 88.0%, 87.8%, 92.5%, 97.6% respectively (Fig. 2).

**Stress of the three fixed FEMs**

The von Mises of the three fixed FEMs, C1PS-C2PS, C1PS-C2IS and C1PS-C2SIS, were different under four loading conditions. Under flexion, extension, lateral bending and axial rotation, the peak von Mises of the C1PS-C2PS model were 101.16MPa, 110.59MPa, 105.09MPa and 170.05MPa respectively. The peak von Mises of the C1PS-C2IS model were 87.98MPa, 87.56MPa, 92.1MPa and 99.16MPa respectively. The peak von Mises of the C1PS-C2SIS model were 88.37MPa, 88.74MPa, 92.37MPa and 119.70MPa respectively. The peak von Mises under axial rotation loading conditions were highest in all three fixations. The stresses of the three models were mainly located in the area of the connection between the screws and the rods (Fig. 3).

**Pullout strength**

The details of the maximum pullout strength for the three FEMs are shown in Fig. 4.

**Discussion**

**Characteristics of the isthmus screw**

The isthmus is a small, thin segment of bone that connects the facet joints at the back of the spine [26]. In 2005, Bristol et al introduced the isthmus screw for the treatment of atlantoaxial instability caused by Effendi II, and achieved satisfactory clinical results [10]. The entry point of isthmus screw was located 2–3 mm lateral to the junction of the midline of the C2 lamina and the lateral mass. The screw was inserted along the direction of the isthmus as long as possible without exceeding the superior articular surface of C2 to achieve maximum screw length. Our initial study found that with the change of mediolateral angle and cephalad angle of the isthmus screw, the length of the screw that could be implanted varied remarkably. It is relatively safe to place the isthmus screw with a diameter of 3.5mm and a length at least of 23mm if the screw is placed at a 10–15° mediolateral angle and 25–35° cephalad angle through the isthmus on both left and right side.
Finite element analysis (FEA) uses mathematical approximations to simulate real spinal structures, and since Belytschko et al. [27] first applied it to the field of spine surgery in 1974, the technique is widely used to analyse the biomechanical properties of a variety of implants in spine [28, 29]. Traditional in vivo mechanical experiments have such problems as difficulty in obtaining specimens, invasive and cannot further analyse stress distribution of the implants inside the body. Finite element analysis has the advantages of being reproducible, time saving and low cost. Therefore, the author applied the finite element method in seeking the biomechanical performance of the C2 isthmus screw.

The results of the study showed that the C1PS-C2IS model indicated the most significant reduction in ROM in all directions under the loading conditions, followed by the C1PS-C2SIS and finally by the C1PS-C2PS. The result seems counterintuitive at first glance, but a closer look reveals that there is something to it. We speculate that it may be related to the following reasons: First, the length of the C2 isthmus screw is 24mm, which is not significantly shorter than the pedicle screw (26mm) in this study. Secondly, the greater cephalad angle of the isthmus screw results in a closer proximity to the cortical bone on the upper surface of the C2 vertebral body, similar to the cortical bone trajectory screw which can provide enhanced screw purchase and interface strength independent of trabecular [30]. As to the C2SIS model, it showed higher reduction in ROM compared with C2PS. One of the possible reasons for this is that the relatively longer length of the isthmus screws in the present study, and the proximity of the model's screw head to the medial margin of the cortex, similar to the bicortical screw fixation mentioned in a previous study which provides sufficient biomechanical stability compared with C2 pedicle screw [16]. These heterogeneous results suggest that a homogeneous experimental design and condition is necessary, and further clinical studies are needed to validate the results of this study.

In our study, the peak von Mises for the three internal fixations (C2PS, C2IS, C2SIS) were highest in axial rotation, and lowest in lateral bending. The von Mises stresses are mainly concentrated at the connection between the screw and the rod, and the results of this study are in consistent with previous studies [16, 31].

As to the pullout strength, the results of our study found that all three C2 unicortical screws showed comparable biomechanical stability. For one thing, the pullout strength were higher than that in vitro cadaveric studies measured by Su et al. [32] and Dmitriev et al. [33], and the reasons for this may be related to the older age of the patients in the cadaveric specimen experiments, the repeated retrieval and placement of the screws. For another, the maximum pullout strength of the C2 modified isthmus screw was higher than that of the C2 pedicle screw, which may be related to the fact that the C2 modified isthmus screws hold the cortical bone more, similar to the lumbar cortical bone trajectory screw to have a better inserted torque [30]. In addition, similar screw length in the present study may be one of the reasons for this phenomenon. In a word, in our FEMs study, C1PS-C2IS was the most stable construct with reference to the ROM, the stress on the implants and pullout strength.

Limitations
C2 pedicle screw is widely used in the clinical application as a standard fixation technique for the posterior approach. Since there have been a plenty of biomechanical studies comparing pedicle screw with laminar screw, spinous screw and transarticular screw [31, 34], the present study used pedicle screw as a standard fixation method and only compared the biomechanical characteristics with the isthmus screw and short isthmus screw. Simultaneously, this study has the following shortcomings: (i) The data of the study from one healthy adult volunteer, and it wasn't possible to verify whether it differed from other comparisons, and more samples should be included in the subsequent study to draw more thorough conclusions; (ii) Muscles are considered to be an important stabilizing cause of the vertebral joints and are thought to be important biomechanical stabilizing structure of the human body, but the three-dimensional finite element analysis model only reconstructed the vertebral body, intervertebral discs and ligaments, and could not analyse the influence of the muscles on biomechanics. (iii) This study is only a simulated biomechanical study, and its specific biomechanical properties should be compared with cadaveric specimen experiments to validate and complement this aspect of the study in order to provide a theoretical basis for clinical application.

In conclusion, this study confirms that the C2 isthmus screw showed favorable biomechanical performance. This technique is a safe and ideal method for posterior fixation in the setting of AAD. Likewise, in the cases with HRVA, short isthmus screw can be an alternative fixation method.

Declarations

Data availability statement: The datasets and materials supporting the conclusions of this article are included within the article, and further inquiries can be directed to the corresponding author.

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Ethical review committee statement: This study have been performed in accordance with the ethical standards in the 1964 Declaration of Helsinki. This study was approved by our institutional review board (approval number: 2017SL015). The requirement for informed consent from the participants was waived because of its retrospective nature.

Conflict of interest statement: We declare that we have no financial and personal relationships with other people or organizations that can appropriately influence our work. There is no professional or other
personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in the manuscript entitled.

**Authors’ contribution:** Minming Lu and Zhenqiang Wang contributed equally to this work, and were listed the first author and the co-first author.

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**Ethical approval:** All procedures performed in studies involving human participants were in accordance with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. This retrospective cohort study was approved by the Ethics Committee of Shanghai Changzheng Hospital's institutional review board. The informed consent of each patient was waived because of its retrospective nature.

**References**


Tables

Table 1 Ligaments and material properties of the FEMs

<table>
<thead>
<tr>
<th>Ligament</th>
<th>Location</th>
<th>Stretch:Force mm:N</th>
<th>Range mm:N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alar ligament</td>
<td>C0-C2</td>
<td>14:350</td>
<td>(7-21):(130-580)</td>
</tr>
<tr>
<td>Apical ligament</td>
<td>C0-C2</td>
<td>10:200</td>
<td>(0-29):(100-300)</td>
</tr>
<tr>
<td>Transverse ligament</td>
<td>C0-C2</td>
<td>25:400</td>
<td>(10-40):(360-500)</td>
</tr>
<tr>
<td>Anterior atlanto-occipital membrae</td>
<td>C0-C1</td>
<td>19:230</td>
<td>(16-22):(200-250)</td>
</tr>
<tr>
<td>Anterior longitudinal ligament</td>
<td>C1-C2</td>
<td>12:280</td>
<td>(5-18):(150-420)</td>
</tr>
<tr>
<td>Anterior longitudinal ligament</td>
<td>C2-C3</td>
<td>9:210</td>
<td>(5-13):(100-300)</td>
</tr>
<tr>
<td>Joint capsules</td>
<td>C0-C2</td>
<td>12:80</td>
<td>(10-14):(30-120)</td>
</tr>
<tr>
<td>Posterior longitudinal ligament</td>
<td>C2-C3</td>
<td>10:80</td>
<td>(0-20):(0-160)</td>
</tr>
<tr>
<td>Posterior atlanto-occipital membrae</td>
<td>C0-C1</td>
<td>18:80</td>
<td>(15-21):(60-100)</td>
</tr>
<tr>
<td>Ligamentum flavum</td>
<td>C1-C2</td>
<td>9:80</td>
<td>(4-14):(30-200)</td>
</tr>
<tr>
<td>Ligamentum flavum</td>
<td>C2-C3</td>
<td>6:90</td>
<td>(5-7):(20-150)</td>
</tr>
<tr>
<td>Ligamenta capsulare</td>
<td>C0-C1</td>
<td>10:320</td>
<td>(2-18):(190-450)</td>
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<tr>
<td>Ligamenta capsulare</td>
<td>C1-C2</td>
<td>9:310</td>
<td>(5-14):(170-460)</td>
</tr>
<tr>
<td>Ligamenta capsulare</td>
<td>C2-C3</td>
<td>9:210</td>
<td>(4-14):(80-340)</td>
</tr>
<tr>
<td>Interspinal ligaments</td>
<td>C0-C3</td>
<td>7:37</td>
<td>(5-9):(35-39)</td>
</tr>
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</table>

Table 2 Material parameters of the cervical spine
<table>
<thead>
<tr>
<th>Element Type</th>
<th>Young's Modulus (MPa)</th>
<th>Poisson Ratio (v)</th>
<th>Element Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screw or rod</td>
<td>110,000</td>
<td>0.3</td>
<td>TetMesh Tet4</td>
</tr>
<tr>
<td>Cortical bone</td>
<td>12,000</td>
<td>0.29</td>
<td>TetMesh Tet4</td>
</tr>
<tr>
<td>Cancellous bone</td>
<td>450</td>
<td>0.29</td>
<td>TetMesh Tet4</td>
</tr>
<tr>
<td>Cartilage</td>
<td>10</td>
<td>0.3</td>
<td>TetMesh Tet4</td>
</tr>
<tr>
<td>End plate</td>
<td>500</td>
<td>0.4</td>
<td>TetMesh Tet4</td>
</tr>
<tr>
<td>Back-end structure</td>
<td>3500</td>
<td>0.3</td>
<td>TetMesh Tet4</td>
</tr>
<tr>
<td>Fibre ring</td>
<td>4.2</td>
<td>0.45</td>
<td>TetMesh Tet4</td>
</tr>
<tr>
<td>Nucleus pulposus</td>
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<td>0.499</td>
<td>TetMesh Tet4</td>
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<tr>
<td>All ligament</td>
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<td></td>
<td>1D Spring</td>
</tr>
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</table>

**Table 3** Comparision of the ROM with previously published data

<table>
<thead>
<tr>
<th>Study</th>
<th>ROM (C1-C2)</th>
<th>Flexion</th>
<th>Extension</th>
<th>Lateral Bending</th>
<th>Axial Rotation</th>
</tr>
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<tbody>
<tr>
<td>Panjabi et al</td>
<td>Intact model</td>
<td>12.3±2.0</td>
<td>12.1±6.5</td>
<td>3.3±2.3</td>
<td>28.4±4.8</td>
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<td>Brolin et al</td>
<td>Intact model</td>
<td>11.3</td>
<td>14</td>
<td>6.0</td>
<td>23.3</td>
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<tr>
<td></td>
<td>Intact model</td>
<td>11.9</td>
<td>10.2</td>
<td>4.2</td>
<td>27.8</td>
</tr>
<tr>
<td></td>
<td>Unstable model</td>
<td>15.8</td>
<td>13.1</td>
<td>6.0</td>
<td>33.1</td>
</tr>
<tr>
<td>Current study</td>
<td>C2 PS</td>
<td>2.1</td>
<td>1.7</td>
<td>0.55</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>C2 MIS</td>
<td>1.8</td>
<td>1.5</td>
<td>0.45</td>
<td>0.75</td>
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<tr>
<td></td>
<td>C2 SIS</td>
<td>1.9</td>
<td>1.6</td>
<td>0.45</td>
<td>0.8</td>
</tr>
</tbody>
</table>

**Figures**
Figure 1

FEMs with three different fixation methods, FEM represent the finite element analysis.
Figure 2

Comparison of the ROM in C0-C1 segment among the three models.
<table>
<thead>
<tr>
<th></th>
<th>C2PS</th>
<th>C2IS</th>
<th>C2SIS</th>
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<tr>
<td><strong>Flexion</strong></td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
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<td><strong>Extension</strong></td>
<td><img src="image4" alt="Image" /></td>
<td><img src="image5" alt="Image" /></td>
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<tr>
<td><strong>Lateral bending</strong></td>
<td><img src="image7" alt="Image" /></td>
<td><img src="image8" alt="Image" /></td>
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<tr>
<td><strong>Axial rotation</strong></td>
<td><img src="image10" alt="Image" /></td>
<td><img src="image11" alt="Image" /></td>
<td><img src="image12" alt="Image" /></td>
</tr>
</tbody>
</table>

**Figure 3**

Von Mises stress of the screw-rod constructs.
Figure 4

Pullout strength-displacement curve of the three kinds of screws.