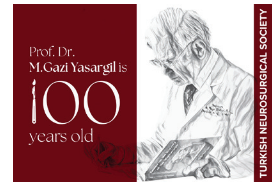
Turk Neurosurg 35(3):395-402, 2025
DOI: 10.5137/1019-5149.JTN.47277-24.2



Original Investigation

Spine and Peripheral Nerves

Received: 11.07.2024
Accepted: 28.08.2024
Published Online: 30.04.2025

Comparison of Mechanical Stress on Implants in Anterior Single and Double Screw Fixation of Odontoid Fractures in a Finite Element Model

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ABSTRACT

AIM: To evaluate the effect of single and double anterior odontoid screw fixation on the ROM of the craniocervical area and the stress distribution on the implants in a Finite Element Analysis which may give us ideas about the possible results for IF and malunion.

MATERIAL and METHODS: A FE model of the craniocervical area was constructed and a type II fracture model was created. In model A, a single screw and in model B two screws were used to fixate the model. The ROM and von Misses stress distribution on implants was evaluated.

RESULTS: The ROM values of the models with fixation closely resembled those of the intact model, showing less than a 10% difference in ROM. Under loading conditions in flexion, extension, rotation and lateral bending directions for each model, both structures exhibited similar stress distributions. In both models, the stress was distributed throughout the whole shaft, whereas during lateral bending and rotation, the stress was localized more on the distal part. But the maximum stress on implants were higher in the single screw model.

CONCLUSION: We believe that double odontoid screws decrease the stress on implants, thus decreasing the risk of IF without significantly affecting ROM.

KEYWORDS: Odontoid fracture, Finite element analysis, Implant failure, Malunion, Double screw fixation

ABBREVIATIONS: AOF: Anterior odontoid fixation, **CT:** Computed tomography, **DICOM:** Digital imaging and communications in medicine, **FE:** Finite element, **FEA:** Finite element analysis, **IF:** Implant failure, **OF:** Odontoid fracture, **ROM:** Range of motion

INTRODUCTION

The C2 vertebra and its odontoid process are an essential component of the craniocervical junction. Odontoid fractures (OF) account for 20% of all cervical fractures. OF can develop in any age group following high-impact trauma such as motorcycle accidents or falls in which hyperextension of the neck produces a posterior displacement of the odontoid. OF is the most prevalent type of cervical fracture in those over the age of 70 years (11). Patients typically complain of neck pain that worsens with movement and, in some cases, dysphagia caused by retropharyngeal compression. Myelopathy and neurological impairments are very rare (2). OF is evaluated using the Anderson-D'Alonzo classification, a simple and accessible decision-making tool. Type I fractures, which span the tip of the odontoid, are normally considered stable and do not require surgical intervention. The fracture line in type II, the most prevalent form of OF, runs transversely across the base of the odontoid and is predicted to be unstable with a high risk for nonunion; thus, patients are candidates for surgery. In type

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III, the fracture line spans the whole odontoid into the lateral masses of C2 and is considered stable as long as there is no significant displacement (1). Analgesics and immobilization with a rigid cervical collar or halo traction are common forms of conservative treatment for type I and most type III fractures. Surgical treatment for type II and displaced fractures remains controversial. There is no clear consensus on the advantages of anterior and posterior approaches for OF. Currently, the anterior approach, with either a single or double screw fixation, is considered the gold standard for patients with OF who have an intact transverse ligament and no atlantoaxial dislocation (15). The OP is made up of dense cortical and trabecular bone, whereas the anterior section of the C2 corpus is composed of hypodense trabecular bone. Because of these distinct anatomical characteristics, fracture resistance is quite low, and using instruments on the C2 vertebra and OP can be challenging (7). Nonunion following anterior odontoid fixation (AOF) is believed to be approximately 13%, while the figures vary between studies (10). One of the most common causes of non-union is implant failure (IF), which occurs when the screws loosen, pull out, or break. Despite several biomechanical and clinical studies comparing single and double screw fixations in OF, no significant differences in surgical outcomes were found between the two procedures (8). When evaluating the literature, no finite element analysis (FEA) was done on this topic. In this paper, we will use an FEA to examine the effect of single and double anterior odontoid screw fixation on the range of motion (ROM) of the craniocervical region and the stress distribution on the implants, which may provide insight into the potential outcomes for IF and malunion.

MATERIAL and METHODS

A healthy male volunteer, aged 30 years, with no history of trauma, tumor, infection, or fractures, was selected to construct a finite element (FE) model of a normal cervical spine. Ethics committee approval was granted (date: 27/07/2022, number: 47), and the volunteer signed the informed consent form. Radiological examination revealed no lesions in any cervical vertebra. The occipitocervical region (C0–C3) was imaged using 256-slice computed tomography (CT; Siemens, Erlangen, Germany) with a 1-mm slice thickness and acquired in the Digital Imaging and Communications in Medicine (DICOM) format. The three-dimensional network structure was structured and homogenized, and a 3D solid model was generated for FE stress analysis. The method required a computer with an Intel Xeon® R CPU 3.30-GHz processor, 500-GB hard drive, 14-GB RAM, and Windows 7 Ultimate Version Service Pack 1. The 3D modeling software Rhinoceros 4.0 (McNeel, Seattle, Washington), VRMesh Studio (VirtualGrid Inc, Bellevue City, Washington), and Algor Fempro (ALGOR Inc., Pittsburgh, Pennsylvania) analysis program were used. After being geometrically created with VRMesh software, the models were transmitted to Algor Fempro software in Standard Triangle Language (.stl) format for preparation and analysis. Table I contains material values such as elastic modulus and Poisson's ratio, which define the physical attributes of each structure in the models (Table I). The software assumed that solid bodies were linearly elastic, homogeneous, and isotropic.

Table I: Material Properties Used for Various Components of the Model

Component	Young's modulus (MPa)	Poisson's ratio	Element number
Cortical	1200	0.3	187865
Cancellous	450	0.3	132759
Cartilago articularis	42	0.45	11343
TL	20	0.3	114
ALL	54.5	0.3	6
PLL	20	0.3	6
CL	20	0.3	25
LF	1.5	0.3	5
LAD	10	0.3	3
AL	7	0.3	2
MT	10	0.3	5
Suboccipital group	150	0.2	8
Implant	110,000	0.33	–

TL: *Transverse ligament,* ***ALL and PLL:*** *anterior and posterior longitudinal ligaments,* ***CL:*** *capsular ligament,* ***LF:*** *flavum ligament,* ***LAD:*** *apical ligament of dens,* ***AL:*** *alar ligament, and* ***MT:*** *membranae tectoria; and suboccipital muscle group, including rectus capitis posterior (RCP) major and RCP minor muscles, musculus obliquus capitis superior, and musculus obliquus capitis inferior.*

Formation of the FE Model of the Normal Atlantoaxial Vertebra

Models built in VR Mesh were sent to Algor as surface data in the.stl- format. These models have to be meshed with a solid interior for Algor analysis to work. Models were meshed with 8-node (brick-type) elements whenever possible. In regions near the center of the structures, fewer node elements were required to complete the structure. This modeling approach aimed to provide the highest quality mesh structure with the most node elements possible to ease calculations. Models were converted to solid models using bricks and tetrahedra elements. In the bricks and tetrahedra solid modeling system, Fempro made extensive use of 8-node elements. When 8-node elements could not provide the necessary data, 7-node, 6-node, 5-node, and 4-node elements were used. All models were considered to use linear, homogeneous, and isotropic materials. The homogeneity of a material indicates that its mechanical properties are consistent throughout all structural elements. In contrast, isotropy refers to a situation in which the material properties of a structural element are the same in all directions. Linear elasticity refers to the proportional variation of deformation or strain in response to applied forces. Table II shows the element and node counts used in mathematical models containing scenarios. To construct a geometric model of cervical vertebrae, CT slices of a healthy adult were exported in DICOM format and loaded into the 3D-Doctor software (Able Software Corp., Lexington, Massachusetts). The bone tissues in the sections were separated using the interactive segmentation approach. The segmented sections were transformed into a 3D model, and complex rendering was used. The generated 3D model underwent simplification in 3D-Doctor, resulting in a memory-efficient, smoothly surfaced model with proportionate elements representing the cervical bone. The 3D model was exported in.stl format from 3D-Doctor. Dimensional and topographic adjustments of the cervical model were created using VR Mesh software. Following these processes, a 3D model was created using the 3D Complex Render method, which represented the bone tissue. The model first emerged in its basic form. Individual vertebrae were extracted from the raw model one by one using a 3D modeling tool. Vertebrae other than those used in the study were excluded, and disks were modeled between the selected vertebrae. To ensure full contact between disks and vertebrae, modeled disks were removed from the bones using the Boolean method, with the assumption that surfaces were in full contact. The modeling processes were done in Rhinoceros, with the models placed in accurate coordinates in three-dimensional space and subsequently converted to 3D format. These modeled versions in.stl format were imported into Fempro while maintaining three-dimensional coordinates. To test our FE model, we immobilized it from the bottom portion of C3 and measured the ROM of the robust C0–C1 and C1–C2 segments (Figure 1A, B). We then compared the ROM values under the same limitations and loading conditions with previous FE studies, which showed reasonable compatibility.

FE Model and Fixation Models of the OF

To improve the FE model of the normal atlantoaxial vertebra, a robust FEA was used to construct the OF model. The fracture model was created by removing the odontoid and bone components close to the C2 vertebral body (7). Screw models for anterior fixation of the OF were developed using the odontoid screw (4.5-mm diameter, 32-mm length) manufactured by Osimplant Spine Restoration Technology Ltd. (Osimplant, Istanbul, Turkey). Screws/implants were surgically implanted into the OF model using traditional methods. Aside from the fracture model, two additional models were developed. Model A was designed for anterior fixation of the OF with

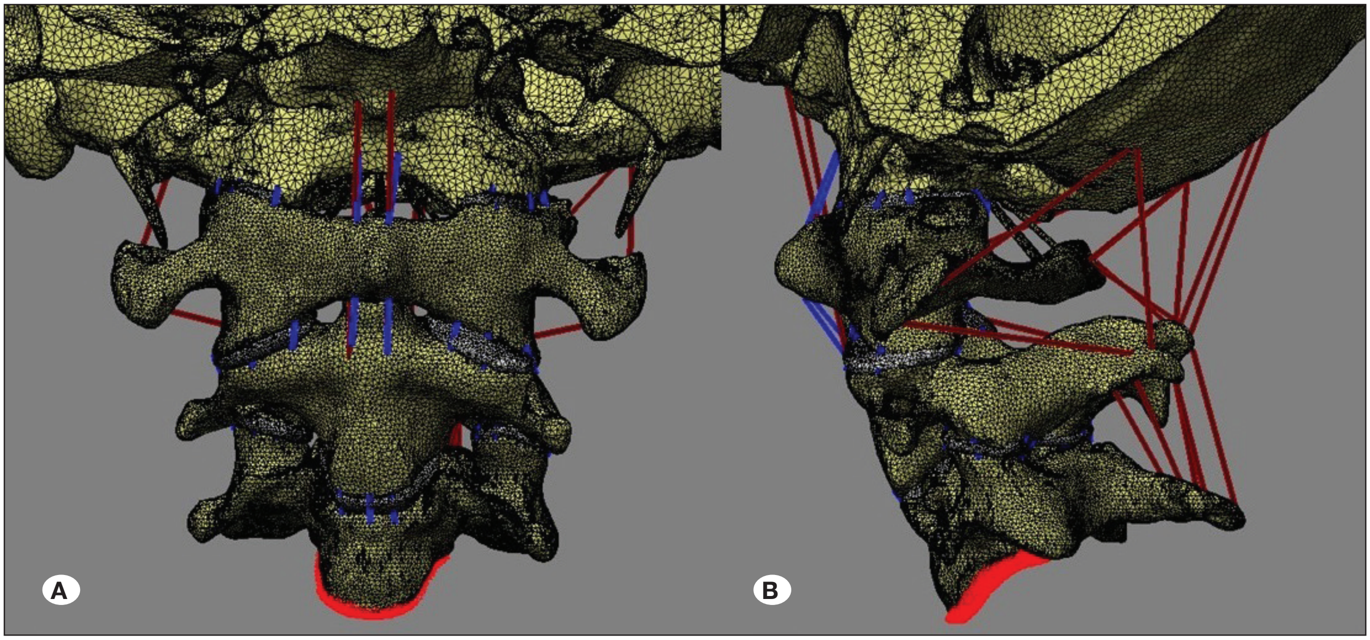

Figure 1: Finite element model of the atlantoaxial joint. **A)** Anterior view, **B)** lateral view.

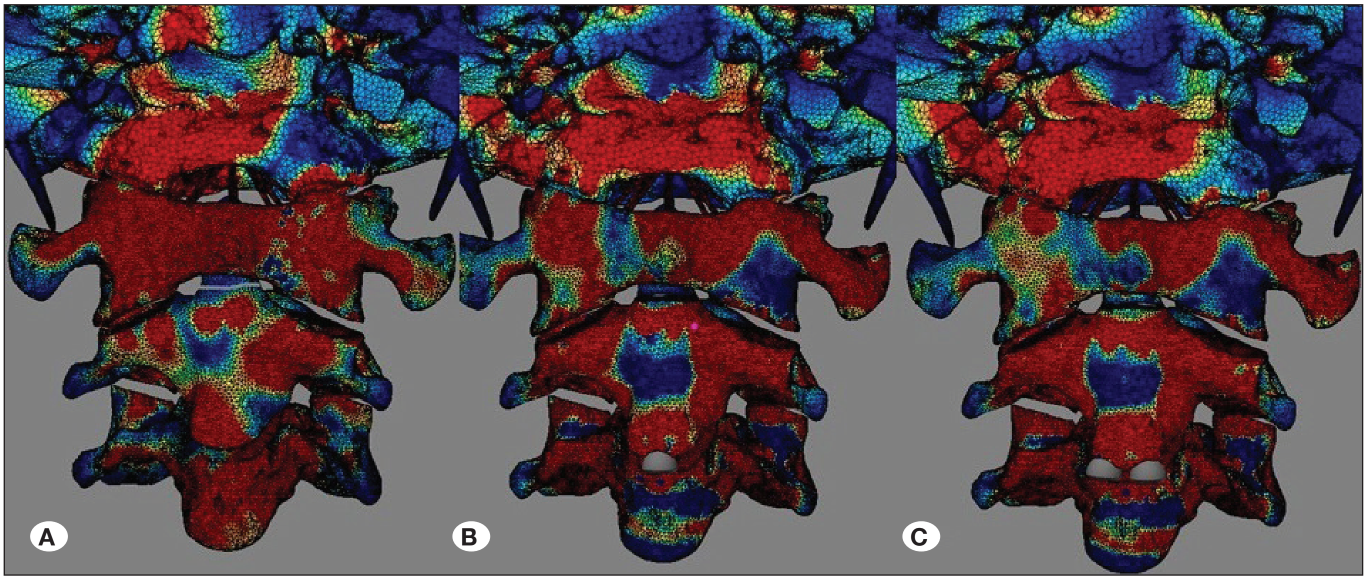

Figure 2: Finite element fracture and stabilization model. **A)** Fracture model, **B)** single screw stabilization model, **C)** double screw stabilization model.

a single screw, whereas Model B used two screws (Figure 2). Given that the implant's hardness significantly exceeds that of human bone tissue, embedding limitations were put between the screw's implanted portion and the surrounding bone. Attachment limitations refer to the interactions of the vertebral body, cartilage, and screws. The bottom surface of C3 was completely restricted. A control point was built on the occipital bone's upper surface, which was linked to all nodes on the same surface (Table II). To simulate flexion, extension, rotation, and lateral bending, a downward vertical force of 40 N and a moment of 1.5 Nm were applied successively to the control point along the *x*-axis, *y*-axis, and *z*-axis (3).

Table II: Numbers of Elements and Nodes Used in Mathematical Models

Group	Nodes and elements
Control	Number of nodes = 197469 Number of elements = 722443
Single Screw	Number of nodes = 260905 Number of elements = 968644
Double Screw	Number of nodes = 315158 Number of elements = 1178398

RESULTS

Three-Dimensional Angular ROM Evaluation of Structures

Each model had its ROM assessed in flexion, extension, rotation, and lateral bending directions (Table III, IV). When the ROM of the atlantoaxial instability model was compared with the intact model, it increased by at least an 80% increase in all measured directions. The ROM values of the models with fixation were nearly identical to those of the intact model, with a difference of less than 10%. The two models differed by 0.3°–0.2°in flexion C0–C1/C1–C2, 0.1°–0.1° in extension C0–C1/C1–C2, 0.3°–0° in lateral bending C0–C1/C1–C2, and 0.2°–0.3° in axial rotation C0–C1/C1–C2.

Stress Distributions on Implants

The von Mises stress on the implants is shown in Figures 3 and 5. Both models had similar stress distributions under loading conditions in flexion, extension, rotation, and lateral bending directions. In both models, the stress was distributed along the shaft; however, during lateral bending and rotation, the stress was localized on the distal region of the screws. However, the maximum stress on implants was notably higher in the single screw model (Figure 3, 5).

Comparison of Maximum Stress in Vertebral Bodies

The screw–bone contact caused the maximum stress in the vertebral bodies (Figure 4). While Model A had a higher peak stress value in flexion and Model B had a higher peak stress value in extension, the peak stress values were the same in lateral bending and axial rotation.

Statistical Analysis

The values produced from FE stress assessments are derived from variance-free mathematical computations, which precludes statistical analysis. The crucial aspect here is the accurate evaluation and interpretation of cross-sectional images, stress quantities, and node distributions.

DISCUSSION

AOF, whether with a single or double screw, is considered the gold standard for Anderson-D'Alonzo type II OF with no cervical dislocation and an intact transverse ligament because it provides immediate stabilization and early mobilization without drastically limiting neck movements. There is no statistical evidence that one approach is superior to the other

Table III: Comparision of Predicted ROMs Under Different Physiological Conditions with Other Studies

Load	Segments	Panjabi et al., (13)	Hao Zhang et al., (17)	Li et al., (8)	Present study
Flexion	C0-1	7.2	14.5	8.34	11.7
	C1-2	12.3	15.0	11.2	10.1
Extension	C0-1	20.2	13.3	8.69	12.8
	C1-2	12.1	12.7	7.33	13.1
Lateral bending	C0-1	4.5	5.5	3.61	2.9
	C1-2	3.3	5.9	5.17	4.8
Axial rotation	C0-1	4.9	8.5	4.7	4
	C1-2	28.4	30.6	28.3	28.6

Table IV: ROM Values of Each Group Under Different Loading Conditions

Load	Segments	Intact Model	Unstable Model	Model A	Model B
Flexion	C0-1	11.7	20.8	10.6	10.9
	C1-2	10.1	18.3	9.8	10
Extension	C0-1	12.8	21.6	12.5	12.4
	C1-2	13.1	23.2	12.8	12.7
Lateral bending	C0-1	2.9	5.3	2.5	2.8
	C1-2	4.8	8.5	4.5	4.5
Axial rotation	C0-1	4	7.3	3.7	3.5
	C1-2	28.6	45.8	27.7	27.4

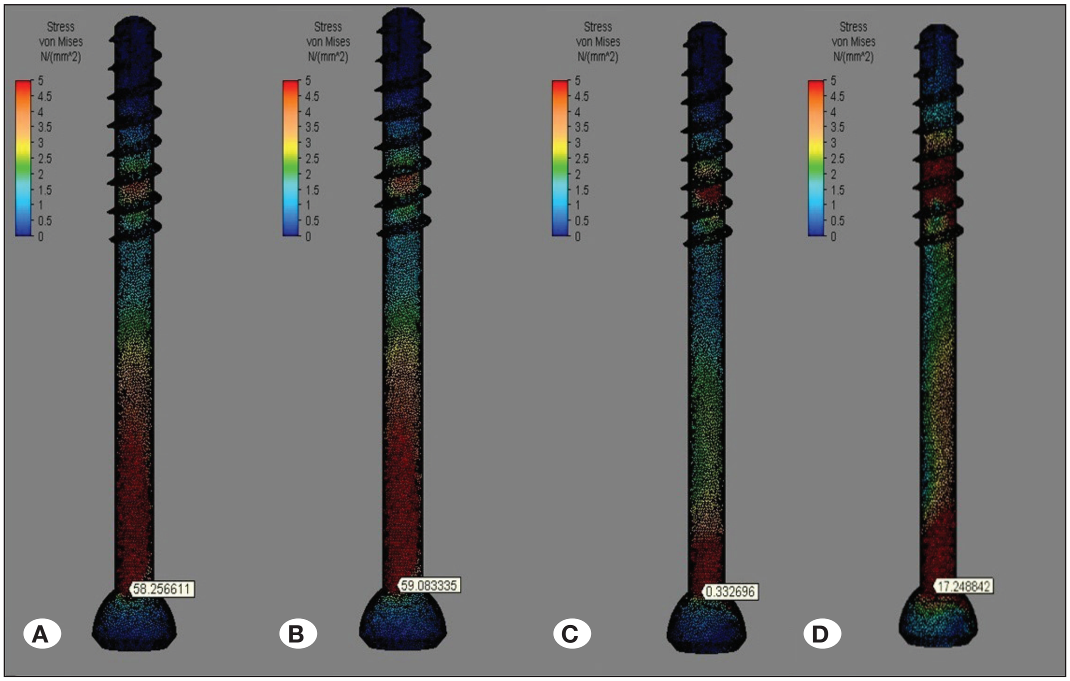

Figure 3: Stress nephogram of the single screw stabilization model during flexion **(A)**, extension **(B)**, rotation **(C)** and lateral bending **(D)**.

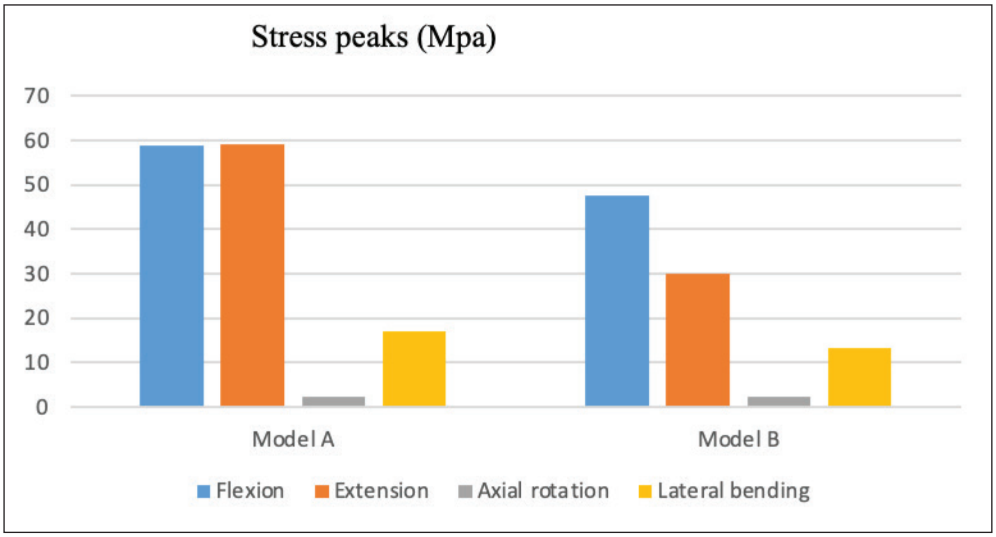

Figure 4: Comparison of stress peaks.

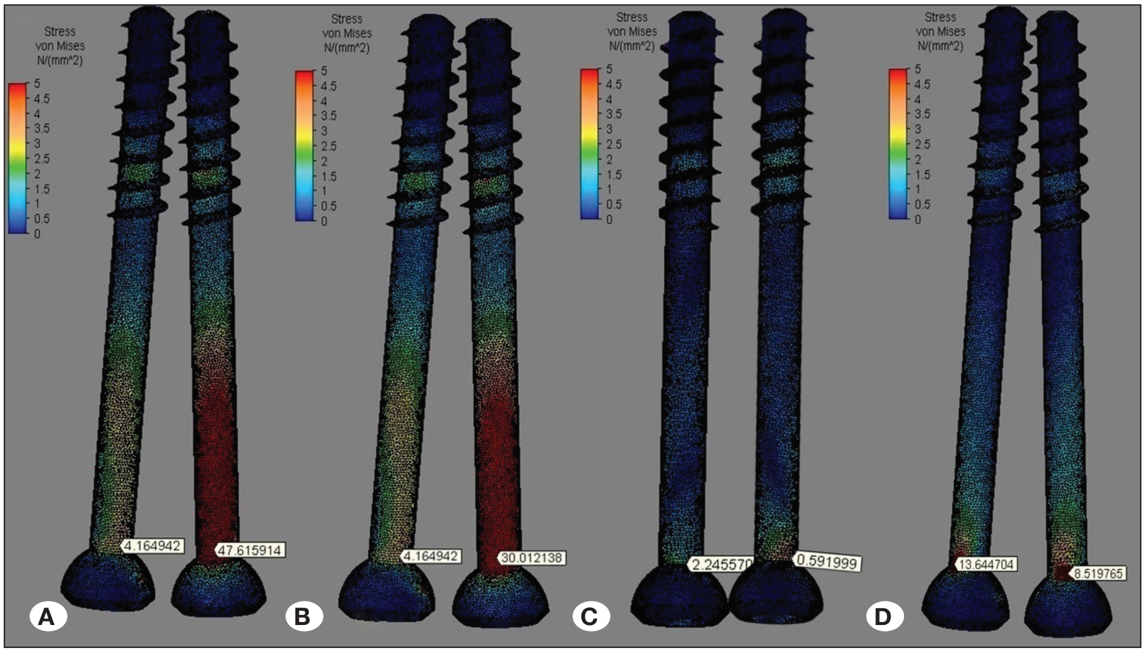

Figure 5: Stress nephogram of the double screw stabilization model during flexion **(A)**, extension **(B)**, rotation **(C)** and lateral bending **(D)**.

because the findings differ throughout the papers. Some authors argue that a single 4-mm anterior odontoid screw is sufficient and that there is no need to increase the surgical time or risk further difficulties by inserting a second screw because many patients lack the anatomical characteristics required. Other authors support double screw stabilization, claiming that fixation with two screws provides a significant area of perforation of the cortical bone on the upper portion of the odontoid, favoring fusion, particularly in osteoporotic patients (4).

Jenkins et al. conducted a retrospective study in 1998 and found no statistically significant difference in postoperative radiographs between single and double screw fixation (6). Otherwise, Pongmanee et al. reported in a retrospective study that even headless double screws with 3-mm diameters are highly effective for OF and have comparable biomechanical strength to traditional screws (14). However, in some cases, double screw fixation may be challenging. According to Nucci et al., the optimal transverse diameter of the dens is at least 9 mm to properly implant two odontoid screws. Radiographic tests have revealed that 30% to 66% of patients do not fit within this range and may be inappropriate for double screw fixation (12). Malunion is one of the most prevalent complications of AOF, affecting up to 13% of all patients and, in severe cases, leading to craniocervical instability and spinal cord injury. The actual etiology of malunion is unclear; however, it may be an age-related reduction in bone quality. The nonunion rate for patients under the age of 50 yr is just 4% compared with 12% for those over the age of 65 yr (16). This may be overcome by using two screws instead of one. Dailey et al. reported in a retrospective study that double screw insertion leads to high consolidation and stiffness, particularly when subjected to axial loads (7). In this study, patients with double screws had a 96% fusion rate compared with 56% in patients with only one screw. In 2021, Lvov et al. indicated in a meta-analysis that double screw insertion in osteoporotic patients had a higher risk for postoperative screw put-out; therefore, there is still a debate regarding this topic (9). IF, eighter by loosening, pulling out, or breaking screws may also result in malunion; however, the specific numbers are unclear. Because of the specific bony characteristics of the C2 vertebra and the odontoid, implant adhesion to quality bone can be challenging. Constant axial and rotational loads on the construct may cause increasing stress on the implants, resulting in IF. Our FEA aimed to examine the ROM and stress levels on implants following eight single- or double screw odontoid fixations. When examining the ROM, both the single and double screw models show similar results to the intact model. We also compared our findings to previous biomechanical studies that examined ROM following AOF or posterior fixation. Our findings were similar to those of the previous studies (Table III) (5,8,14). Neither single nor double screw fixation appreciably reduces ROM, and both mimic normal anatomy (Table IV). On the von Mises stress nephogram, the majority of the stress was consolidated throughout the whole shaft of the screw with a maximum distribution of 59 MPa, whereas on rotation and lateral bending, the stress accumulated on the screw heads and the distal shaft with 0.3 and 17 MPa, respectively. In the double screw model, stress is distributed only on the medially straight screw across the screw shaft during extension and flexion movements, with 47 and 30 MPa, respectively. However, the stress on the more lateral angulated screw was modest throughout the implant, measuring 4 MPa in both flexion and extension. The stress distribution during rotation was modest between both screws, with 2 MPa on the lateral and 0.5 MPa on the medial screw. The lateral bending measurements were 13 and 8 MPa, respectively. These data indicate that stress is distributed similarly in the single and double screw models. The double screw model places maximum stress on the whole shaft in flexion and extension and more distally during rotation and lateral bending, although the maximum stress values are lower. It also indicates that the second screw absorbs part of the stress-energy, resulting in reduced maximum stress in the double screw model.

CONCLUSION

AOF is the gold standard for the treatment of Anderson-D'Alonzo type II fractures in patients with intact transverse ligaments and no dislocation. Double odontoid screws reduce mechanical stress on implants, lowering the risk of IF while without significantly altering ROM. In patients who are physically appropriate for double screw insertion, we recommend this technique to reduce the risk of IF and malunion.

Declarations

Funding: None.

Availability of data and materials: The datasets generated and/or analyzed during the current study are available from the corresponding author by reasonable request.

Disclosure: The authors declare no competing interests.

AUTHORSHIP CONTRIBUTION

Study conception and design: KP

Data collection: OB

Analysis and interpretation of results: KP

Draft manuscript preparation: IA

Critical revision of the article: KP

Other (study supervision, fundings, materials, etc...): IA

All authors (KP, IA, OB) reviewed the results and approved the final version of the manuscript.

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