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ORIGINAL ARTICLE

Maximum Safety Limits of Laminectomy of the C1 Vertebra for Chiari Malformation Surgery: A Finite Element Analysis

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Abstract

Background The treatment of Chiari malformations generally consists of posterior fossa decompression. C1 laminectomy is required in selected cases. However, cases of iatrogenic anterior arch fractures at C1 without high-energy trauma have been reported. Developing theoretical models of atlas C1 bones that have undergone a laminectomy can help researchers identify the regions where fractures may occur as a result of sudden loads.

Methods In this study, we created a detailed three-dimensional solid finite element model of the human atlas bone (C1) using geometric data. The loadings of the laminectomy dimension were evaluated on the basis of three groups. Group I comprised atlas bones that had not undergone a laminectomy. For Group II, the lateral border of the laminectomy was determined as the projection of the lateral mass medial border on the lamina. For Group III, the bilateral sulcus arteriosus was determined as the border for the lateral border of the laminectomy. The analysis results, which are in good agreement with those of previous reports, showed high concentrations of localized stress in the anterior and posterior arches of the atlas bone.

Results The analysis results showed that the stress increased in the laminectomy models. The maximum stress observed was consistent with the clinical observations of fracture sites in previous studies.

Conclusion In the treatment of patients with Chiari malformations, C1 laminectomy is often required. The width of this laminectomy can lead to iatrogenic anterior arch fractures. This is the first study to evaluate C1 laminectomy width using finite element modeling.

Keywords Chiari · Finite element · Laminectomy · Limit

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Abbreviations

CMT1 Chiari malformation type 1
CSF Cerebrospinal fluid

Introduction

Chiari malformations comprise a diverse set of illnesses characterized by structural abnormalities of the cerebellum, brain stem, and craniocervical component that arise when the cerebellum, alone or in combination with the medulla, is pushed toward the spinal canal [1]. Chiari malformation type 1 (CMT1) is a congenital disorder in which the cerebellar tonsils are improperly formed and shifted beyond the level of the foramen magnum [2]. The goal of surgical therapy for Chiari malformations is to clear the craniocervical junction and restore normal cerebrospinal fluid (CSF) flow at the level of the foramen magnum [1].

Atlas fractures constitute approximately 10% of cervical-spine fractures [3]. Jefferson was the first to report that atlas fractures were caused by axial loading [4]. Furthermore, Panjabi reported that this type of fracture can occur with an axial load of 3,050 N [5]. C1 laminectomy is performed in the surgical treatment of CMT1 cases. In this type of iatrogenic C1 posterior arch defect, anterior arch fractures at C1 occur without high-energy trauma [6, 7]. Disruption in the circular structure of atlas bones treated with a C1 laminectomy without fusion creates mechanical stress in the anterior arch. Hence, spontaneous fractures can occur in the anterior arch of the atlas bone. A previous study concluded that the transverse ligament is an important mechanical support that reduces this stress and prevents these fractures [8, 9].

The aim of our study was to determine the risk of fracture in the anterior arch of the C1 vertebra according to the width of the laminectomy performed while achieving clinically adequate decompression with surgical planning for C1 laminectomy in patients with CMT1.

Materials and Methods

The loadings of the laminectomy dimension were evaluated on the basis of three groups. Group I comprised atlas bones that had not undergone a laminectomy. The sulcus arteriosus was used as a landmark to differentiate Group II and Group III. For Group II, the lateral border of the laminectomy was determined as the projection of the lateral mass medial border on the lamina. For Group III, the bilateral sulcus arteriosus was determined as the border for the lateral border of the laminectomy (Fig. 1). We used a finite element model to analyze the data from these three groups.

Model Geometry

Because the human C1 model used in this study was taken from an open source, no ethics committee approval was required. First, the C1 bone was cut using ANSYS 2021 R1 SpaceClaim, a computer program designed for the finite element method. Then the sharp corners in the C1 bone model were corrected to improve the accuracy of the analysis results after cutting. Finally, a solid model was created, and all the models were transferred to workbench for analysis. The atlas bone is approximately symmetrical in the midsagittal plane. The solid model was developed in two phases before the analysis: surface generation and solid definition. After the surface was created, the physical model was used to perform a detailed comparison of the surfaces of all the models to obtain accurate results. The four authors, three of whom were mechanical engineers and one of whom was a neurosurgeon, carried out the model creation and comparison. Then the solid model was devised by creating volume. The material properties of the C1 bone were obtained from previous studies and assigned to the finite element program [5, 10–13]. The modulus of elasticity and Poisson's ratio for the C1 bone are 12,000 MPa and 0.29, respectively [14].

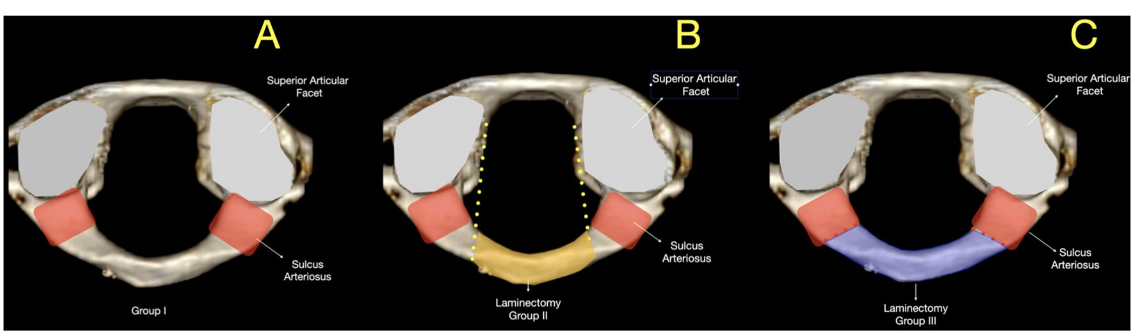

Fig. 1 Summary of Groups; **A** Group I, **B** Group II, **C** Group III

Mesh

After the solid model was created, the fine mesh was created based on the model, and precision in sharp corners was ensured. The material properties of the C1 bone's components were assumed to be linear elasticity, homogeneity, and isotropy [14, 15].

The solid model without a laminectomy had 51,787 nodes and 30,032 elements. The solid model with a 25-mm laminectomy had 42,888 nodes and 24,813 elements, whereas the solid model with a 30-mm laminectomy had 44,315 nodes and 25,720 elements.

Loading and Boundary Conditions

To better detect the damage, the head postures of individuals were imitated, and stress was applied to both sides of the upper surface in a direction perpendicular to the articular surface. The average weight of an adult human head in the neutral position was assumed to be 5 kg, and a load of approximately 5 kg (55 N) was applied to C1 [16]. The lower surfaces in contact with C2 were fixed. At the same time, the anterior region was restricted to moving perpendicularly to the articular surface and, anatomically, prevented from moving in the anteroposterior direction. These movement constraints allowed for the analysis of the C1 bone during sudden loading. A compressive force of 55 N was applied axially from the upper surface to imitate the load of the head in the neutral position.

Results

The estimated stress distribution for different loading configurations under different boundary conditions is presented in this section. The 55-N load was kept constant throughout the analysis.

The maximum von Mises stress for the atlas bone was 0.92276 MPa. The maximum total deformation was found to be 3.1061e-004 mm, and the maximum strain was 9.5062e-005 mm. The maximum von Mises stress for the C1 bone in Group II was found to be 1.531 MPa. The maximum total deformation was 3.8797e-004 mm, and the maximum strain was 1.5408e-004 mm. The maximum von Mises stress for the C1 bone in Group III was found to be 3.1862 MPa. The maximum total deformation was 7.8168e-004 mm, and the maximum strain was 3.4766e-004 mm.

The analysis showed that the laminectomy groups exhibited greater stress increases compared to the non-laminectomy group. The stress distribution exhibited a significant difference between the non-laminectomy group, on one hand, and the laminectomy models, on the other. The maximum stress observed was consistent with the clinical observations of fracture sites in previous studies. The elongation and lateral bending of the C1 bone in Group III exhibited extremely high stress in the left attachment region. The highest von Mises stress value (3.1862 MPa) was observed in the C1 bone in Group III (Figs. 2, 3, 4).

Discussion

Chiari malformations comprise a diverse set of illnesses characterized by structural abnormalities of the cerebellum, brain stem, and craniocervical component that arise when the cerebellum, alone or in combination with the medulla, is pushed toward the spinal canal [1]. CMT1 is a congenital disorder in which the cerebellar tonsils are improperly formed and shifted beyond the level of the foramen magnum [2].

The goal of surgical therapy for Chiari malformations is to clear the craniocervical junction and restore normal CSF flow at the level of the foramen magnum [1]. Before surgery, the results of the patient's computed tomography and magnetic resonance imaging examination should be thoroughly evaluated, and the dimensions of the tonsillar herniation should be determined. In surgical planning, the transverse width of decompression at the foramen magnum and C1 levels should be carefully calculated. If the tonsil has descended to the C2 level, C1 laminectomy alone is insufficient. In this case, at least the upper part of C2 must also be removed. It has been reported that when decompression is performed in young children, bone may develop again in the craniectomy area, and the disease may recur, albeit rarely [17]. In their study of minimally invasive surgical treatment for CMT1, Hu et al. defined adequate bone decompression as 3 cm for suboccipital craniotomy and 2.5 cm for C1 laminectomy [1]. Excessive bleeding, CSF leak, infection, no alleviation of symptoms, paralysis, swallowing difficulty, strange eye movements, and anesthetic complications are the associated surgical risks [18]. However, wide laminectomy increases the possibility of vertebral artery injury in the sulcus arteriosus.

Depending on the amount of descent of the tonsil, the surgery may involve suboccipital craniectomy and cervical laminectomy. Even after duraplasty, an insufficient wide cervical laminectomy of the C1 arch may result in persistent compression at the level of the obex [19]. In their study of the importance of C1 laminectomy in the surgical treatment of CMT1, Kumar et al. reported that no standard had been established for the procedure. After reviewing old data, they found that a 3-cm width was routine and sufficient for suboccipital craniotomy and C1 laminectomy, but the literature has not reported a standardization of this width [19]. Hirano et al. reported that the standard suboccipital craniotomy

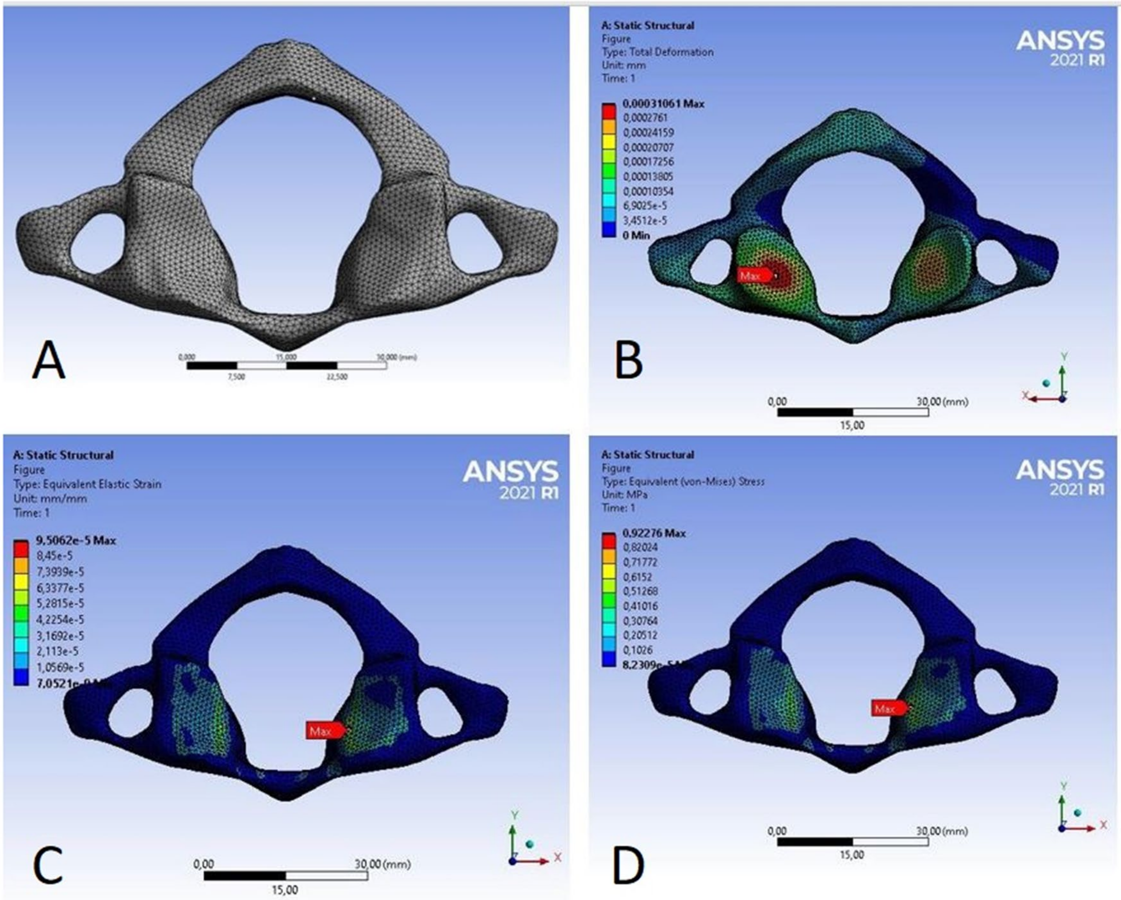

Fig. 2 **A** C1 atlas bone (Group I)**, B** maximum total deformation zone for full model C1 atlas bone**, C** strain zone for full model C1 atlas bone**, D** stress (Von-Mises) region for full model C1 atlas bone

width is 3 cm for CMT1, but they did not specify a standard width for C1 laminectomy [20].

The absence of instability is important for C1 laminectomy without fusion [21]. C1 laminectomy is a simple, minimally invasive procedure with a low complication rate in appropriate cases. In a cohort of 157 patients, Aghakhani et al. performed a C1 laminectomy in all the cases of foramen magnum decompression and observed clinicoradiological improvements in more than 90% of the cases [22]. Furtado et al. documented satisfactory results in 20 patients who had a C1 laminectomy and a condyle-to-condyle foramen magnum decompression during 9-year period [23]. However, depending on the width of the C1 laminectomy, iatrogenic anterior arch fractures may be observed [6–9, 20]. Gebauer et al. described the effect of axial force applied to the superior facet of the atlas bone and observed that the facet joint expanded laterally. This effect was defined as a factor of increased stress on atlas bones with impaired circular integrity [24]. Baghdassarian et al. detected an anterior arch fracture of an atlas bone with torticollis in a child with a history of C1 laminectomy; according to the authors, this was the first reported case of an anterior arch fracture of the atlas bone associated with surgery [6]. Jin et al. described a fracture of the anterior arch of the atlas bone without high-energy trauma due to a congenital cleft in the posterior arch of the bone. They observed hypertrophy in the anterior arch of patients that was due to chronic mechanical stress [25]. The width of this laminectomy can lead to iatrogenic anterior arc fractures. The aim of our study was to use finite element modeling to evaluate the effect of laminectomy width on the anterior arch in patients who underwent a C1 laminectomy for CMT1.

Finite element analysis is a well-known method and is used in various sectors and research projects. It allows novel ideas to be extensively “tried out” before a prototype is created, as well as components and systems that are difficult to experiment with and diagnostic inquiries. Finite element models have substantially improved our knowledge of the spine and its components [12, 26, 27].

In their study, Teo et al. applied tensile analysis to C1 that was not subjected to laminectomy. They compared the analysis results with computed tomography images of

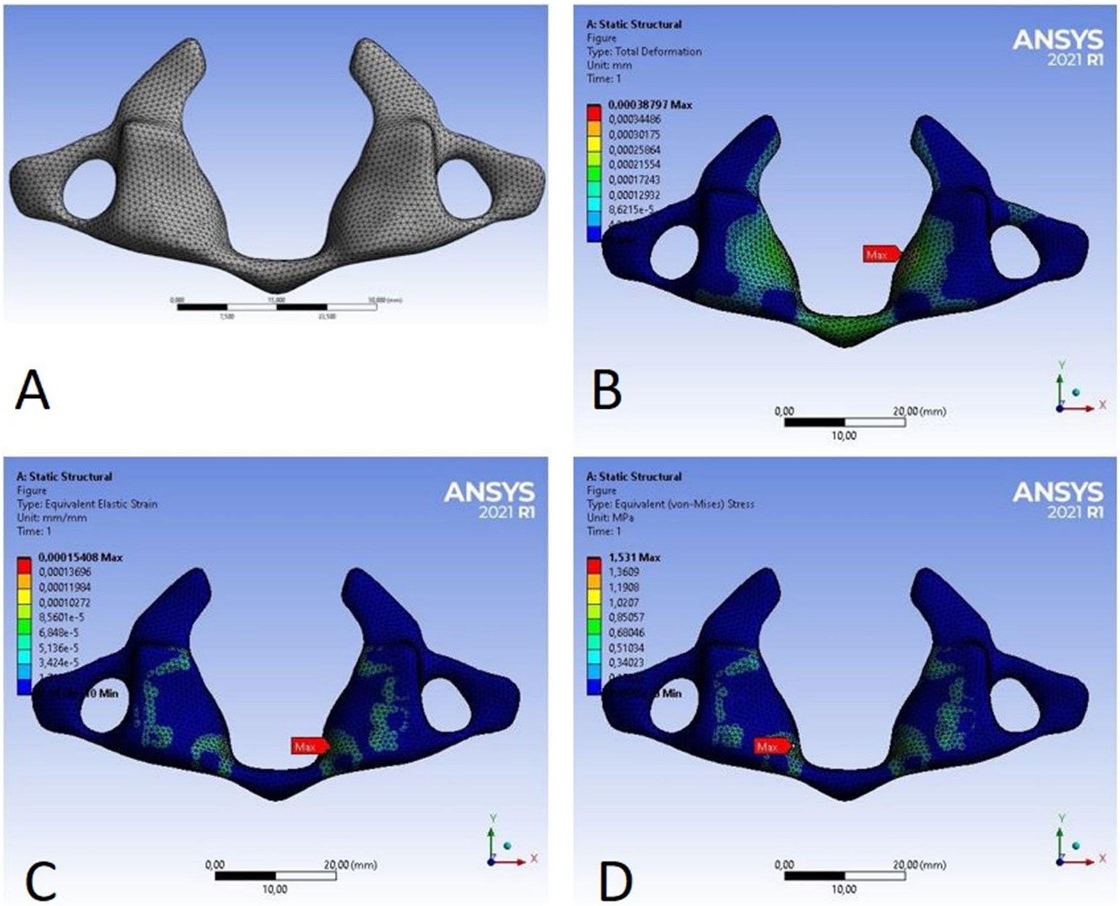

Fig. 3 **A** C1 bone laminectomy in Group II, **B** m aximum total deformation zone for C1 bone in Group II, **C** strain zone for C1 bone in Group II, **D** C1 bone stretch (Von-Mises) region in Group II

fractured C1. The results of the analysis of the C1 bone were in good agreement with those reported in the literature [10]. Shimizu et al. analyzed human C1 bone, which is located at the posterior arch approximately 25 mm from the laminectomy bone, and showed that the stress intensity observed in the finite element model was consistent with the clinically observed fracture zone [8]. According to Shimizu et al., the load on the anterior arch after a C1 laminectomy was 3.55 times higher than normal. This type of fracture is rare, but it can occur even after minimal trauma, such as that caused by coughing, and may also be asymptomatic [8]. The incidence rate of incidental anterior arch fractures after a C1 laminectomy is thought to be higher than reported. Another study reported that 14.2% of patients who underwent a C1 laminectomy after CMT1 surgery had an anterior arch fracture [9]; however, this study did not contain information about laminectomy width [8]. In our study, we used the finite element model to determine the extra load on the anterior arch of the atlas bone after C1 laminectomy without fusion in CMT1 cases. As the laminectomy width increases, the load on the anterior vertebral corpus increases. Based on three C1 vertebrae conditions, we examined the load distribution on the anterior arch of the vertebra using the finite element model. Using the results of the data analysis, we calculated the load on the anterior arch; the load was 1.415 in Group I (no laminectomy), 2.029 in Group II, and 6.719 in Group III.

The literature review revealed that no previous study has reported similar data. In addition, similarities were observed between the cases of anterior arch fracture that developed after C1 laminectomy and the fracture locations reported in the literature. Anterior arch fractures typically develop in the immediate vicinity of the anterior arch–odontoid junction. O'Shaughnessy et al. reported two cases of anterior arch fracture after C1 laminectomy performed during CMT1 surgery. In both cases, the fracture was localized in the immediate vicinity of the anterior arch–odontoid junction [7]. Fractures in the same location were found in the cases presented as examples in the study conducted by Shimizu and Hirano et al. [8, 20]. Therefore, in patients undergoing a C1 laminectomy for CMT1, the laminectomy should

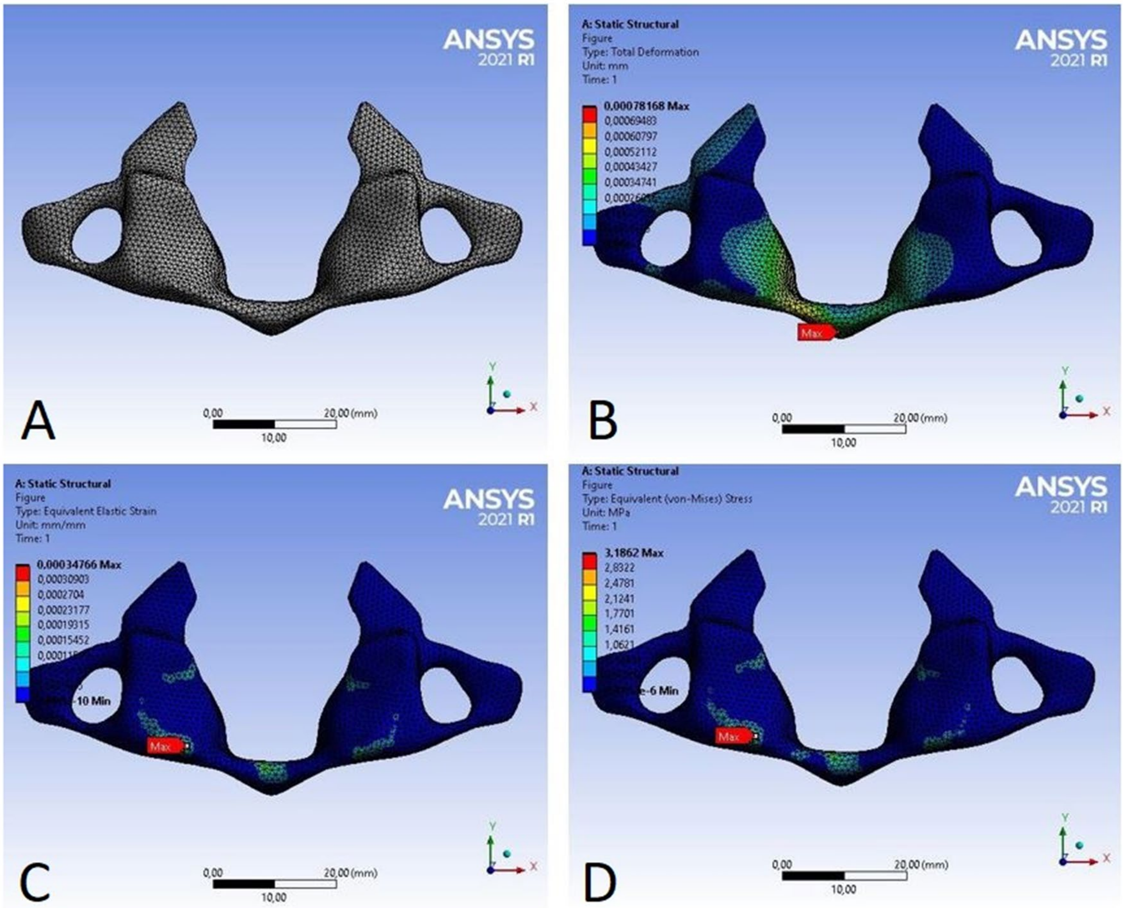

Fig. 4 **A** C1 bone laminectomy in Group III, **B** maximum total deformation zone for C1 bone in Group III, **C** strain zone for C1 bone in Group III, **D** C1 bone stretch (Von-Mises) region in Group III

be wide enough to ensure adequate decompression but sufficiently limited in width to prevent subsequent fractures. Our study is in line with the literature data. Unlike previous studies, ours defines laminectomy width according to anatomical landmarks rather than the centimeter measurement unit. Because lamina sizes may differ between women, men, and children, we believe our approach will provide a more precise assessment measure.

The central limitation of our study is that it used only finite element modeling and compressive force and did not include a case series. Therefore, multicenter studies that investigate a larger number of cases and use six degrees of freedom [28] should be conducted in the near future.

Conclusion

Our study using finite element modeling reveals that as the width of the laminectomy increases, the load on the anterior arch increases, which can cause anterior arch fractures. This is the first finite element modeling study to evaluate C1 laminectomy width in Chiari malformation surgery.

Author Contribution All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by AEK, EK, BAT, BB. The first draft of the manuscript was written by AEK, CKY, MUE, ATÇ, and SN contributed to the editing and reviewing of the manuscript during the revision phase. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability statement The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Declarations

Conflict of Interest The authors have no relevant financial or non-financial interests to disclose.

Ethical Approval This is an observational study. The Umraniye Training and Research Hospital Ethics Committee has confirmed that no ethical approval is required.

Consent to Participate This study does not include patient data

Consent to Publish This study does not include participant images

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