fortune Journals

Research Article

JOURNAL OF SPINE RESEARCH AND SURGERY

ISSN: 2687-8046

C1-Ring Osteosynthesis as a Safe and Effective Method for C1 Fractures

Maria Goldberg[1*], Felix Bader[2], Maria Wostrack[1], Bernhard Meyer[1], Nicole Lange[1]

Abstract

Background: C1 fractures are traditionally treated with C1–2 fixation and fusion because they are thought to provide a better level of stability. However, this surgical treatment is associated with a reduced range of motion. C1 ring osteosynthesis is an alternative technique that provides adequate fracture healing while preserving the range of motion. We aimed to describe the clinical and radiological outcomes of patients with C1 fractures treated with C1 osteosynthesis.

Methods: This retrospective single-center study included all patients with C1 fractures who underwent C1-ring osteosynthesis surgery during 2007–2023. Lateral mass displacement (LMD), atlantodental interval (ADI), hospital stay, surgical duration, and surgical complications were analyzed.

Results: Overall, 38 patients were identified. Thirty patients received C1 ring osteosynthesis alone, and eight patients had associated polytrauma and multiple surgeries including other spondylodesis in the cervical spine (17 female, 21 male; age: 57.3 ± 23.7 years). The mean operative duration was 94 ± 17 minutes. The mean hospital stay was 18.2 ± 7.6 days, however, after excluding polytraumatic patients with long intensive care treatment, the mean hospital stay was 9.8 ± 1.4 days. No postoperative neurological deterioration was observed. All patients reported pain relief shortly after surgery. ADI and bi- and unilateral LMD were significantly reduced after surgery.

Conclusion: Based on this analysis, C1 ring osteosynthesis is a safe and feasible procedure for treating C1 fractures. Radiographic and clinical parameters were significantly improved, while complication rates were comparable to those of other methods.

Keywords: C1 fracture; C1 fixatio; C1-Ring Osteosynthesis; Open Reduction and Internal Fixation (ORIF), Atlas fracture, ADI, LMD

Introduction

Cervical spine fractures account for approximately 10% of injuries in trauma patients [1,2]. One-Tenth of cervical spine injuries are atlas fractures [3], with falls and motor vehicle accidents being the most common traumatic mechanisms [4]. More than two-thirds of C1 fractures are associated with codominant injuries, mostly C2 fractures [5]. The most recent report estimated the incidence of C1 fractures to be 157 per million people aged >50 years [6]. A distinct age distribution was observed, with one population centered at age 30 years and the other at 70 years [7].

Although C1 fractures represent a relatively small subset of cervical spine injuries, they are often overlooked and are associated with complications such as atlantoaxial or atlantooccipital instability [8].

Affiliation:

[1]Department of Neurosurgery, School of Medicine, Klinikum rechts der Isar, Technical University of Munich, 81675 Munich, Germany.

[2]School of Dentistry, Ludwig-Maximilian University of Munich, 80539 Munich, Germany.

***Corresponding author:**
Maria Goldberg, Department of Neurosurgery, School of Medicine, Klinikum rechts der Isar, Technical University of Munich, 81675 Munich, Germany.

Citation: Maria Goldberg, Felix Bader, Maria Wostrack, Bernhard Meyer, Nicole Lange. C1-Ring Osteosynthesis as a Safe and Effective Method for C1 Fractures, Journal of Spine Research and Surgery. 6 (2024): 93-99.

Received: August 07, 2024
Accepted: August 19, 2024
Published: August 31, 2024

The management of atlas fractures remains controversial despite the incidence nearly doubling [3]. Based on the widely used Gehweiler classification, isolated C1 fractures can be divided into stable and unstable fractures [9]. Gehweiler fracture types 1, 2, and 5 are considered stable and are often treated conservatively with a halo brace for up to 12 months [10]. However, recent data have shown that consolidation failure occurs in approximately 15% of all conservatively treated patients [11]. It is widely accepted that unstable atlas fractures should be treated surgically. However, there remains a discrepancy between the diagnosis used to assess stability and the choice of treatment [10]. The rate of surgical intervention has been steadily increasing over the last decade [12].

Among surgical interventions, C1–2 fusion has traditionally been the most widely used technique to treat isolated C1 fractures and ensure atlantoaxial stability [13–15] However, this method compromises the mobility of adjacent joints. A new technique, C1 ring osteosynthesis, has been introduced to preserve the range of motion [16–19].

There is currently no standard treatment for C1 fractures. Hence, this study aimed to evaluate and describe a single-segment C1 stabilization method for the treatment of C1 fractures in terms of clinical and radiographic characteristics and complication rates.

Material and Methods

Patient population

All patients with atlas fractures between 2006 and 2023 were retrospectively analyzed at our institution. Of the 164 patients, 38 were treated surgically, and the rest were treated conservatively with a cervical collar. Those who were treated conservatively either had a stable fracture with no band disruption or elected not to undergo surgery. All fractures were treated with the posterior approach and ring osteosynthesis using pedicle screws and rods. All patients had documented symptoms, timing of surgery, hospital stay, imaging data, and complications during hospitalization. Of the 38 patients, 8 had associated polytrauma and multiple operations, including cervical spondylodesis other than C2. The mean age of the patients was 57 ± 24 years. Six patients were injured in a motor vehicle accident, 30 in a fall, and 2 in a fall from a height. Neurological deficits were observed in 7 patients (5 polytrauma patients with head trauma or other cervical fractures), while the rest reported cervical pain and no other acute neurological symptoms.

Radiographical and clinical data

All patients underwent computed tomography (CT) before and after surgery during their hospital stay. CT was used to classify the fracture type and assess stability. Bilateral and unilateral lateral mass displacement (LMD) and atlantodental interval (ADI) were analyzed before and after fixation using coronal and sagittal reconstructed views (Figure 1).

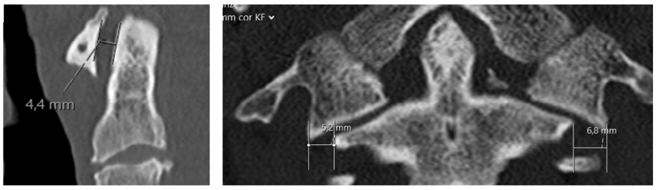

Fig 1: Examples of ADI and LMD measurements

a. Atlantodental interval (ADI) as the horizontal distance between the lateral cortex of the dens and the medial cortex of the lateral masses. b. lateral masses displacement (LMD) as the sum of the overhang of the lateral mass of C1 over C2 or an interval on a prominent sight.

Preoperatively, 36 patients underwent magnetic resonance imaging (MRI) to evaluate the integrity of the craniovertebral junction ligaments. Radiological measurements were performed using picture archiving and communication system software.

Additionally, surgical complications, such as vertebral artery injury, screw malposition, increased hospital stay and operative duration, and short-term postoperative complications (such as infection and pulmonary embolism) were analyzed.

Surgical procedure

The patient's head was placed in a Mayfield cranial clamp in the prone position, with slight head traction and tilt. A posterior midline incision was made from the occiput to C2. The dorsal arch of C1 was exposed. A 2.6-mm cannulated drill was used to place the lateral mass screws under fluoroscopic control. The two screws were connected to a horizontal rod (Neon; Ulrich GmbH & Co., Ulm, Germany). No postoperative collar fixation was performed. Intraoperative fluoroscopy or C-arm 3D imaging was used during surgery to check the screw position. CT scans were obtained shortly after surgery and during the hospital stay.

Statistics

Data are presented as frequencies (n) with percentages (%) and standard errors of the mean (SEMs). Statistical analyses were performed using GraphPad Prism v. 8.3.1 (GraphPad Software, Boston, MA, USA). A paired t-test was used to compare radiological characteristics before and after surgical treatment. The significance level was set at $p < 0.05$.

Results

Clinical data

A total of 38 patients (17 female, 21 male; mean age 57.3 ± 23.7 years) with atlas fractures who underwent surgical treatment with posterior C1 osteosynthesis were analyzed (Table 1). All patients underwent surgical stabilization as the primary treatment. None of the patients underwent secondary surgery after failure of conservative treatment. The initial radiological diagnosis was based on the Gehweiler fracture classification. Three patients had a Gehweiler type 1 fracture, 25 had a Gehweiler type 3 fracture, and 10 had a Gehweiler type 4 fracture. Radiographs of each type of fracture are shown in Figure 2. Of the 25 type 3 fractures, 11 had ligament lesions confirmed via MRI. Dickman types I and II transverse atlas ligament (TAL) injuries were observed in three and eight patients, respectively.

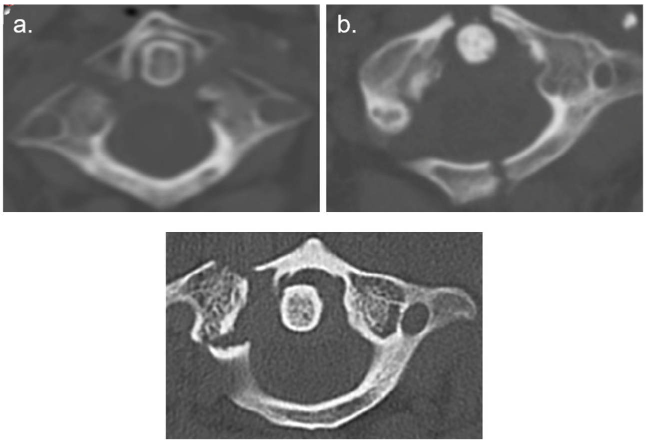

Fig 2: Examples of C1 fractures

a. Gehweiler type 1, b. Gehweiler type 3, c. Gehweiler type 4.

The mean operative duration was 94 ± 17 minutes. The mean length of hospital stay was 18 ± 8 days. However, after excluding polytraumatic patients with long intensive care treatment, the mean hospital stay was 9 ± 2 days. Vertebral artery injury was documented in 4 procedures (10%), screw malposition requiring revision in 1 patient (3%), and pulmonary embolism in 1 patient (3%). No infectious complications were observed. One patient reported mild neck pain one year after surgery without evidence of material loosening. No neurological deterioration was observed after surgery, even in cases of vertebral artery injury. All patients with pain syndromes reported relief of pain and stiffness shortly after surgery.

Radiographical data

ADI was used to assess the atlantoaxial instability. Another parameter used to assess the transverse ligament displacement was the unilateral overhang of the lateral masses. Radiographic measurements were performed on coronal CT scans obtained after the injury and immediately after surgical treatment. ADI was defined as the distance between the posterior cortex of the atlas and the anterior cortex of the dens. The sum of the lateral mass overhang and unilateral displacement of the atlas against the axis were measured (Figure 3). Postoperative CT showed good screw and rod placement and satisfactory fracture reduction in all cases.

Table 1: Patient population

Patients Characteristics	C1-ring osteosynthesis (n = 38)
Sex	
Female	17
Male	21
Age, years	57.3 ± 23.7
Fracture type:	
Gehweiler 1	3 (8%)
Gehweiler 2	0
Gehweiler 3	25 (66%)
Gehweiler 4	10 (26%)
Gehweiler 5	0
Neurological symptoms prior to surgery	7
Neurological deterioration after surgery	0
Complication:	
Injury of vertebral artery	4 (10%)
Pulmonary embolism	1 (3%)
Screw mispositioning	1 (3%)
Screw loosening/revisions	0
Infection	0

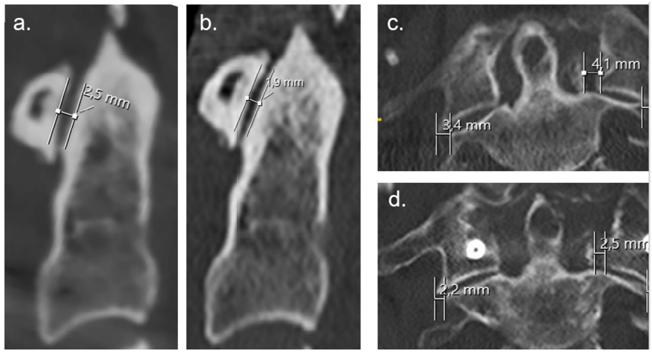

Fig 3: ADI and LMD measurements before and after surgery

Explamles of atlantodental interval (ADI) measurement a. before and b. after C1 osteosynthesis, as well as lateral mass displacement (LMD) c. before and d. after surgery. Addtitionaly fracture line distance is marked on pictures c. and d.

A summary of the radiological parameters is shown in Table 2. The mean preoperative ADI was 2.1 ± 1.2 mm, and was significantly reduced postoperatively (1.45 ± 1.0 mm; p = 0.002674). The preoperative LMD was 5.5 ± 2.5 mm. The overhang was significantly reduced after C1 osteosynthesis (4.2 ± 2.6 mm; p = 0.045909). The same trend was observed for unilateral LMD (3.6 ± 1.6 mm vs. 2.5 ± 1.4 mm; p = 0.000063; Table 2 and Figure 4). There was no evidence of internal fixation loosening or fracture on the postoperative CT scans.

Table 2: Radiological characteristics

ADI			LMD bilateral			LMD unilateral		
preop	postop	p	preop	postop	p	preop	postop	p
2.1 ± 1.2	1.45 ± 1.0	0.002674	5.5 ± 2.5	4.2 ± 2.6	0.045909	3.6 ± 1.6	2.5 ± 1.4	0.000063

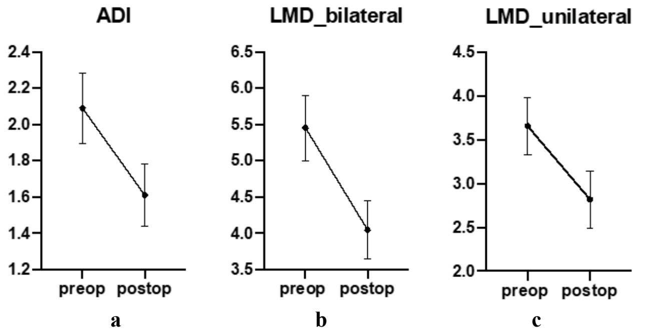

Fig 4: Graphical presentation of ADI and LMD reduction after surgery

Data are presented as SEM for a) atlantodental interval (ADI), b) sum of lateral mass displacement (LMD bilateral), and c) lateral mass displacement at a more prominent sight (LMD unilateral). The y-axis represents the interval in millimeters. The x-axis shows the two parameters before and after surgery.

Discussion

The C1 vertebra has a unique anatomy that allows the vertical and horizontal mobility of the head and cervical spine. The treatment of choice for atlas injuries remains controversial and there are no guidelines. Various classifications have been proposed to guide the choice of conservative or surgical treatment. Fractures involving only the anterior or posterior arch are defined as stable because they are unlikely to disrupt the ligaments. Burst and Jefferson fractures are defined as unstable fractures due to the involvement of both arches and a higher likelihood of ligament damage. Lateral masses or transverse process fractures are also considered stable fractures [20,21]. External fixation is the treatment of choice for isolated C1 fractures. Fracture types 1, 2, 4, and 5 are defined as stable fractures and have been treated conservatively by many authors [22]. However, conservative treatment, especially in older patients, is more often associated with non-consolidation, regardless of the fracture type. In patients with stable fractures who were treated conservatively, a consolidation rate of only 84% was achieved [22]. Some authors have reported a nonunion rate of >20% after conservative treatment [23]. Nonunion with subsequent surgical treatment does not yield as good results as primary surgery [24]. Another report found that 10% of elderly patients underwent secondary surgery after inadequate alignment [25]. Recent data suggest that type 4 fractures associated with TAL injuries cannot be treated adequately with external fixation. Moreover, all radiographic and clinical parameters worsened after conservative treatment [26]. Conservative treatment with a halo brace is also associated with a higher rate of complications such as dysphagia and respiratory instability, especially in elderly patients [27,28].

Unstable atlas fractures are traditionally treated using C1–2 or C0–2 fusion techniques. These techniques provide high degrees of bone stability and fusion [29]. However, this is associated with limited axial rotation [30].

To preserve this motion, other methods that stabilize only one segment have been introduced [31–37] A recent study showed the superiority of C1 osteosynthesis over C1-2 fusion in terms of operative time, complications, and clinical outcomes [38].

At our center, isolated C1 fractures without additional discoligamentous injuries are treated using posterior monosegmental osteosynthesis. Most patients with isolated atlas fractures do not present with neurological symptoms besides neck stiffness and pain. We did not observe any worsening of neurological symptoms, which is consistent with other reports [36]. The rate of intraoperative complications, such as vertebral artery injury or screw malposition, is comparable to that of other surgical techniques [39,40].

Fracture stability can be defined based on ligament integrity. TAL is considered the strongest ligament in the spine, providing stability to the upper cervical spine [41]. Dickman et al. introduced the concept of anterior instability of C1–2 based on TAL rupture [42]. However, biomechanical studies have shown that longitudinal ligaments have sufficient capacity within the physiological loading range to maintain the stability of the atlantoaxial joint, even in the presence of concomitant ligament injuries, making C1 osteosynthesis a good alternative to multisegmental fusion techniques [43].

Traditionally, ADI of >3 mm and total LMD of >6.9 mm have been considered good predictors of TAL rupture. First described by Spence in 1970, many researchers still use this cutoff [43]. However, this measure has been questioned recently. New data show that the probability of TAL injury is high when the LMD exceeds 3.8 mm [44]. In another study, the mean overhand lateral mass in patients with confirmed TAL injury was 5.3 mm [45]. However, there is a documented case of confirmed TAL injury with an LMD measuring <1 mm [46]. Both the ADI and LMD were lower than average in our study, supporting the above findings. We observed a significant reduction in both parameters after C1-ring osteosynthesis on postoperative CT scans.

All the patients reported pain relief during their hospital stay. Unfortunately, follow-up radiological control is not part of postoperative management. Only one patient reported persistent neck pain (VAS; 2/10) 1 year after surgery, with no screw loosening found on imaging.

The limitations of this study were its retrospective nature and the lack of follow-up. Long-term clinical and radiographic results provide valuable information for the characterization of C1-ring osteosynthesis. Despite these facts, we believe that this technique is appropriate for the treatment of isolated atlas fractures. However, this did not result in a higher rate of complications and provided motion preservation. This is a fast and safe method that can be used as standard treatment for unstable C1 fractures.

Conclusion

C1 osteosynthesis is a safe and reliable method for treating isolated atlas fractures. The rates of intra and postoperative complications were similar to those of other stabilization techniques. No postoperative neurological deterioration was observed after the described procedure. Atlas fractures can be successfully treated without compromising cervical spinal mobility.

Statements and Declarations:

Funding: The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Competing Interests

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

Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Maria Goldberg and Felix Bader. The first draft of the manuscript was written by Maria Goldberg and all authors commented on previous versions of the manuscript. Maria Wostrack Bernhard Meyer and Nicole Lange read and approved the final manuscript.

Ethics approval

This is an observational study. The Research Ethics Committee of Technical University of Munich has confirmed that no ethical approval is required.

Consent to participate

Written consent was waved by the local Research Ethics Committee of Technical University of Munich.

Consent to publish

Written consent was waved by the local Research Ethics Committee of Technical University of Munich.

Data availability

The datasets generated during the current study are available from the corresponding author on reasonable request.

References

1. Umana E, Khan K, Baig M, et al. Epidemiology and Characteristics of Cervical Spine Injury in Patients Presenting to a Regional Emergency Department. Cureus (2018).
2. Fredø HL, Rizvi SAM, Lied B, et al. The epidemiology of traumatic cervical spine fractures: a prospective population study from Norway. Scand J Trauma Resusc Emerg Med 20 (2012): 85.
3. Matthiessen C, Robinson Y. Epidemiology of atlas fractures—a national registry–based cohort study of 1,537 cases. The Spine Journal 15 (2015): 2332-2337.
4. Kakarla UK, Chang SW, Theodore N, et al. Atlas Fractures. Neurosurgery 66 (2010): A60-67.
5. Utheim NC, Helseth E, Stroem M, et al. Epidemiology of traumatic cervical spinal fractures in a general Norwegian population. Inj Epidemiol 9 (2022): 10.
6. Lyons J, Mian H. Epidemiology of atlas fractures in the United States: A 20-year analysis. J Craniovertebr Junction Spine 13 (2022): 85.
7. Cloney MB, El-Tecle N, Dahdaleh NS. Traumatic atlas fracture patients comprise two subpopulations with distinct demographics and mechanisms of injury. Clin Neurol Neurosurg 221 (2022): 107414.
8. Mead LB, Millhouse PW, Krystal J, et al. C1 fractures: a review of diagnoses, management options, and outcomes. Curr Rev Musculoskelet Med 9 (2016): 255-262.
9. Fiedler N, Spiegl UJA, Jarvers J-S, et al. Epidemiology and management of atlas fractures. European Spine Journal 29 (2020): 2477-2483.
10. Laubach M, Pishnamaz M, Scholz M, et al. Interobserver reliability of the Gehweiler classification and treatment strategies of isolated atlas fractures: an internet-based multicenter survey among spine surgeons. European Journal of Trauma and Emergency Surgery 48 (2022): 601-611.
11. Lleu M, Charles YP, Blondel B, et al. C1 fracture: Analysis of consolidation and complications rates in a prospective multicenter series. Orthopaedics & Traumatology: Surgery & Research 104 (2018): 1049-1054.
12. Armaghani SJ, Grabel ZJ, Vu C, et al. Variations in treatment of C1 fractures by time, age, and geographic

Goldberg M, et al., J Spine Res Surg 2024
DOI:10.26502/fjsrs0079

region in the United States: An analysis of 985 patients. Orthop Rev (Pavia) (2018): 10.

13. Kakarla UK, Chang SW, Theodore N, et al. Atlas Fractures. Neurosurgery 66 (2010): A60-67.

14. Zhang Y, Zhang J, Yang Q, et al. Posterior osteosynthesis with monoaxial lateral mass screw-rod system for unstable C1 burst fractures. The Spine Journal 18 (2018): 107-114.

15. Kim HS, Cloney MB, Koski TR, et al. Management of Isolated Atlas Fractures: A Retrospective Study of 65 Patients. World Neurosurg 111 (2018): e316-322.

16. Harms J, Melcher RP. Posterior C1–C2 Fusion With Polyaxial Screw and Rod Fixation. Spine (Phila Pa 1976) 26 (2001): 2467-2471.

17. Abeloos L, De Witte O, Walsdorff M, et al. Posterior Osteosynthesis of the Atlas for Nonconsolidated Jefferson Fractures. Spine (Phila Pa 1976) 36 (2011): E1360-1363.

18. Ruf M, Melcher R, Harms J. Transoral Reduction and Osteosynthesis C1 as a Function-Preserving Option in the Treatment of Unstable Jefferson Fractures. Spine (Phila Pa 1976) 29 (2004): 823-827.

19. He B, Yan L, Zhao Q, et al. Self-designed posterior atlas polyaxial lateral mass screw-plate fixation for unstable atlas fracture. The Spine Journal 14 (2014): 2892-2896.

20. Dvorak MF, Johnson MG, Boyd M, et al. Long-term health-related quality of life outcomes following Jefferson-type burst fractures of the atlas. J Neurosurg Spine 2 (2005): 411-417.

21. Kakarla UK, Chang SW, Theodore N, et al. Atlas Fractures. Neurosurgery 66 (2010): A60-67.

22. Lleu M, Charles YP, Blondel B, et al. C1 fracture: Analysis of consolidation and complications rates in a prospective multicenter series. Orthopaedics & Traumatology: Surgery & Research 104 (2018): 1049-1054.

23. Horn EM, Theodore N, Feiz-Erfan I, et al. Complications of halo fixation in the elderly. J Neurosurg Spine 5 (2006):46-49.

24. Hein C, Richter H-P, Rath SA. Atlantoaxial Screw Fixation for the Treatment of Isolated and Combined Unstable Jefferson Fractures - Experiences with 8 Patients. Acta Neurochir (Wien) 144 (2002): 1187-1192.

25. Ylönen H, Danner N, Jyrkkänen H-K, et al. Surgically Treated C1 Fractures: A Population-Based Study. World Neurosurg 154 (2021): e333-342.

26. Kim WJ, Park J-B, Park H-J, et al. Clinical and radiological outcomes of conservative treatment for unilateral sagittal split fractures of C1 lateral mass. Acta Orthop Traumatol Turc 53 (2019): 402-407.

27. Kandziora F, Chapman JR, Vaccaro AR, et al. Atlas Fractures and Atlas Osteosynthesis: A Comprehensive Narrative Review. J Orthop Trauma 31 (2017): S81-89.

28. Horn EM, Theodore N, Feiz-Erfan I, et al. Complications of halo fixation in the elderly. J Neurosurg Spine 2006;5: 46-49.

29. Sim HB, Lee JW, Park JT, et al. Biomechanical Evaluations of Various C1-C2 Posterior Fixation Techniques. Spine (Phila Pa 1976) 36 (2011): E401-407.

30. Hadley MN, Walters BC, Grabb PA, et al. Guidelines for the management of acute cervical spine and spinal cord injuries. Clin Neurosurg 49 (2002): 407-498.

31. Zou X, Ouyang B, Wang B, et al. Motion-preserving treatment of unstable atlas fracture: transoral anterior C1-ring osteosynthesis using a laminoplasty plate. BMC Musculoskelet Disord 21 (2020): 538.

32. Ruf M, Melcher R, Harms J. Transoral Reduction and Osteosynthesis C1 as a Function-Preserving Option in the Treatment of Unstable Jefferson Fractures. Spine (Phila Pa 1976) 29 (2004): 823-827.

33. Shatsky J, Bellabarba C, Nguyen Q, et al. A retrospective review of fixation of C1 ring fractures—does the transverse atlantal ligament (TAL) really matter? The Spine Journal 16 (2016): 372-379.

34. Abeloos L, De Witte O, Walsdorff M, et al. Posterior Osteosynthesis of the Atlas for Nonconsolidated Jefferson Fractures. Spine (Phila Pa 1976) 36 (2011): E1360-1363.

35. Ma W, Xu N, Hu Y, et al. Unstable atlas fracture treatment by anterior plate C1-ring osteosynthesis using a transoral approach. European Spine Journal 22 (2013): 2232–2239.

36. Zhang Y, Zhang J, Yang Q, et al. Posterior osteosynthesis with monoaxial lateral mass screw-rod system for unstable C1 burst fractures. The Spine Journal 18 (2018): 107-114.

37. He B, Yan L, Zhao Q, et al. Self-designed posterior atlas polyaxial lateral mass screw-plate fixation for unstable atlas fracture. The Spine Journal 14 (2014): 2892–2896.

38. Yan L, Du J, Yang J, et al. C1-ring osteosynthesis versus C1–2 fixation fusion in the treatment of unstable atlas fractures: a multicenter, prospective, randomized controlled study with 5-year follow-up. J Neurosurg Spine 37 (2022): 157–165.

39. Lall R, Patel NJ, Resnick DK. A Review of Complications Associated With Craniocervical Fusion Surgery. Neurosurgery 67 (2010): 1396-1403.

40. Stulík J, Vyskocil T, Sebesta P, Kryl J. [Harms technique of C1-C2 fixation with polyaxial screws and rods]. Acta Chir Orthop Traumatol Cech 72 (2005): 22–27.

Goldberg M, et al., J Spine Res Surg 2024
DOI:10.26502/fjsrs0079

41. PANJABI MM, ODA T, CRISCO JJ, OXLAND TR, KATZ L, NOLTE L-P. Experimental Study of Atlas Injuries I. Spine (Phila Pa 1976) 16 (1991): S460-465.

42. Dickman CA, Greene KA, Sonntag VKH. Injuries Involving the Transverse Atlantal Ligament: Classification and Treatment Guidelines Based upon Experience with 39 Injuries. Neurosurgery 38 (1996): 44-50.

43. Spence KF, Decker S, Sell KW. Bursting atlantal fracture associated with rupture of the transverse ligament. J Bone Joint Surg Am 52 (1970): 543-549.

44. Woods RO, Inceoglu S, Akpolat YT, et al. C1 Lateral Mass Displacement and Transverse Atlantal Ligament Failure in Jefferson's Fracture: A Biomechanical Study of the "Rule of Spence." Neurosurgery 82 (2018): 226-231.

45. Radcliff KE, Sonagli MA, Rodrigues LM, et al. Does <scp> C 1 </scp> Fracture Displacement Correlate with Transverse Ligament Integrity? Orthop Surg 5 (2013): 94-99.

46. Perez-Orribo L, Snyder LA, Kalb S, et al. Comparison of CT versus MRI measurements of transverse atlantal ligament integrity in craniovertebral junction injuries. Part 1: A clinical study. J Neurosurg Spine 24 (2016): 897-902.