C1–C2 arthrodesis after transoral odontoidectomy and suboccipital craniectomy for ventral brain stem compression in Chiari I patients

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Abstract Chiari I malformations are often associated with congenital craniocervical anomalies such as platybasia, basilar invagination, and retroflexion of the odontoid process. Management of ventral brain stem compression associated with Chiari I malformations remains controversial, but several authors report a significant rate of failure with suboccipital decompression alone in the presence of pronounced ventral brain stem compression (VBSC). Treatment options described in the literature for these patients involve anterior, posterior, or combined decompressions with or without concurrent arthrodesis. A combined anterior and posterior approach provides a definitive circumferential decompression but also significantly disrupts the stability of the occipitocervical junction usually necessitating occipitocervical fixation. We describe an alternative surgical treatment for Chiari I patients with significant ventral brain stem compression where a combined anterior and posterior decompression was considered necessary. We report two patients who underwent transoral odontoidectomy with preservation of the anterior arch of the atlas and suboccipital craniectomy with C1 laminectomy followed by C1–C2 arthrodesis. Preservation of the anterior arch of the atlas in conjunction with C1–C2 arthrodesis stabilizes the occipito–atlanto-axial segments while conserving more cervical mobility as compared to an occipitocervical fusion.

Keywords Chiari malformation · Ventral brain stem compression · Spinal fusion · Transoral odontoidectomy · Atlanto-axial joint

Introduction

Chiari I malformations are generally defined as cerebellar tonsillar descent greater than 5 mm below the foramen magnum. When symptomatic it is usually treated by suboccipital decompression [6, 12, 17, 38]. Management of Chiari malformations with ventral brain stem compression (VBSC) remains a more controversial issue. Ventral brain stem compression associated with Chiari I malformation usually arises from basilar invagination or odontoid retroflexion and has a reported incidence of 4–31% [12, 19, 34, 43]. Treatment options include a standard suboccipital craniectomy, a transoral odontoidectomy, or a combination of either or both with additional internal stabilization [8, 11, 12, 15, 17, 19, 27, 33, 35, 45, 50].

Some authors advocate a surgical approach that addresses the primary location of compression and pathology [46, 50]. Therefore, a suboccipital craniectomy would be the treatment of choice for standard Chiari I malformations, a transoral odontoidectomy would be preferable for ventral pathology, and a combined decompression for VBSC with a Chiari malformation. Grabb et al. have proposed that ventral brain stem compression less than 9 mm, as measured by a perpendicular line transecting the line from the basion to the posterior body of C2 (pB–C2), be managed with a suboccipital craniectomy alone [19]. They also reported a case with VBSC greater than 9 mm where dorsal decompression alone failed to improve symptoms. In addition, many other reports have described progression of symptoms from VBSC, either

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immediately or in a delayed fashion, after suboccipital craniectomy alone [3, 5, 19, 32, 43, 44, 50].

Variations in techniques performed with suboccipital craniectomies include duraplasty, opening the arachnoid, cauterization of the cerebellar tonsils, obex plugging, and removal of the posterior arch of the atlas or axis [6, 12, 17, 38]. Unless pre-operative instability exists, a suboccipital craniectomy is not routinely supplemented with internal fixation. However, after transoral-transpharyngeal odontoidectomy many authors advocate external orthoses or internal stabilization [12, 33, 50]. After a circumferential decompression with odontoidectomy and suboccipital craniectomy with cervical laminectomy, the integrity of the atlanto-axial complex is significantly disrupted and internal stabilization is required. An occipitocervical fusion typically has been utilized in other reports. Occipitocervical fusion, however, limits cervical motion in a functionally significant manner. In light of this, we sought to adapt previously described techniques to allow for circumferential decompression in patients with Chiari I malformations and significant VBSC while obviating the need for occipitocervical fusion. We present two patients with significant ventral brain stem compression associated with Chiari I malformations who underwent transoral odontoidectomy with preservation of the anterior arch of C1 and suboccipital craniectomy and C1 laminectomy with posterior C1–C2 arthrodesis. This method allows for an excellent circumferential decompression while preserving occipitocervical motion.

Materials and methods

Case 1

The first patient was a 32-year-old woman who developed progressively worsening symptoms of cough headaches, difficulty swallowing, left hand numbness and fatigue over 3 years (Fig. 1). On examination, she was diffusely hyper-reflexive. Pre-operative MRI flow studies showed impaired CSF flow across the cervico-medullary junction and a pB-C2 measurement greater than 9 mm. She underwent a complete transoral odontoidectomy with preservation of the anterior arch of C1. The base of the clivus was drilled and decompressed to the rostral edge of the arch of C1. The patient then underwent a suboccipital craniectomy and duraplasty with C1 laminectomy and C1–C2 arthrodesis using C1 lateral mass fixation and C2 pars interarticularis screws (Figs. 2, 3). The C1–C2 articular joint was debrided and packed with autograft from the craniectomy and laminectomy. As per our routine post-operative transoral odontoidectomy protocol, the patient was extubated the following day and received nutrition by nasogastric tube

Fig. 1 Pre-operative T2 sagittal MRI displaying significant VBSC and Chiari I malformation

Fig. 2 Post-operative CT reconstruction (VRT) displaying suboccipital craniectomy and C1–C2 arthrodesis

for 1 week. She was maintained in a hard collar for 12 weeks post-operatively until reassessed in follow-up (Figs. 4, 5). At last follow-up, 14 months post-operatively, she had complete relief of her pre-operative symptoms and has continued to do well. Post-operative flexion and

Fig. 3 Post-operative CT sagittal reconstruction after suboccipital decompression and odontoidectomy with preservation of the anterior arch of the atlas

Fig. 4 Post-operative sagittal T2 MRI with resolution of tonsillar herniation

extension radiographs have shown complete atlanto-axial arthrodesis with no instability and a good decompression.

Case 2

The second patient was an 18-year-old woman with progressively worsening cough headaches, tremors, and numbness in her maxillary distribution as well as her hands. Pre-operative imaging confirmed impaired flow at

Fig. 5 Post-operative lateral cervical X-ray

the cervico-medullary junction secondary to ventral brain stem compression and a Chiari I malformation. Furthermore, the posterior arch of C1 was noted to be incomplete. She underwent a transoral odontoidectomy with preservation of the anterior arch of C1 and suboccipital decompression with duraplasty and C1 laminectomy. She was then stabilized using C1 lateral mass fixation and C2 pars interarticularis screws with rods. Her post-operative course was uncomplicated and similar to patient 1. At 10-month follow-up, she had resolution of her symptoms and continues to do well.

Surgical technique

After oral intubation, the odontoidectomy was performed first. Patients were positioned in 3-point fixation using Mayfield pins in slight extension. Access to the basion and base of C2 in the final head position was confirmed using fluoroscopy. A standard transoral odontoidectomy exposure was performed. Approximately 1 mm of the inferior rim of the anterior arch of C1 was removed to improve exposure of the rostral odontoid. The drilling of the anterior arch of the atlas is limited to only 1 mm of the inferior rim as opposed to the traditional transoral odontoidectomy where the complete arch is removed. The apical ligament was then transected with the Orion EMF Tissue Vaporizer (Orthodevelopment, Salt Lake City, UT). The base of the

odontoid was then removed using a Midas Rex Legend EHS Stylus drill. The anterior arch of C1 was preserved and the tip of the odontoid was pushed down into view with a nerve hook placed above the arch of C1. This was then drilled away using the curved Midas Rex Legend drill bit.

After closure of the pharyngeal incision, the patient was turned prone onto a Wilson frame and underwent a suboccipital craniectomy and C1 laminectomy with duraplasty. After decompression, the lateral masses of C1 and C2 were exposed and C1 lateral mass screws, C2 pars interarticularis screws and connecting rods were placed along with autograft as described by other authors [21] (Figs. 6, 7, 8).

Discussion

Management of Chiari I malformations involves expanding the posterior fossa and relieving compression at the foramen magnum. Suboccipital decompression is the conventional treatment although variations exist on the use of duraplasty, cervical laminectomy, plugging of the obex, division of the arachnoid membrane, and cauterization of the cerebellar tonsils [6, 12, 17, 38]. Treatment of Chiari I malformations can sometimes be complicated by skeletal anomalies such as platybasia, basilar invagination, and occipitalization of the atlas [50]. Basilar invagination exists concurrently with Chiari malformations in 4–31% of cases and can contribute significantly to ventral brain stem compression at the foramen magnum [12, 19, 34, 43]. Furthermore, retroversion or retroflexion of the odontoid

Fig. 6 Post-operative CT reconstruction (VRT) from a ventral view

Fig. 7 Post-operative CT reconstruction (VRT) from a dorsal view

Fig. 8 Post-operative CT reconstruction (VRT) edited to highlight areas of bone removed (*faded and outlined*) and screw heads. The blue transparent area represents the resected odontoid

(odontoid process of epitropeus) can also contribute significantly to VBSC [40]. The presence of ventral compression concurrently with posterior herniation of the cerebellar tonsils has led some authors to advocate both anterior and posterior decompression [5, 7, 9, 31, 46, 50]. Proponents of combined surgeries emphasize the importance of treating both areas of compression and have reported resolution of symptoms with good results.

Grabb et al. found posterior decompression alone to be sufficient treatment in all their patients with pB-C2 measurements less than 9 mm and even in many of those with values greater than 9 mm. However, they did report a patient who worsened after a posterior decompression alone and required an odontoidectomy to relieve symptoms [19]. Several reports have described immediate or delayed progression of symptoms with significant neurological sequelae after posterior decompression alone in the presence of VBSC [3, 5, 9, 12, 19, 31, 33, 43, 44, 50]. Hypotheses explaining immediate worsening of symptoms include further instability after dorsal decompression creating more VBSC or intra-operative flexed positioning causing increased ventral odontoid compression. It is unclear if a posterior fusion at the time of decompression would prevent worsening in these cases. Progressive cervical kyphosis has also been reported with suboccipital craniectomies for tumor or Chiari decompression in the pediatric population. The risk of post-operative kyphosis in children has been associated to the caudal extent of laminectomies. Preservation of ligamentous attachments to C2 may limit the development of post-operative kyphosis [2, 29, 42].

In the presence of significant ventral compression many authors advocate ventral decompression through a transoral-transpharyngeal odontoidectomy [12, 27, 32, 33]. Although not a standard treatment, many cases have been described where anterior decompression alone has led to resolution of symptoms [8, 12, 27]. Many of these reports describe interval improvement prior to staged posterior surgical intervention, but some cases of anterior surgery alone or anterior decompression with fusion have been reported [8, 16, 25, 27]. Most authors have discarded using an anterior fusion given the risk of infection through the oral cavity combined with a devascularized bone graft and instrumentation [16, 33, 44]. Also, biomechanical studies have shown anterior transoral plates to be less effective than transarticular screws in immobilizing the atlanto-axial articulation [25]. Impairment of CSF flow across the foramen magnum with VBSC is largely secondary to osseous compression and therefore preservation of the tectorial membrane and alar ligaments can address the underlying pathophysiology while maintaining stability.

Odontoidectomy alone as management of VBSC is limited by its destabilization of the atlanto-axial junction. Dickman et al. found significant increases in translation and range of motion (ROM) in all movements except axial rotation after odontoidectomy [9]. Clinical series have found up to 70% of transoral odontoidectomy patients develop instability requiring instrumentation [7, 9, 12, 16, 44, 46]. The incidence of instability after odontoidectomy for Chiari malformations is likely slightly lower as other pathologies are often associated with greater degrees of

atlanto-axial instability such as rheumatoid arthritis [9]. Goel et al. found only one case (5%) of basilar invagination associated with Chiari malformations reduced with traction, whereas all others not associated with Chiari malformations corrected with traction [16]. They also have reported several cases of anterior and posterior decompression of Chiari malformations without subsequent destabilization [16]. The extent of ligamentous disruption or stabilization from arthritic change may partially explain the discrepancy from other series and also justify preserving motion through an atlanto-axial arthrodesis as opposed to the traditional occipitocervical fixation for Chiari I pathology.

The occipito-atlanto-axial joint contributes greater than 50% of cervical spine motion [48] and arthrodesis across the joint severely limits post-operative cervical motion. Biomechanical studies have supported that the occipito-atlantal joint provides 3–8° of axial rotation [10, 18, 36], and 14–25° of flexion–extension [4, 18, 47]; whereas the atlanto-axial articulation supports 10–25° of flexion–extension [4, 30, 47]. Furthermore, the atlanto-axial joint provides approximately 2.3–20° of lateral bending and 36–75° of axial rotation [4, 18, 30, 48]. Puttlitz et al. compared differing techniques of occiput to C2 arthrodesis and noted significant reduction in motion with successful fusion [39]. In cadaveric models, normal axial rotation was reduced from 82.1 to 2.6° after occipito-axial fusion. Furthermore, flexion–extension motion was reduced from 52 degrees to 3.5% of the normal range of motion and lateral bending was limited from 23.6 to 1.3°. Therefore arthrodesis between the occiput and axis significantly limits range of cervical motion.

Alternative fusion techniques such as atlanto-axial fixation maintain significant ROM and provide a stable biomechanical option. Atlanto-axial arthrodesis limits axial rotation of the cervical spine, but preserves the flexion–extension range of motion from the atlanto-occipital joint [22]. If the pathology is reducible pre-operatively and significant basilar invagination is present, occipitocervical fusion may be preferred. However, as mentioned previously, Goel et al. found only 5% of cases with basilar invagination and associated Chiari malformations to reduce with traction and even reported stability in cases after anterior and posterior decompression [16].

Multiple biomechanical models have compared various atlanto-axial fixation techniques such as C1 lateral mass screws and C2 pars interarticularis screws, transarticular screws, Brooks, Gallie, atlas claws and combinations of techniques of fusion [20, 22, 23, 28, 30, 41]. Suboccipital craniectomy and C1 laminectomy limit available techniques for arthrodesis, but other well-established alternatives are still viable. Transarticular screw fixation and atlanto-axial screw and rod fixation provide greater

resistance to motion and better stabilization than the other alternatives and can still be utilized after laminectomy of the atlas [20, 22, 23, 28, 30, 41]. When supplementation of transarticular screws with posterior wiring and interlaminar graft is not possible, C1 lateral mass and C2 pars screw fixation provides greater stabilization [28, 30]. Both techniques have high rates of fusion, strong resistance to motion, good resistance to screw pull-out and supply sufficient stability [23, 24]. However, transarticular screws have been associated with a 2.6–4.1% risk of vertebral artery injury [14, 49]. Furthermore transarticular screw placement may be limited by anatomic variations in the vertebral artery; up to 18–23% of patients may have an unusual course of the vertebral artery prohibiting transarticular screw placement [37]. Although some consideration should be given to the anatomic differences of the cervical spine between adults and children, atlanto-axial arthrodesis using C1 lateral mass screws and C2 pars interarticularis screws have been described in children as young as 2 years of age [21].

Although not a standard technique, we opted to preserve the anterior arch of the atlas. With atlanto-axial fixation, preservation of the anterior arch of C1 is not mandatory, but an intact anterior arch of the atlas theoretically provides greater support in the coronal plane and may act as a physiologic cross-link. Preservation of the atlas offers another axis of support and may help to limit lateral displacement of the lateral masses of C1. The preservation of the anterior arch of C1 is easily accomplished and can be facilitated with endoscopic techniques if necessary [1, 13, 26].

When a combined anterior and posterior surgical intervention is preferred, timing and order of the procedures should be carefully considered. We prefer to perform both procedures at one time, but others have delayed the posterior exposure by months. Some surgeons first perform a transoral odontoidectomy to decompress the VBSC in hopes of avoiding progressive neurological worsening from an initial posterior procedure. However, other surgeons may prefer to initially decompress posteriorly and stabilize the segments prior to a ventral decompression. Extension of the neck during positioning for a transoral exposure shifts the odontoid ventrally and potentially alleviates compression; whereas flexion for a suboccipital craniectomy may worsen ventral compression of the brain stem by moving the odontoid dorsally. Therefore, with anterior and posterior compression, we opt to perform a ventral decompression first prior to the suboccipital craniectomy [9, 43, 50]. If staged intervention is adopted, post-operative stability should be evaluated. Perhaps ventral decompression alone is adequate to relieve symptoms from VBSC in Chiari malformations and consideration should be given to postponing posterior surgery if stability and symptomatic relief are present.

Given the degree of VBSC and incidence of instability after transoral odontoidectomy, we chose to manage both patients with combined decompressions and posterior arthrodesis. We report a viable alternative to management of patients with significant VBSC and Chiari malformations. Preservation of the anterior arch of the atlas provides an additional degree of stability while atlanto-axial fixation preserves additional cervical motion.

Reference

1. Alfieri A, Jho HD, Tschabitscher M (2002) Endoscopic endonasal approach to the ventral cranio-cervical junction: anatomical study. *Acta Neurochir* 144(3):219–225
2. Aronson DD, Kahn RH, Canady A, Bollinger RO, Towbin R (1991) Instability of the cervical spine after decompression in patients who have Arnold-Chiari malformation. *J Bone Joint Surg Am* 73(6):898–906
3. Bindal A, Dunsker S, Tew JJ (1995) Chiari I malformation: classification and management. *Neurosurgery* 37:1069–1074
4. Bogduk N, Mercer S (2000) Biomechanics of the cervical spine. I. Normal kinematics. *Clin Biomech* 15(9):633–648
5. Collignon FP, Cohen-Gadol AA, Krauss WE (2004) Circumferential decompression of the foramen magnum for the treatment of syringomyelia associated with basilar invagination. *Neurosurg Rev* 27(3):168–172
6. DeBarros M, Farias W, Ataide L, Lins S (1968) Basilar impression and Arnold-Chiari malformation. *J Neurol Neurosurg Psychiatr* 31:596–605
7. Di Lorenzo N (1992) Craniocervical junction malformation treated by transoral approach. A survey of 25 cases with emphasis on postoperative instability and outcome. *Acta Neurochir* 118(3–4):112–116
8. Dickerman RD, Lefkowitz M, Arinsburg SA, Schneider SJ (2005) Chiari malformation and odontoid panus causing crani-overtebral stenosis in a child with Crouzon's syndrome. *J Clin Neurosci* 12(8):963–966
9. Dickman CA, Crawford NR, Brantley AG, VKI Sonntag (1995) Biomechanical effects of transoral odontoidectomy. *Neurosurgery* 36(6):1146–1152
10. Dvorak J, Panjabi MM, Gerber M, Wichmann W (1987) CT-functional diagnostics of the rotatory instability of the upper cervical spine: an experimental study in cadavers. *Spine* 12: 197–205
11. Dvorak MF, Fisher C, Boyd M, Johnson M, Greenhow R, Oxland TR et al (2003) Anterior occiput-to-axis screw fixation. I. A case report, description of a new technique, and anatomical feasibility analysis. *Spine* 28(3):E54–E60
12. Dyste GN, Menezes AH, VanGilder JC (1989) Symptomatic Chiari malformations: An analysis of presentation, management, and long-term outcome. *J Neurosurg* 71(2):159–168
13. Frempong-Boadu AK, Faunce WA, Fessler RG (2002) Endoscopically assisted transoral-transpharyngeal approach to the craniovertebral junction [see comment]. *Neurosurgery* 51(5 Suppl):S60–S66
14. Gluf W, Schmidt M, Apfelbaum R (2005) Atlantoaxial transarticular screw fixation: a review of surgical indications, fusion rate, complications, and lessons learned in 67 pediatric patients. *J Neurosurg Spine* 2:155–163
15. Goel A, Achawal S (1995) The surgical treatment of Chiari malformation associated with atlantoaxial dislocation. *Br J Neurosurg* 9(1):67–72

16. Goel A, Bhatjiwale M, Desai K (1998) Basilar invagination: a study based on 190 surgically treated patients. *J Neurosurg* 88:962–968
17. Goel A, Desai K (2000) Surgery for syringomyelia: an analysis based on 163 surgical cases. *Acta Neurochir* 142(3):293–301
18. Gonzales L, Crawford NR, Chamberlain RH, Perez Garza L, Preul M, Sonntag VK et al (2003) Craniovertebral junction fixation with transarticular screws: biomechanical analysis of a novel technique. *J Neurosurg* 98(2 Suppl):202–209
19. Grabb P, Mapstone T, Oakes W (1999) Ventral brain stem compression in pediatric and young adult patients with Chiari I malformations. *Neurosurgery* 44(3):520–527
20. Grob D, Crisco JJIII, Panjabi MM, Wang P, Dvorak J (1992) Biomechanical evaluation of four different posterior atlantoaxial fixation techniques. *Spine* 17(5):480–490
21. Harms J, Melcher RP (2001) Posterior C1–C2 fusion with polyaxial screw and rod fixation. *Spine* 26(22):2467–2471
22. Hartl R, Chamberlain RH, Fifield MS, Chou D, Sonntag VK, Crawford NR (2006) Biomechanical comparison of two new atlantoaxial fixation techniques with C1-2 transarticular screw-graft fixation. *J Neurosurg Spine* 5(4):336–342
23. Hong X, Dong Y, Yunbing C, Qingshui Y, Shizheng Z, Jingfa L et al (2004) Posterior screw placement on the lateral mass of atlas: an anatomic study. *Spine* 29(5):500–503
24. Hott JS, Lynch JJ, Chamberlain RH, Sonntag VK, Crawford NR (2005) Biomechanical comparison of C1-2 posterior fixation techniques. *J Neurosurg Spine* 2(2):175–181
25. Kandziora F, Kerschbaumer F, Starker M, Mittlmeier T (2000) Biomechanical assessment of transoral plate fixation for atlantoaxial instability. *Spine* 25(12):1555–1561
26. Kassam AB, Snyderman C, Gardner P, Carrara R, Spiro R (2005) The expanded endonasal approach: a fully endoscopic transnasal approach and resection of the odontoid process: technical case report. *Neurosurgery* 57(1 Suppl):E213
27. Kohno K, Sakaki S, Shiraishi T, Matsuoka K, Okamura H (1990) Successful treatment of adult Arnold-Chiari malformation associated with basilar impression and syringomyelia by the transoral anterior approach. *Surg Neurol* 33(4):284–287
28. Kuroki H, Rengachary SS, Goel VK, Holekamp SA, Pitkanen V, Ebraheim NA et al (2005) Biomechanical comparison of two stabilization techniques of the atlantoaxial joints: transarticular screw fixation versus screw and rod fixation. *Neurosurgery* 56(1 Suppl):151–159
29. McLaughlin MR, Wahlig JB, Pollack IF (1997) Incidence of postlaminectomy kyphosis after Chiari decompression. *Spine* 22(6):613–617 (erratum appears in *Spine* 1997 Jun 1;22(11):1276)
30. Melcher RP, Puttlitz CM, Kleinstueck FS, Lotz JC, Harms J, Bradford DS et al (2002) Biomechanical testing of posterior atlantoaxial fixation techniques. *Spine* 27(22):2435–2440
31. Menezes AH, Graf CJ, Hibri N (1980) Abnormalities of the cranio-vertebral junction with cervico-medullary compression. A rational approach to surgical treatment in children. *Childs Brain* 7(1):15–30
32. Menezes AH, VanGilder JC, Graf CJ, McDonnell DE (1980) Cranio-cervical abnormalities: a comprehensive surgical approach. *J Neurosurg* 53(4):444–455
33. Menezes AH, VanGilder JC (1988) Transoral-transpharyngeal approach to the anterior craniocervical junction. Ten-year experience with 72 patients. *J Neurosurg* 69(6):895–903
34. Milhorat T, Chou M, Trinidad E, Kula R, Mandell M, Wolpert C et al (1999) Chiari I malformation redefined: clinical and radiographic findings for 364 symptomatic patients. *Neurosurgery* 44(5):1005–1017
35. Nishikawa M, Ohata K, Baba M, Terakawa Y, Hara M (2004) Chiari I malformation associated with ventral compression and instability: one-stage posterior decompression and fusion with a new instrumentation technique. *Neurosurgery* 54(6):1430–1434
36. Panjabi MM, Dvorak J, Duranceau J, Yamamoto I, Gerber M, Rauschnig W et al (1988) Three-dimensional movements of the upper cervical spine. *Spine* 13:726–730
37. Paramore C, Dickman C, Sonntag V (1996) The anatomical suitability of the C1-2 complex for transarticular screw fixation. *J Neurosurg* 85:221–224
38. Pollack IF, Pang D, Albright AL, Krieger D (1992) Outcome following hindbrain decompression of symptomatic Chiari malformations in children previously treated with myelomeningocele closure and shunts. *J Neurosurg* 77(6):881–888
39. Puttlitz CM, Melcher RP, Kleinstueck FS, Harms J, Bradford DS, Lotz JC et al (2004) Stability analysis of craniovertebral junction fixation techniques. *J Bone Joint Surg Am* 86A(3):561–568
40. Quebada PB, Duhaime AC (2005) Chiari malformation Type I and a dolichoodontoid process responsible for sudden cardiorespiratory arrest: case report. *J Neurosurg* 103(6 Suppl):567–570
41. Richter M, Schmidt R, Claes L, Puhl W, Wilke HJ (2002) Posterior atlantoaxial fixation: biomechanical in vitro comparison of six different techniques. *Spine* 27(16):1724–1732
42. Steinbok P, Boyd M, Cochrane D (1989) Cervical spinal deformity following craniotomy and upper cervical laminectomy for posterior fossa tumors in children. *Childs Nerv Syst* 5(1):25–28
43. Tubbs S, Wellons J, Blount J, Grabb P, Oakes W (2003) Inclination of the odontoid process in the pediatric Chiari I malformation. *J Neurosurg* 98:43–49
44. Tuite GF, Veres R, Crockard HA, Sell D (1996) Pediatric transoral surgery: indications, complications, and long-term outcome. *J Neurosurg* 84(4):573–583
45. Vale FL, Oliver M, Cahill DW (1999) Rigid occipitocervical fusion. *J Neurosurg* 91(2 Suppl):144–150
46. VanGilder JC, Menezes AH (1983) Craniovertebral junction abnormalities. *Clin Neurosurg* 30:514–530
47. White A, Johnson R, Panjabi MM, Southwick W (1975) Biomechanical analysis of clinical stability in the cervical spine. *Clin Orthop* 105:85–96
48. White A, Panjabi MM (1978) The clinical biomechanics of the occipitoatlantoaxial complex. *Orthop Clin North Am* 9(4):867–878
49. Wright N, Laurysen C (1998) Vertebral artery injury in C1-2 trans-articular screw fixation: results of a survey of the AANS/CNS Section on Disorders of the Spine and Peripheral Nerves. *J Neurosurg* 88:634–640
50. Zileli M, Cagli S (2002) Combined anterior and posterior approach for managing basilar invagination associated with type I Chiari malformation. *J Spinal Disord* 15(4):284–289