Among the pathological processes involving the craniocervical junction, basilar invagination remains a therapeutic challenge. As illustrated in the widely used paradigm,\textsuperscript{4,5} it is essential to determine whether the invagination is reducible. Reducible lesions obviate a ventral decompression and require a dorsal-only approach for stabilization with or without a suboccipital decompression.

Methods. The authors describe a technique of intraoperative reduction of basilar invagination with the use of general anesthesia and neuromuscular blockade in the presence of crown halo traction. Using the O-arm device, a 3D CT scan is generated in the sagittal plane to demonstrate the reduction intraoperatively. This technique was successful in 6 pediatric patients with basilar invagination.

Results. The average age of the patients was 10.8 years, and they were followed for a mean period of 8.5 months. The patients had mild basilar invagination or partial reduction in extension on preoperative MR imaging. Intraoperative reduction was demonstrated in all patients by using the reported technique with intraoperative CT. All patients underwent occipitocervical fusion, and all but one underwent a suboccipital decompression. There were no complications related to the operation, and all but one reported improvement of symptoms on the last postoperative visit.

Conclusions. Intraoperative reduction performed using neuromuscular blockade and intraoperative traction is an effective method for further reduction of basilar invagination in the pediatric age group. This is the first reported application of intraoperative CT imaging performed using the O-arm device in craniocervical surgery in which successful reduction is demonstrated in detail. (http://thejns.org/doi/abs/10.3171/2011.11.PEDS11332)

Key Words • basilar invagination • craniocervical junction • intraoperative reduction • occipitocervical fusion • O-arm device

Abbreviations used in this paper: CM-I = Chiari malformation Type I; CVJ = craniocervical junction; FM = foramen magnum; SSEP = somatosensory evoked potential.

Application of neuromuscular blockade and intraoperative 3D imaging in the reduction of basilar invagination

Technical note

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Object. The treatment of basilar invagination in the pediatric age group is dependent on the possibility of preoperative reduction. Reducible lesions obviate a ventral decompression and require a dorsal-only approach for stabilization with or without a suboccipital decompression.

Methods. The authors describe a technique of intraoperative reduction of basilar invagination with the use of general anesthesia and neuromuscular blockade in the presence of crown halo traction. Using the O-arm device, a 3D CT scan is generated in the sagittal plane to demonstrate the reduction intraoperatively. This technique was successful in 6 pediatric patients with basilar invagination.

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of the O-arm device (Medtronic, Inc.) to generate an intraoperative CT, first in the supine and then in the prone position. These patients then underwent a dorsal-only approach that involved fixation with or without decompression.

Methods

A retrospective review of pediatric patients in whom basilar invagination requiring operative intervention was diagnosed between January 2007 and March 2011 was conducted. Six consecutive patients with mild invagination or who did not achieve satisfactory reduction of their invagination on extension MR imaging were identified. These patients underwent successful intraoperative reduction with the use of intraoperative traction and neuromuscular blockade. Adequate reduction was confirmed with the use of the O-arm device to generate a 3D image. The patients’ records, imaging studies, and condition on their last follow-up visit were reviewed.

Illustrative Cases

Case 1

History and Physical Examination. This 8-year-old girl was referred to our clinic for evaluation of a CVJ anomaly. She presented with a 1-year history of neck pain. Her mother noticed that whenever the child tried to turn her head, she would also move her whole body in the same direction. Her eating habits revealed a preference for liquids more than solids. The neurological examination showed decreased sensation to pinprick and pain over her hands bilaterally. Her motor power was normal in both upper and lower extremities. She had hyperactive deep tendon reflexes of her upper extremities, and those of her lower extremities were normal.

Neuroimaging Findings. A CT scan of the cervical spine showed hypoplasia of the basioccipital portion of the clivus as well as the occipital condyles. The tip of the odontoid process was positioned 1.6 cm above the Chamberlain line. The odontoid process was retroflexed, with a clivus canal angle measuring 82°. A split atlas was noted. An MR imaging study of the cervical spine showed basioccipital hypoplasia and basilar invagination with the clivus-odontoid articulation indenting into the ventral medulla (Fig. 1A–C). The patient was then scheduled for crown halo application, and an attempt at intraoperative reduction and dorsal occipitocervical fusion was made. In the event that the patient did not achieve satisfactory reduction, a transoral resection of the odontoid process followed by dorsal occipitocervical fusion was planned.

Intraoperative Reduction and Operation. The patient underwent fiberoptic intubation, and general anesthesia was induced. Neuromuscular blockade was achieved using rocuronium, and SSEP monitoring was conducted. The crown halo was then applied with the patient supine, with 8 lbs of traction. Using the O-arm device, an intraoperative 3D CT image of the craniocervical junction was obtained, showing that the tip of the odontoid process was further distracted from the basioccpit, and that the clivus canal angle measured 110° (Figs. 1D, 2A, and 2B). This indicated reduction and decompression at the cervicomedullary junction, obviating a transoral resection of the odontoid process. The patient then was placed prone, and another intraoperative 3D image was obtained showing persistence of adequate reduction, with distraction of the odontoid process from the basioccpit and a clivus canal angle measuring 106° (Figs. 1E and 2C). The patient then underwent dorsal occipitocervical fusion, which was performed using titanium loop and wiring as well as rib autograft. There were no changes detected with SSEP monitoring throughout the operation.

Postoperative Course. The patient was kept intubated for 48 hours. She was then fitted with an Aspen Minerva brace and ambulated with physical therapy. The patient had an uneventful hospital course and was discharged on postoperative Day 7. At her 4-month clinical follow-up visit, the patient had no complaints, with normal eating habits and normal results on her neurological examination. Her radiographs indicated good alignment at the CVJ and no hardware complications (Fig. 1F).

Case 2

Presentation and Physical Examination. This 14-year-old girl was referred to our clinic for evaluation of a CVJ anomaly. She was known to have a CM-I, with a previous posterior fossa decompression at 3.5 years of age and supratentorial parietooccipital “expansive craniotomy” performed at another institution. The main symptom at that time was headaches induced by the Valsalva maneuver. The headaches improved for approximately 1.5 years postoperatively. She then started complaining of an increasing pressure-type headache at the occiput region. She also complained of headaches that occurred after jumping, laughing, coughing, or sneezing. Her neurological examination revealed that she had decreased sensation below the clavicles for light touch and pinprick compared with the face, and she had a depressed gag reflex. Her motor power was 5/5 bilaterally for upper and lower extremities. She had hyperreflexic deep tendon reflexes in the upper extremities.

Neuroimaging. Admission MR imaging of the craniocervical junction showed basilar invagination with ventral compression of the cervicomedullary junction (Fig. 3A and B). Dynamic flexion/extension T2-weighted sagittal images showed that the clivus canal angle changed from 90° in flexion to 112° in extension. This was found to be fairly reducible (Fig. 3C and D).

Operation. The patient underwent fiberoptic intubation, and general anesthesia was induced. Neuromuscular blockade was achieved using rocuronium, and SSEP monitoring was conducted. The crown halo was applied with the patient supine, with 8 lbs of traction. An intraoperative 3D CT image of the craniocervical junction was obtained using the O-arm device. This showed that the tip of the odontoid process was further distracted from the basioccpit, indicating reduction and decompression at
Intraoperative reduction of basilar invagination

Fig. 1. Case 1. Sagittal images of the cervical spine showing hypoplasia of the basioccipital portion of the clivus. A: The tip of the odontoid process was positioned 1.6 cm above the Chamberlain line on the CT scan. The odontoid process is retroflexed, with a clivus canal angle measuring 82°. B: A sagittal T2-weighted MR sequence of the cervical spine shows basilar invagination, with the clivus-odontoid articulation indenting into the ventral medulla. C: A 3D CT reconstruction showing the same abnormality. D: After crown halo traction and induction of anesthesia and muscle paralytics, an intraoperative CT scan obtained with the patient supine shows further distraction of the tip of the odontoid process from the basiocciput, and the clivus canal angle measures 110°. E: This alignment persists in an intraoperative CT scan obtained with the patient prone. F: A lateral radiograph demonstrating Oc–C3 fusion with titanium loop and cables.

the cervicomedullary junction (Fig. 3E). The possibility of transoral resection of the odontoid process was abandoned. The patient then was placed prone, and another intraoperative 3D image was obtained, which showed persistence of adequate reduction. The patient subsequently underwent posterior fossa exploration with decompression and removal of new bone formation and scar tissue. A dorsal occipitocervical fusion was made with the following instrumentation and materials: occipital plate, C-2 pars interarticularis and C-3 lateral mass screws with rod interconnection, and rib allograft (Fig. 3F). There were no changes with SSEP monitoring throughout the operation.

Postoperative Course. The patient was extubated after 48 hours, fitted with an Aspen Minerva brace, and ambulated with physical therapy. The patient had an uneventful hospital course, and was discharged on postoperative Day 9. During her 3-month clinical follow-up the patient did not report any headaches, and had normal eating habits and normal findings on the neurological examination. Plain radiographs indicated good alignment of the CVJ and no hardware complications.

Case 3

History, Examination, and Operation. This 10-year-old girl presented for the evaluation of quadriplegia and gait ataxia. The patient was using a walker to ambulate. Preoperative MR imaging revealed atlas assimilation and basilar invagination, with ventral compression at the cervicomedullary junction resulting in a holocord syrinx (Fig. 4A and B). The patient underwent successful intraoperative reduction, with crown halo application and traction as well as neuromuscular blockade induced using rocuronium. This was verified with intraoperative 3D CT imaging, with the clivus canal angle changed from 84° to

Fig. 2. Intraoperative photographs showing the O-arm device in place and the patient in traction (A), and the O-arm being used to obtain an intraoperative CT scan with the patient supine (B) and then prone (C).
The patient therefore underwent dorsal suboccipital decompression and partial C-1 laminectomy as well as fusion with a titanium loop and cable construct with rib autograft. We used SSEP monitoring throughout the operation, without any documented changes.

**Postoperative Course.** Postoperatively the patient was fitted with an occipitocervical orthosis. At discharge she was ambulating independently. At her 6-week follow-up evaluation, she continued to improve neurologically. A postoperative MR imaging study showed good dorsal decompression and improved ventral invagination and decompression at the cervicomedullary junction. Moreover, the size of the syrinx was smaller (Fig. 4C). There was good alignment and no hardware complications on her follow-up radiograph (Fig. 4D). She continued to improve neurologically, as seen on her last follow-up visit 5 months later.

A summary of all 6 cases is provided in Table 1.

**Results**

The average age of the patients was 10.8 ± 4.6 years (mean ± SD). Five of 6 patients were girls. Four patients had associated CM-I, and 3 had atlas assimilation. The presenting symptoms are listed in Table 1. Two patients underwent previous surgery consisting of suboccipital decompression. In 3 patients the basilar invagination was partially reduced on extension, according to preoperative dynamic MR imaging; in 1 it was partially reduced with preoperative traction; and 2 did not undergo dynamic MR imaging or traction. All patients underwent occipitocervical fusion, and 5 of 6 patients underwent a suboccipital or redo suboccipital decompression. The SSEP monitoring was conducted intraoperatively in all cases, with no documented changes during the operation. Our average follow-up was 8.5 ± 8.3 months. The symptoms in 5 of 6 patients improved on their last clinical follow-up visit. All patients had either evidence of bone fusion on radiographs or no motion on dynamic radiographic imaging on their last follow-up visit.

**Discussion**

Basilar invagination is a congenital abnormality of the CVJ in which the odontoid process prolapses into the FM. Although there are a variety of causes for this anomaly, the treatment algorithm is universal. A key factor in the evaluation and management process is the determination of the reducibility of the lesion. This dictates the surgical approach: a dorsal-only decompression and
Intraoperative reduction of basilar invagination

The treatment strategy is evolving due to the availability of better imaging techniques. One milestone was the ability to assess the dynamic anatomical relationship between osseous, ligamentous, and neural structures by using dynamic MR imaging and CT scanning in the presence of distraction forces applied using crown halo traction. Lesions that satisfactorily reduced necessitated a dorsal-only decompression and fixation, obviating the need for anterior decompression through the transoral route. For lesions that did not achieve adequate reduction during preoperative evaluation, a transoral decompression was required.

Here we describe the possibility of further reduction through intraoperative induction of general anesthesia and the use of neuromuscular relaxants in the presence of crown halo traction. We use the O-arm device in generating intraoperative CT scans with 3D sagittal reconstruction of the CVJ to assess the degree of distraction in the prone position, which is the position for dorsal fusion. With the advent of intraoperative CT scanning, the use of the O-arm and similar devices has been gaining popularity in a variety of neurosurgical and spinal operations. This modality has favorable features in that it can efficiently generate 2D and 3D images. This report demonstrates the first application of this technology in the setting of CVJ surgery. The advantages of O-arm technology compared with plain radiography or the C-arm are mainly related to image detail. First, the 3D sagittal image generated with the O-arm device clearly shows the osseous details of the upper cervical spine related to the spinal canal and FM compared with the image generated with simple radiography, and hence more confidently confirms reduction. Second, the O-arm device has the ability to reconstruct images in the coronal and axial planes, allowing the examination of various osseous and canal relationships at multiple craniocaudal and parasagittal levels. Third, the O-arm has the ability to change the osseous image density though “windowing,” and hence to a certain extent it allows visualization of neural elements, comparable to CT images, in relation to osseous structures.

We have used rocuronium as the agent to achieve neuromuscular blockade. It is a nondepolarizing neuromuscular agent and has rapid onset of action, achieving maximal relaxation within 100 seconds. Other intraoperative reduction techniques are also used to maximize distraction potential.

This technique has been successful in the cases summarized in Table 1. We have used this technique only in pediatric patients because there is more laxity of the nonossified osseous and ligamentous structures compared with the adult patient, allowing further reduction with muscle relaxation. Moreover, we have used this technique in patients with evidence of partial reduction in extension during dynamic MR imaging or in those who had minimal basilar invagination on preoperative imaging. We have also been using this technique in the reduction of rotatory atlantoaxial subluxation. In addition to the pediatric age (younger than 14 years), and those whose invagi-
nation reduces with extension on MR imaging, another predictor of the success of reduction that we use is in patients with atlas assimilation and failure of segmentation between C-2 and C-3, because classically the likelihood that the invagination in these patients will reduce with preoperative traction is higher.

The hazard of this approach is the increase in the radiation exposure. However, with appropriate lead protection of the rest of the patient’s body and the potential reduction achieved, the benefits outweigh the hazards and the prolonged hospitalization of a transoral decompression of the odontoid process.

Conclusions

We described the use of neuromuscular blockade and intraoperative CT imaging in reducing pediatric basilar invagination. This technique has 3 main advantages. First, it uses general anesthesia and neuromuscular blockade to aid in preoperative reduction, and second it allows a 3D scan to be obtained with the patient prone, confirming in detail the preservation of the planned alignment prior to instrumentation and fixation. Third, this technique has obviated the need for preoperative halo traction in children in whom there is evidence of preoperative partial reduction on dynamic MR imaging.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author contributions to the study and manuscript preparation include the following. Conception and design: all authors. Acquisition of data: Dahdaleh. Analysis and interpretation of data: all authors. Drafting the article: all authors. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Menezes.

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