CHONDROPLASIA is an autosomal-dominant, inherited dwarfism syndrome characterized by short stature, macrocephaly, and a myriad of skeletal abnormalities. In the pediatric population, stenosis and compression at the level of the cervicomedullary junction commonly occurs. The goal in this study was to assess the outcomes in children with achondroplasia who underwent cervicomedullary decompression.

Methods. Forty-three pediatric patients with heterozygous achondroplasia and foramen magnum stenosis underwent 45 cervicomedullary decompressions at the authors’ institution over an 11-year period. After surgical decompression, complete resolution or partial improvement in the preoperative symptoms was observed in all patients. There were no deaths in the treated patients. The surgical morbidity rate was low and usually consisted of a cerebrospinal fluid (CSF) leak in patients in whom the dura mater had been opened (either intentionally or accidentally). This problem was successfully managed in all cases with local measures (wound oversewing) or CSF diversion.

Conclusions. In this review the authors demonstrate that decompression of the cervicomedullary junction in the setting of achondroplasia may be accomplished safely with significant clinical benefit and minimal morbidity.

Key Words • achondroplasia • cervicomedullary compression • foramen magnum • decompression surgery • pediatric neurosurgery

Achondroplasia is an autosomal-dominant, inherited dwarfism syndrome characterized by short stature, macrocephaly, shortening of the extremities, and a cluster of other skeletal abnormalities. This disorder is due to a point mutation in the gene for the fibroblast growth factor receptor on chromosome 4 and affects one in 26,000 live births annually.24 Although the gene is inherited in an autosomal-dominant manner, approximately 75% of cases are due to a new, sporadic mutation.3 When sporadic mutations occur, they are almost always associated with the paternal allele, which is consistent with the association of this disorder with advanced paternal age.

Patients with achondroplasia are susceptible to neurological compression at a number of levels along the neuraxis. In the pediatric population, one region commonly affected is the craniocervical junction. Neurological dysfunction may result from compression on the brainstem or upper cervical spinal cord in this setting.

The manifestations of neurological dysfunction in this patient population may be subtle and difficult to detect clinically. Patients with achondroplasia are well known to be hypotonic during early infancy, and they achieve motor milestones at a slightly slower pace than do unaffected individuals.10 In addition, nonskeletal abnormalities may mask or confound the clinical picture. For example, patients with achondroplasia may often suffer from concurrent central and obstructive apnea attributable to neurological compression (central apnea) and upper airway causes such as micrognathia and tonsillitis (obstructive apnea).

In this paper we review our clinical experience with the surgical treatment of symptomatic cervicomedullary compression over an 11-year period (1993–2003) in pediatric patients with achondroplasia. We identified 43 patients from our database who were treated during this period, and our clinical experience with these individuals is presented here.

Clinical Material and Methods

The records of all pediatric patients with heterozygous achondroplasia who underwent neurosurgical treatment at our institution between 1993 and 2003 were reviewed retrospectively. Forty-three patients who underwent cervicomedullary decompression during that 11-year period were identified. The charts of these patients were reviewed for all demographic data and presenting symptoms.

Patient Population

Of the 43 patients identified from our database of children
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with achondroplasia who underwent a cervicomedullary decompression, 16 were girls and 27 were boys. The mean age at the time of operation at our institution was 70 months (range 2–199 months), and the mean duration of symptoms was just longer than 7 months (range 1–12 months). One patient was clinically asymptomatic, yet had evidence of severe cervicomedullary compression on MR imaging.

Clinical Evaluation

The clinical evaluation in all patients was performed by a multidisciplinary team that included pediatric neurosurgeons, pediatric neurologists, neuroradiologists, pediatricians, and pulmonologists. All patients underwent a thorough neurological examination preoperatively, with particular attention to signs and symptoms of brainstem or spinal cord compression. In addition, all patients underwent an MR imaging study of the craniocervical junction to assess the degree of compression on the neural elements. Many of the patients with suspected sleep apnea underwent overnight polysomnography to help define central compared with obstructive origins.

Diagnostic Criteria

The diagnosis of cervicomedullary compression was made based on neuroimaging criteria. The presence of this disorder on imaging studies may not necessarily imply clinically relevant compression. Nonetheless, the clinical diagnosis was made based on the combination of neuroimaging findings and clinical symptoms. All patients included in this review underwent MR imaging of the craniocervical junction. The criteria used to make the diagnosis of cervicomedullary compression included the following: 1) the presence of signs or symptoms of chronic brainstem compression (such as apnea, lower cranial nerve dysfunction, swallowing difficulties, hyperreflexia or hypertonia, paresis, or clonus); and 2) neuroimaging evidence of foramen magnum stenosis with or without neurological manifestations.

Surgical Procedure

All patients with a diagnosis of clinically significant cervicomedullary compression underwent a foramen magnum decompression and upper cervical laminectomy, with or without a duraplasty. The surgical procedure has been described previously by the senior author (B.S.C.).

Because of the high incidence of CSF leaks and hydrocephalus in this patient population, individuals with neuroimaging or clinical evidence of hydrocephalus underwent placement of a shunt or EVD prior to or at the time of cervicomedullary decompression. When an EVD was placed, it was opened to drain immediately postoperatively, and the drainage pop-off pressure was gradually increased over a 2- to 3-day period. The drain was removed in patients who remained clinically asymptomatic and without evidence of a CSF leak, whereas those in whom symptoms of intracranial hypertension or CSF leakage developed underwent placement of a permanent shunt.

During the cervicomedullary decompression, the patients were placed prone after the induction of general anesthesia. The head was carefully supported in a slightly flexed position on a well-padded pediatric horseshoe. Care was taken to ensure that no pressure was present on the eyes during the surgical procedure. The SSEP modality was used routinely throughout the positioning and the surgical procedure. A midline suboccipital incision and a subperiosteal dissection were made to expose the occiput and the arch of C-1. Care was exerted to avoid removing the muscle attachments to the C-2 spinous process whenever possible.

The occiput and the midline posterior arch of C-1 were removed using a high-speed drill and small curettes. The bone removal was limited to approximately 3 cm in width to avoid the complications of cerebellar sagging or cranio-cervical instability. Invariably the posterior rim of the foramen magnum was thickened, and its orientation was more horizontal than usual. Once the bone removal was completed, the thickened reactive fibrous tissue band was carefully separated from the underlying dura mater. Care was taken to avoid entering the dura at this stage of the operation. Frequently, once this band was removed, the dura mater was able to expand significantly from its previous position. Ultrasonography was then used to assess the adequacy of CSF pulsations around the brainstem.

Adequate decompression was believed to have been accomplished when there was clear CSF space both ventral and dorsal to the brainstem and upper cervical spinal cord as well as free pulsation of the neural structures. If compression remained at this stage of the operation, a duraplasty was performed by first making a midline incision in the dura mater. Copious venous bleeding was sometimes encountered after incising the dura in this region because of the well-developed circular sinus in young patients. This bleeding was controlled using bipolar cautery or packing with a hemostatic agent. Once adequate CSF pulsations were observed, a paraspinal fascia flap was sewn in place. The wound was then closed in multiple layers. Once awakened from general anesthesia and when movement in all four extremities was confirmed, the patient was taken to the intensive care unit.

Postoperative Evaluation

Postoperatively, the patients were observed carefully for improvement or resolution of their preoperative neurological symptoms. Serial neurological examinations were performed prior to discharge. Patients were discharged when they were stable medically and when all wounds appeared to be healing well. Periodic follow-up data were obtained for all patients, either by return clinic visits or communication with the referring primary care physician. Resolution or persistence of presenting signs and symptoms was determined, and the patient’s neurological status was assessed.

Results

Clinical Findings

The most common presenting symptom in our patient population was respiratory difficulty. Twenty patients (46.5%) presented with respiratory symptoms in the form of excessive snoring or apneic breathing spells. As a routine part of the multidisciplinary workup for these patients, a sleep study is often performed. Information regarding preoperative sleep assessments was available for 23 of our 43 patients. Findings consistent with obstructive sleep apnea (15 patients) were much more common than those of cen-
tral apnea (seven patients). Four of the seven patients with central sleep apnea had concurrent evidence of obstructive apnea.

The next most common clinical findings were hypertonia and clonus; these were present in 21 of 43 patients preoperatively. Hypotonia was another common finding (12 of 43 patients). Although hypotonia is a common finding in infants with achondroplasia, these 12 individuals were believed to have hypotonia that was not within the normal disease-specific range. Frank motor weakness was demonstrated in 10 patients on their preoperative assessments.

Our patients’ parents often noted that these infants preferred to sleep with their heads extended (10 patients). Additionally, eight patients were noted preoperatively to have delayed attainment of developmental milestones, as is common for children with achondroplasia.

Surgical Results and Complications

No surgery-related death was noted among the patients in this study. The mean length of stay postoperatively was approximately 14 days (range 3–48 days). The most common surgical complication encountered was a CSF leak; this occurred in seven patients. In three cases, the leak occurred from the exit site after removal of the EVD. In the other four patients who experienced this complication, the leakage arose from the suboccipital incision. Two infections occurred in patients in whom a CSF leak from the EVD exit site had developed, and two occurred in those with leakage from the suboccipital incisions. All infections responded to a culture-specific course of intravenous antibiotic drugs.

No patient experienced a clinical deterioration immediately after surgery, but symptoms returned in five after a period of improvement. In these patients, repeated neuroimaging and surgical exploration demonstrated recurrent stenosis of the foramen magnum. This residual compression was caused by both osseous and soft-tissue structures. All five patients responded well to a repeated operation and had complete resolution of their symptoms. One patient experienced a transient seventh cranial nerve palsy and another had a transient fifth cranial nerve palsy of unclear origin. Both patients attained complete resolution of these cranial nerve deficits before discharge.

Twenty patients exhibited neuroimaging and/or clinical signs or symptoms of hydrocephalus. Nine of them exhibited clinical symptoms from hydrocephalus before cervicomedullary decompression, and therefore had undergone VP shunt placement prior to foramen magnum decompression. Eight patients had neuroimaging evidence of hydrocephalus at the time of foramen magnum decompression, and therefore an EVD was placed at surgery. After a period of ICP monitoring postoperatively, only two of these eight ultimately required placement of a VP shunt. In one of these two patients a shunt infection subsequently developed, which required removal of the device, placement of an EVD, and intravenously administered antibiotic drugs. Surprisingly, this patient tolerated prolonged periods of EVD clamping without clinical deterioration or significant ICP spikes, thus resulting in removal of the EVD and shunt independence.

An infection developed 2 weeks postoperatively in a patient in whom a shunt had been implanted before decompression; this complication required readmission, intravenous antibiotic medications, and removal of the shunt. The patient recovered without incident and did not require replacement of the shunt. In three other patients, clinically symptomatic hydrocephalus developed after decompression of the foramen magnum. One of these patients had previously passed a trial of EVD clamping. Nevertheless, this patient continued to experience progressive ventricular enlargement, and a shunt was implanted without incident on postoperative Day 9. Another patient in whom the ventricles were enlarged preoperatively experienced a persistent CSF leak postoperatively that was refractory to local measures (that is, wound oversewing and revision), and this patient therefore underwent shunt implantation with complete resolution of the leak.

The overall infection rate in our group of patients was 9% (four patients). In one of those in whom an infection developed, a VP shunt was placed before the cervicomedullary decompression. All patients who experienced this complication had evidence of a CSF leak postoperatively. The patient who had previously undergone shunt placement experienced leakage from the suboccipital incision line. In one other patient, leakage occurred from the suboccipital incision site, and in the other two there was a CSF leak from the exit site of the EVD that had been placed at the time of surgery.

In one patient a pseudomeningocele developed in the suboccipital region that required a repeated surgical exploration. The source of the CSF egress was located and sealed using suture closure and fibrin glue. This patient had no further complications and was discharged with no other incidents.

We encountered no clinical cases of postoperative craniovertebral instability among our group of patients. As a matter of course, we do not typically evaluate our patients for instability in the absence of symptoms after cervicomedullary decompression.

Clinical Follow-Up Duration

The mean duration of follow up was 62.5 months (range 1–123 months). Two patients were lost to clinical follow-up review after the initial postoperative visit and were therefore excluded from analysis. At the time of the last follow-up evaluation, no patient had experienced a clinical return of symptoms.

Discussion

Patients with heterozygous achondroplasia have a higher mortality rate for all age groups when compared with unaffected individuals. In patients 4 years of age and younger, there is a disproportionately high incidence of sudden infant death syndrome, which is believed to be caused at least in part by neurological compression at the level of the cervicomedullary junction. Furthermore, in the 5- to 24-year-old age group, central nervous system and respiratory causes of death account for approximately one half of all cases.

Determining which patients are most at risk for neurological problems is difficult in some cases. Some authors have used the absolute dimensions of the foramen magnum as a guideline, whereas others have not found this to be helpful in many cases. Only one of our patients had no clinically detectable signs, despite significant neural com-
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pression seen on MR images obtained in this individual. We believed that “prophylactic” surgery was warranted in this case, given the impressive imaging findings. This patient experienced no adverse effects from the operation and was developing normally 18 months postsurgery. Other authors likewise believe that prophylactic surgery is warranted in cases of severe compression, given the high incidence of sudden infant death in this patient population.6,18

Cervicomedullary Stenosis

Stenosis at the level of the foramen magnum begins early in infancy. Studies have demonstrated that the foramen magnum is comparatively small at birth in patients with achondroplasia.4,16 Furthermore, severely impaired growth of the foramen magnum is seen in these patients during the 1st year of life. This is due not only to the defect in endochondral bone formation that is pathognomonic of achondroplasia, but also to the abnormal placement and premature fusion of the synchondroses.4,7,15 Displacement of the two posterior synchondroses and their premature fusion is believed to account, at least in part, for the thickened posterior rim of the foramen magnum that is so commonly found at the time of surgery.

Respiratory Dysfunction

Respiratory complications are reported in 10 to 85% of individuals with achondroplasia.9,11 Manifestations include apnea, tachypnea, excessive snoring, cor pulmonale, recurrent pneumonia, and sudden infant death syndrome.2 These symptoms may result from primary pulmonary problems such as a small thoracic cage or airway obstruction, neurological compression, or a combination of factors. Compression of the brainstem’s respiratory centers may interfere with central respiratory drive and cause central sleep apnea. Additionally, compression of the lower motor neurons innervating the diaphragm and other respiratory muscles may cause weak and ineffective respiratory efforts.1,11

Sleep apnea was the most common presenting symptom among this group of surgically treated patients (53%). Central sleep apnea was demonstrated in seven (30%) of 23 cases, and obstructive apnea findings were present in 15 cases (65%) on overnight polysomnography. This discrepancy between the percentage of patients presenting with subjective respiratory symptoms and objective findings is not uncommon, and does not correlate with the eventual resolution of these complaints after surgical decompression.9 This is a higher incidence than has been found in other studies and is undoubtedly due to the fact that this group was composed purely of patients requiring surgery. As observed in our patients, there is often dramatic improvement in respiratory symptoms soon after the surgical decompression is completed.17 Nonetheless, some respiratory symptoms may persist after adequate surgical decompression. This undoubtedly happens because of the multifactorial nature of this problem in patients with achondroplasia. Other possible contributing factors must therefore be considered and addressed before surgical intervention when respiratory symptoms are the primary presenting complaint.

As discussed earlier, respiratory failure in the pediatric population is responsible for more than one half of all deaths among patients with achondroplasia. Given this fact, we believe that prophylactic surgery is warranted if there is radiographic evidence of significant neural compression. Early detection and treatment of these patients may prevent unnecessary deaths or permanent neurological injury.2 As with our group of patients, surgical decompression can often completely alleviate many respiratory symptoms and thus reduce the risk of sudden death.

Neurological Manifestations

Neurological manifestations are identified in as many as 50% of patients with achondroplasia.3 Symptoms may be subtle and nonspecific even in the face of severe compression in some children. Infants may experience hypotonia, feeding problems, and poor head control. Because hypotonia and motor delay are characteristic, determining when these signs may indicate cervicomedullary compression may be difficult. Hyperreflexia and clonus, when present, have been found to correlate directly with significant cervicomedullary stenosis and the need for decompression of the foramen magnum.20 After thorough neurological examinations we found evidence of hyperreflexia and/or clonus in 21 (49%) of our patients. Relative hypotonia, when present, has also been shown to correlate with the need for surgical decompression of the foramen magnum. This decreased tone may be difficult to detect at times. Frank motor weakness is a less frequent finding; it was seen in 10 of our 43 patients, but when present it may be a harbinger of permanent neurological sequelae. This is often due to the older age of patients with this finding and the more protracted clinical course.

Determining, based on neuroimaging criteria, which patients are most at risk for symptomatic foramen magnum stenosis remains difficult at best. Although the growth rate of the foramen magnum in patients with achondroplasia has been shown to be different in symptomatic and asymptomatic individuals, this difference did not reach statistical significance.4 In a prospective study of a cohort of patients with achondroplasia, it was found that longitudinal and transverse measurements of the foramen magnum that were below the diagnosis-specific mean on computerized tomography scans were an independent risk factor for the ultimate need for a cervicomedullary decompression.10 Intrinsic medullary or cervical signal changes on T2-weighted MR images is a sign of severe pathological conditions and possible irreversible damage. Untreated, these cases of severe pathological conditions of the spine may result in irreversible changes in the spinal cord and lower medulla. Furthermore, histological changes are observed that are similar to those seen with traumatic central cord syndrome. These changes are believed to be a result of arterial insufficiency rather than direct impact.20

Surgical Decompression

Familiarity with the altered anatomy of the cervicomedullary region in this patient population is essential. As discussed earlier, the posterior rim of the foramen magnum often has a much more horizontal orientation than one is accustomed to find (Fig. 1). In addition, the posterior lip of the foramen magnum is often quite thickened. The use of the high-speed drill to perform the suboccipital craniectomy makes this portion of the procedure much safer. Furthermore, the bone decompression should extend bilaterally to the medial aspects of the occipital condyles to ensure
an adequate bone decompression. The total width of the bone decompression is typically less than 3 cm. In addition, meticulous care must be taken to define the plane between the bone of the occiput and the posterior rim of the first cervical vertebra, and the underlying fibrous band and dura mater. Accidental injury to the dura mater with the high-speed drill may add significantly to the morbidity of the procedure by creating a postoperative CSF leak.

Care must also be taken to avoid passing any instrument beneath the intact bone in attempting to define the underlying plane. The degree of compression present and the small amount of space available for the neural structures at this level make such a maneuver particularly dangerous (Fig. 2). Our preferred approach is to use the high-speed drill to thin the bone as much as possible, and then use the small curette to flick gently the remaining rim of bone away from the dura mater and underlying tissues.

The need to take down the thickened, fibrous band present between the bone and the dura mater cannot be overemphasized. This layer often causes significant constriction of the cervicomedullary junction. In our experience, once this band is removed, the dura mater significantly expands and becomes much more pulsatile. This step may help avert the need to perform a duraplasty, which increases the risk of a postoperative CSF leak.

**Risks Related to Duraplasty**

The most common complication related to the surgical procedure was a CSF leak. It has been well described that patients with achondroplasia often have altered CSF flow dynamics. This is believed to be due, at least in part, to obstruction of venous outflow secondary to foraminal narrowing at the skull base. The senior author has previously published his experience with cervicomedullary decompressions in a smaller group of patients. In this previous study, a CSF leak developed in four (27%) of 15 treated patients and required permanent CSF diversion with a VP shunt. It is for these reasons that we have stopped routinely performing a duraplasty as part of the surgical decompression. Given the altered CSF dynamics and the relative morbidity associated with a CSF leak, we have found that this step entails a high risk. In addition, we have found this step to be unnecessary to decompress the suboccipital region adequately. Furthermore, the use of intraoperative ultrasonography to assess for residual compression at the time of surgery aids in the decision whether to open the dura mater. Visualization of adequate CSF spaces on axial and sagittal ultrasound images can eliminate the need to open the dura and perform a duraplasty. In this group of 43 patients, a duraplasty was believed to be warranted in only two. Both patients went on to experience CSF leaks that were manageable by local maneuvers (wound oversewing).

**Causes of Hydrocephalus**

Macrocranium has long been associated with achondroplasia. With the development of neuroimaging techniques such as computerized tomography and MR imaging, it has become apparent that this head enlargement is due at least in part to the ventriculomegaly that is commonly seen in patients with achondroplasia. The altered CSF dynamics in patients with achondroplasia is believed to be a result of venous outflow obstruction at the cranial base. This theory has been supported by studies reporting angiographic evidence of venous outflow obstruction at the level of the skull base. Additionally, obstructions at the levels of the foramen magnum and the fourth ventricular outlets have also been postulated to play a role.

In our study we found radiographic evidence of ventric-
ulomegaly in 20 patients. Nine had undergone placement of VP shunts before surgery for symptomatic hydrocephalus, and one of these nine remained clinically asymptomatic after the shunt became infected and was removed. In eight patients an EVD was placed at the time of surgery; however, only two were found to have significantly elevated ICP that would warrant CSF shunting. One of these two patients was subsequently able to have his shunt removed without clinical symptoms after it became infected, leaving only nine (21%) of the 43 patients shunt dependent at last follow-up review. These findings are consistent with other authors’ reports of a higher incidence of radiographically confirmed ventriculomegaly than clinical hydrocephalus.\(^{12,14}\) Many patients with achondroplasia will experience arrested hydrocephalus and will remain asymptomatic clinically. Therefore, careful screening for signs and symptoms attributable to hydrocephalus should be performed before committing the patient to shunt implantation. Also, placement of an EVD at the time of surgery can allow direct ICP monitoring to determine which patients are likely to benefit from CSF shunting.

The alteration in CSF flow dynamics increases the risk of a CSF leak developing postoperatively. Our rate of CSF leakage was 15.5% in this group of patients (seven of 45 procedures). Two of the patients in whom duraplasties were performed experienced leakage from the suboccipital wound. Additionally, the other patients in whom a leak developed had a dural fenestration at the time of surgery (two patients), and in three there was leakage from the exit site where the EVD had been removed. This underscores the high leak potential and the need to achieve watertight dural and wound closures.

**Intraoperative Ultrasonography**

We believe that the use of intraoperative ultrasonography is of tremendous benefit for surgical decompression in the setting of achondroplasia. Other authors have also reported on the benefits of this intraoperative technique.\(^{13}\) After completion of the bone and fibrous tissue decompressions, ultrasonography allows real-time assessment of CSF spaces around the brainstem and upper cervical spinal cord. Pulsatility of the upper cervical spine and brainstem generally suggests a satisfactory decompression. If any indication of continued compression remains, the dura mater may be opened and a duraplasty performed to provide adequate space.

**FIG. 2.** Preoperative T₁-weighted (left) and T₂-weighted (right) MR images demonstrating the typical findings in the craniocervical junction in patients with achondroplasia. Note the horizontal orientation of the posterior rim of the foramen magnum, causing kinking of the cervicomedullary junction. Also note the lack of CSF space at the level of the foramen magnum caused by the bone compression.
Intraoperative SSEPs

In cases of severe compression of the cervicomedullary junction, SSEPs may increase the safety of this procedure. Intraoperative SSEPs were used in 29 of our 45 cases; in all but two of these, the authors believed that the use of SSEPs provided critical feedback throughout the positioning and surgical procedure. In two cases, however, the signals were difficult to establish and SSEP testing was therefore abandoned. Both of these patients were profoundly myelopathic at the time of surgery, and one had tremendous intrinsic spinal cord changes at the cervicomedullary junction on T2-weighted MR images. There were no cases in which intraoperative SSEPs were lost during the surgical procedure. Based on our experience with other spinal procedures, however, this real-time feedback allows earlier intervention (that is, blood pressure elevation or administration of steroid drugs) in the event of a problem.

Conclusions

Cervicomedullary compression is both a common and potentially devastating occurrence in achondroplasia. In this retrospective review we demonstrate that this complex problem can be treated safely, with minimal patient morbidity and tremendous clinical benefit. The need for a multidisciplinary team approach involving pediatric neurosurgeons, pediatric neurologists, pediatricians, pulmonologists, geneticists, and neuroradiologists cannot be overemphasized.

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