Evaluating the relationship of the pB–C2 line to clinical outcomes in a 15-year single-center cohort of pediatric Chiari I malformation

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OBJECT The clinical significance of radiological measurements of the craniocervical junction in pediatric Chiari I malformation (CM-I) is yet to be fully established across the field. The authors examined their institutional experience with the pB–C2 line (drawn perpendicular to a line drawn between the basion and the posterior aspect of the C-2 vertebral body, at the most posterior extent of the odontoid process at the dural interface). The pB–C2 line is a measure of ventral canal encroachment, and its relationship with symptomatology and syringomyelia in pediatric CM-I was assessed.

METHODS The authors performed a retrospective review of 119 patients at the Monroe Carell Jr. Children's Hospital at Vanderbilt University who underwent posterior fossa decompression with duraplasty, 78 of whom had imaging for review. A neuroradiologist retrospectively evaluated preoperative and postoperative MRI examinations performed in these 78 patients, measuring the pB–C2 line length and documenting syringomyelia. The pB–C2 line length was divided into Grade 0 (< 3 mm) and Grade I (≥ 3 mm). Statistical analysis was performed using the t-test for continuous variables and Fisher's exact test analysis for categorical variables. Multivariate logistic and linear regression analyses were performed to assess the relationship between pB–C2 line grade and clinical variables found significant on univariate analysis, controlling for age and sex.

RESULTS The mean patient age was 8.5 years, and the mean follow-up duration was 2.4 years. The mean pB–C2 line length was 3.5 mm (SD 2 mm), ranging from 0 to 10 mm. Overall, 65.4% of patients had a Grade I pB–C2 line. Patients with Grade I pB–C2 lines were 51% more likely to have a syrinx than those with Grade 0 pB–C2 lines (RR 1.513 [95% CI 1.024–2.90], $p = 0.021$) and, when present, had greater syrinx reduction (3.6 mm vs 0.2 mm, $p = 0.002$). Although there was no preoperative difference in headache incidence, postoperatively patients with Grade I pB–C2 lines were 69% more likely to have headache reduction than those with Grade 0 pB–C2 lines (RR 1.686 [95% CI 1.035–2.747], $p = 0.009$). After controlling for age and sex, pB–C2 line grade remained an independent correlate of headache improvement and syrinx reduction.

CONCLUSIONS Ventral canal encroachment may explain the symptomatology of select patients with CM-I. The clinical findings presented suggest that patients with Grade I pB–C lines, with increased ventral canal obstruction, may experience a higher likelihood of syrinx reduction and headache resolution from decompressive surgery with duraplasty than those with Grade 0 pB–C2 lines.

<http://thejns.org/doi/abs/10.3171/2014.9.PEDS14176>

KEY WORDS Chiari I malformation; syringomyelia; craniocervical junction; posterior fossa decompression

ABBREVIATIONS CD = cord diameter; CM-I = Chiari I malformation; MSD = maximum syrinx diameter; PFDD = posterior fossa decompression with duraplasty; ROC = receiver operating characteristic.

SUBMITTED April 8, 2014. **ACCEPTED** September 8, 2014.

INCLUDE WHEN CITING Published online December 5, 2014; DOI: 10.3171/2014.9.PEDS14176.

DISCLOSURE The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper. T.R.L. received funding from the CNS/CSNS Medical Student Summer Fellowship in Socioeconomic Research.

POSTERIOR fossa decompression with duraplasty (PFDD) is a common surgical correction for Chiari I malformation (CM-I) in children. A recent meta-analysis found that 78.6% of pediatric patients have clinical improvement and 87% have a reduction in syrinx size postoperatively with PFDD.³ A preoperative evaluation to predict success of PFDD in clinical outcomes could assist with identifying patients who are likely to respond well to PFDD and allow the surgeon to counsel families regarding treatment.

Radiological measurements of the craniocervical junction may be useful. A posteriorly inclined odontoid process has previously been implicated in CM-I.^{5,15} Odontoid process retroflexion has been demonstrated in between 26.3%¹⁴ and 84%¹⁵ cases of CM-I depending on radiological methodology. However, a relationship has not been observed with degree of posterior inclination and postoperative resolution of symptoms and syringomyelia.¹⁵ The pB-C2 line, a measure of ventral canal encroachment, was initially developed to evaluate ventral brainstem compression in CM-I.⁶ The pB-C2 line is drawn perpendicular to a line drawn between the basion and the inferior posterior aspect of the C-2 vertebral body, at the most posterior extent of the odontoid process at the dural interface (Fig. 1). Only 2 previous studies have evaluated clinical implications of pB-C2 line length, finding no correlation with symptoms, but a modest relationship with tonsillar ectopia;^{6,15} however, a line longer than 9 mm may suggest brainstem compression and may be an indication for anterior decompression.⁶

In the present study, we examine an institutional experience with the pB-C2 line in children with CM-I, and we report preoperative and postoperative clinical and radiological features. We discuss the prognostic importance of this line in preoperative syrinx burden and postoperative headache improvement and syrinx resolution.

Methods

Patient Assessment

After obtaining institutional review board approval, we retrospectively created a database from medical records and review of imaging of all patients younger than 18 years who underwent posterior fossa decompression and had an ICD-9 diagnosis code of 348.4. The database was queried for patients with CM-I at the Monroe Carrell Jr. Children's Hospital at Vanderbilt University, Nashville, Tennessee, between January 1998 and August 2012. This search yielded 119 cases. Seventy-eight patients had preoperative and postoperative MRI studies for review. The follow-up duration was calculated using the last clinic or hospital encounter.

Radiological Data

A single neuroradiologist (M.A.D.) retrospectively evaluated pre- and postoperative MRI examinations obtained in 78 patients for whom imaging was available. Markup tools included in IMPAX (AGFA Healthcare) were used for all measurements. Radiological measurement methodology has been previously described by Tubbs et al.¹⁵ A diagram of each of the measurements used in this study is presented

FIG. 1. Measurements made on MR images. **A:** B = basiocciput, measured from basion to sphenoccipital synchondrosis; C = clivus length, measured from basion to the posterior clinoid process; E = distance from caudal extent of tonsils to the midpoint of McRae line; H = odontoid process height; M = McRae line; O = distance from obex to midpoint of McRae line; T = vertical distance of tonsils below McRae line. **B:** Angle F is the angle of retroflexion, formed between a line drawn through the odontoid synchondrosis and its intersection with a line drawn from the odontoid tip. **C:** Angle V is the angle of retroversion, formed between the line drawn from the base of C-2 and its intersection with a line drawn from the odontoid tip. **D:** The pB-C2 line (between the arrows) is drawn perpendicular to the line from the C-2 body and the basion, at the posterior extent of the odontoid process. **E:** C = cord diameter at the level of the maximum syrinx diameter; S = maximum syrinx diameter is drawn through the longest AP segment in the axial plane. Note: Panels B-D demonstrate T1-weighted imaging for illustrative purposes; however, in the study these measurements were made using T2-weighted imaging (as in Fig. 2).

in Fig. 1. The preoperative midsagittal T1-weighted brain MRI sequence was used for the following measurements: McRae line, vertical distance of the obex to the midpoint of McRae line, vertical distance of the tonsils below a midpoint of the McRae line, distance of tonsils below the McRae line, basiocciput length, clivus length, and caudal extent of the tonsils in relation to C1-2 posterior arches. In 20 patients who did not undergo preoperative brain MRI, preoperative midsagittal T2-weighted MRI of the cervical spine was used to obtain the same measurements. In preparation for this study, we found that the basiocciput measure was often inconsistent due to technical artifacts and/or a fused/distorted sphenoccipital synchondrosis. While we retained the basiocciput measurement to maintain con-

sistency in the literature, the clivus length, which was not originally measured in the Tubbs et al. study, was selected as an additional, more consistent and reproducible, proxy measure for posterior fossa size.

The preoperative midsagittal T2-weighted MRI sequence of the cervical spine was used for the following length measurements: odontoid length, pB–C2 line, angle of odontoid process retroflexion, and angle of retroversion. The following measurements/observations were made of the pre- and postoperative spine MR images using the T2-weighted axial and sagittal sequences. The most recently obtained MRI study was used for the postoperative measurements. The presence or absence of a syrinx was assessed. If present, the region of cord involvement (cervical, thoracic, or lumbar), cord region with maximal syrinx diameter, maximal syrinx diameter, and diameter of the cord at the level of maximal syrinx diameter were recorded. The maximal axial anteroposterior extent was used for syrinx and cord diameter measurements.

Outcome Assessment

The independent demographic variables were defined as age at operation, sex, and race. Clinical variables were defined as procedures performed, presence of headache, and preoperative symptoms other than headache. The dependent variables included symptom resolution, complications, and radiological outcomes. Headache outcome was defined as complete resolution, regression, no significant change, or progression. For analysis of headache outcome, complete resolution or regression was defined as headache improvement. Persistent postoperative symptoms were recorded. Complications were categorically defined as CSF leakage, pseudomeningocele, infection, intracranial hemorrhage, subdural fluid collection, hydrocephalus, meningitis, or death. Need for anterior decompression or surgical site revision was also assessed. Preoperative and postoperative maximum syrinx diameters (MSDs) were recorded.

Surgical Technique

All patients were treated by one of 2 established pediatric neurosurgeons at our institution using a standardized operative technique during the time period reviewed. All patients were placed prone. A suboccipital decompression and C-1 laminectomy were performed. The craniectomy extended from the foramen magnum to the inferior nuchal line. The dura mater was opened in all cases in a Y-shaped fashion prior to expansile duraplasty. An attempt was made to spare the intradural arachnoid adhesions, and no attempt was made to coagulate or manipulate the cerebellar tonsils on a routine basis. Dural closure was accomplished using a 5-0 Vicryl suture using an expansile triangular allograft with one of several materials, the majority of which were Medtronic Durepair Dura Regeneration Matrix (n = 69).

Determination of pB–C2 Line Grading

Grabb et al. originally defined pB–C2 line grading in pediatric and young adult patients with CM-I to assess ventral brainstem compression and the need for anterior

decompression.⁶ The grading system herein is to assign the relationship between the pB–C2 line and syringomyelia; to our knowledge no prior classification exists. We hypothesized that ventral CSF flow abnormalities would occur before brainstem compression, making the Grabb classification less useful in this setting. In the absence of a prior classification system, we developed a new system based on the characteristics of our population. Descriptive statistics of the pB–C2 line measurements were collected. Receiver operating characteristic (ROC) curve analysis was performed to identify the sensitivity and specificity of varying pB–C2 line lengths for syringomyelia. Other published normative data of pB–C2 line length were consulted. This cutoff value was then compared with normative data in the literature and validated by univariate and multivariate analysis within our patient population.

Statistical Analysis

Statistical analysis was performed using t-tests for continuous variables and Fisher's exact test for categorical variables in SPSS Statistics (version 20, IBM). One-way ANOVA was used to compare pB–C2 line length among the following age groups: 0–6, 7–12, and 13–17 years. Multivariate analysis (categorical dependent variables: binary logistic regression; continuous dependent variables: linear regression) was additionally performed. Radiological resolution of syrinx was assessed by several criteria: postoperative MSD, absolute reduction in MSD, MSD/cord diameter (MSD:CD) ratio (at the level of MSD), and absolute reduction in MSD/CD ratio. Mean values are presented as the mean with the SD in parentheses.

Results

Characteristics of the Entire Cohort of 119 Patients With CM-I

Two surgeons performed PFDD in 119 patients during the study period. Patient characteristics are presented in Table 1. The mean patient age was 8.5 years; 46.2% of patients were female. The mean follow-up duration was 2.4 years. Patients most commonly presented with headache, neck/back pain, upper-extremity numbness, upper/lower extremity pain, and gait abnormalities. A list of presenting symptoms is shown in Table 2. Sixty-eight patients (57.1%)

TABLE 1. Demographics of all 119 patients with CM-I

Characteristic	Value*
Mean age in yrs	8.5 (4.2)
Mean follow-up duration in yrs	2.4 (2.9)
Sex	
Male	64 (53.8%)
Female	55 (46.2%)
Race/ethnicity	
Black/African descent	8 (6.7%)
White/Caucasian, non-Hispanic	107 (89.9%)
White/Caucasian, Hispanic	4 (3.4%)

* Values are reported as the number of patients unless indicated otherwise. Mean values are presented as the mean with the SD in parentheses.

TABLE 2. Symptoms of all 119 patients with CM-I

Symptom	No. of Patients (%)	
	Preop	Postop
Headache	68 (57.1)	38 (31.9)
Complete resolution		37 (54.4)
Regression		11 (16.2)
No significant change		15 (22.1)
Progression		5 (7.4)
Vomiting	3 (2.5)	0 (0)
Dizziness	5 (4.2)	1 (0.8)
Dysphagia	5 (4.2)	1 (0.8)
Neck pain	15 (12.6)	1 (0.8)
Back pain	10 (8.4)	5 (4.2)
Upper-extremity pain	6 (5)	0 (0)
Upper-extremity weakness	4 (3.4)	0 (0)
Upper-extremity numbness	10 (8.4)	0 (0)
Lower-extremity pain	8 (6.7)	2 (1.7)
Lower-extremity weakness	2 (1.7)	0 (0)
Lower-extremity numbness	4 (3.4)	1 (0.8)
Gait abnormality	6 (5)	1 (1)
Urinary incontinence	3 (2.5)	1 (0.8)

presented with headache. Of these patients, 48 (70.6%) had complete headache resolution or significant headache regression. Forty-seven percent of patients presented with a syrinx. Postoperatively, 71% of patients experienced reduction in syrinx size.

Several other associated diagnoses were found in our population, which are summarized in Table 3. The most frequent spinal anomalies included scoliosis (19.3%), atlantooccipital fusion (2.5%), basilar invagination (1.7%), and Klippel-Feil anomaly (0.8%). Other common diagnoses included hydrocephalus (4.2%), epilepsy (3.4%), and neurofibromatosis Type 1 (1.7%). More rare diagnoses in this population included Pfeiffer syndrome (0.8%) and idiopathic growth hormone deficiency (0.8%).

Surgical Outcomes of the Entire Cohort

Our surgical outcomes are summarized in Table 4. The complication rate was 15.1%. Reoperation was required in 9.2% of patients. The most frequent reason was a CSF leak

TABLE 4. Surgical outcomes of all 119 patients with CM-I

Characteristic	Value*
Mean estimated blood loss in ml	13.6 (7.65)
Reop reason	
Persistent syrinx	3 (2.5%)
CSF leak	6 (5.04%)
Other	2 (1.68%)
Reop type	
Reexploration	4 (3.4%)
Extended laminectomy	1 (0.84%)
Syrinx shunt	3 (2.52%)
Ventriculoperitoneal shunt	3 (2.52%)
Complications	
Pseudomeningocele	1 (0.8%)
CSF leak	7 (5.9%)
Infection	4 (3.4%)
Intracranial bleed	1 (0.8%)
Subdural fluid collection	3 (2.52%)
Hydrocephalus	7 (5.88%)
Meningitis	10 (8.40%)

* Values are number of patients unless indicated otherwise. The mean value is presented as the mean with the SD in parentheses.

(5% of patients). Three patients received a syrinx shunt for persistent syringomyelia. No patients received an anterior decompression.

Relevant Radiological Measurements of the Craniocervical Junction in 78 Patients With Imaging

Of the 119 patients in our series, 78 patients had satisfactory preoperative and postoperative MRI studies of the craniocervical junction available for review. Discussion of radiological features and relationship to clinical outcomes concerns these 78 patients. The caudal extent of cerebellar tonsils was located above C-1 in 3 cases (3.8%), at C-1 in 39 (50%), between C1–2 in 17 (21.8%), and at C-2 in 19 cases (24.4%). Fifty-four patients (69.2%) presented with a syrinx. Segmental level of involvement was as follows: cervical 44 (56.4%), thoracic 45 (57.7%), and lumbar 8 (10.3%). The mean MSD was 7.2 (3.5) mm, ranging from 1 to 14 mm. We found no statistically significant relationship with clinical outcomes or syringomyelia among tonsillar ectopia, caudal extent of tonsils relative to cervical bony anatomy, length of the McRae line, distance of the obex to a midpoint of the McRae line, length of the odontoid process, midsagittal distance of cerebellar tonsils below the McRae line, basiocciput length, or clival length.

Determination of pB–C2 Line Grading

The Grabb classification of the pB–C2 line is as follows: low (< 6 mm), medium (6–9 mm), and high (> 9 mm).⁶ The distribution in our population was 62 (79.5%), 15 (19.2%), and 1 (1.3%), respectively. This distribution was far different from that of the Grabb study (12 [30%], 16 [40%], and 12 [30%], respectively). In our cohort, the mean pB–C2 line length was 3.5 (2) mm and the median

TABLE 3. Associated diagnoses for all 119 patients with CM-I

Diagnosis	No. of Patients (%)
Scoliosis	23 (19.3)
Hydrocephalus	5 (4.2)
Epilepsy	4 (3.4)
Atlantooccipital fusion	3 (2.5)
Basilar invagination	2 (1.7)
Neurofibromatosis Type 1	2 (1.7)
Idiopathic growth hormone deficiency	1 (0.8)
Klippel-Feil anomaly	1 (0.8)
Pfeiffer syndrome	1 (0.8)

length was 3 mm. The range of pB–C2 length was 0–10 mm. The area under the ROC curve of pB–C2 line versus syringomyelia was 0.610 ($p = 0.123$). Upon consulting the curve coordinates, the most acceptable sensitivities and specificities were as follows: pB–C2 line ≥ 2.5 mm: 74.1% and 54.2%, respectively; and pB–C2 line ≥ 3.5 mm: 51.9% and 66.7%, respectively. Therefore, based on measures of central tendency and ROC curve analysis, patients were divided into 2 groups: pB–C2 line < 3 mm (Grade 0) and pB–C2 line ≥ 3 mm (Grade I).

Relevant Preoperative Findings of the pB–C2 Line in 78 Patients With Imaging

Preoperative and postoperative midsagittal MRI measurements of the pB–C2 line were available in 78 patients. Analysis of these measurements is presented in Table 5. Fifty-one patients (65.4%) had a pB–C2 line length ≥ 3 mm (Grade I) and 27 (34.6%) had a pB–C2 line length < 3 mm (Grade 0). The odontoid process in patients with a Grade I pB–C2 line was on average longer, more retroverted, and more retroflexed than that in patients with a Grade 0 pB–C2 line. However, there was no apparent difference in the displacement of the brainstem at the level of the obex or the degree of tonsillar ectopia.

The pB–C2 line was longer in girls on average (4.1 vs 2.8 mm $p = 0.003$), and girls were more likely to have a Grade I pB–C2 line (RR 1.49 [95% CI 1.039–2.142], $p = 0.036$). The pB–C2 line length also increased with age, and patients with a Grade I pB–C2 line were older than those with a Grade 0 pB–C2 line on average (9.2 vs 6.3 years, $p = 0.002$). The mean pB–C2 line length varied significantly across age groups as well: 0–6 years, 2.2 (1.3) mm; 7–12 years, 4.5 (1.8) mm; and 13–17 years, 4.6 (2.1) mm; $p < 0.001$. Upon multivariate linear regression analysis, age (Beta = 0.401, $p < 0.001$) and male sex (Beta = -0.255 , $p = 0.013$) were significant correlates of pB–C2 line length, accounting for approximately one-quarter of the variance of pB–C2 line length: $F(2,75) = 13.164$, $p < 0.001$, $R^2 = 0.260$.

Patients with a Grade I pB–C2 line were 51% more likely to have a syrinx preoperatively ($p = 0.021$) (Table 6). Syrinx was present in 78.4% of patients with a Grade I pB–C2 line compared with 51.8% of those with a Grade 0 pB–C2 line. Patients with Grade I pB–C2 lines were 80% more likely to have a syrinx in the cervical segment ($p = 0.017$) and were 85% more likely to have a syrinx in the thoracic segment ($p = 0.009$). There was no statistically significant difference in MSD, MSD/CD ratio, or headache burden between groups preoperatively.

Relevant Postoperative Findings of the pB–C2 Line in 78 Patients With Imaging

A Grade I pB–C2 line was associated with a greater postoperative syrinx reduction (Table 5). On paired t-test, patients with a Grade I pB–C2 line had a mean MSD reduction of 3.6 mm ($p < 0.0001$), whereas those with a Grade 0 pB–C2 line had a 0.2 mm MSD reduction ($p = 0.8514$). Postoperative MSD, MSD/CD ratio, and absolute change in MSD/CD ratio also correlated with the pB–C2 line grade. Figure 2 demonstrates the difference in syrinx outcome between representative patients with Grade I compared with Grade 0 pB–C2 line. Patients with a Grade I pB–C2 line were also 69% more likely to have improvement in headache postoperatively, either complete resolution or frequency/severity regression ($p = 0.009$). Overall, 90% of patients with Grade I pB–C2 lines had improvement in headache compared with 53.3% of those with Grade 0 pB–C2 lines. Analyzed individually, there was a trend toward more likely resolution and regression of headache in patients with Grade I pB–C2 lines, although these relationships did not reach statistical significance. Twenty percent of patients with Grade 0 pB–C2 lines had progression of their headache postoperatively, which did not occur in patients with Grade I pB–C2 lines (0%).

Multivariate Analysis of Clinical Variables

Tables 7 and 8 demonstrate the relationship between pB–C2 line grade and select clinical variables, controlling

TABLE 5. Grade I versus Grade 0 pB–C2 lines: continuous variables

Characteristic	Mean (SD)		p Value
	Grade 0	Grade I	
Preop factors			
Patient age in yrs	6.1 (3.8)	9.2 (3.9)	0.002
Length of odontoid process in mm	15.4 (3.2)	17.7 (2.3)	0.002
Odontoid retroflexion in degrees	85.9 (11.6)	79 (10.2)	0.013
Odontoid retroversion in degrees	75 (5.5)	70.7 (4.8)	0.001
Tonsillar ectopia in mm	13.7 (5.2)	15 (6.4)	0.352
Obex to midpoint of McRae line in mm	13.7 (4.9)	14 (3.3)	0.805
MSD in mm	6.6 (3.7)	7.4 (3.5)	0.475
MSD/CD ratio	0.64 (0.24)	0.68 (0.18)	0.511
Postop outcomes			
MSD in mm	6.6 (3.6)	3.47 (2)	0.019
Change in MSD in mm	0.2 (3)	3.6 (3.1)	0.002
MSD/CD ratio	0.64 (0.20)	0.48 (0.20)	0.022
Absolute change in MSD/CD ratio	0 (0.21)	-0.21 (0.20)	0.008

TABLE 6. Grade I versus Grade 0 pB–C2 lines: categorical variables

Characteristic	No. of Patients (%)		Relative Risk (95% CI)*	p Value
	Grade 0	Grade I		
Preop factors				
Male sex	17 (62.9)	18 (35.3)	0.561 (0.350–0.898)	0.031
Syrinx present	14 (51.8)	40 (78.4)	1.513 (1.024–290)	0.021
Cervical	10 (37)	34 (66.7)	1.799 (1.060–3058)	0.017
Thoracic	10 (37)	35 (68.6)	1.852 (1.095–3.135)	0.009
Lumbar	1 (3.7)	7 (13.7)	3.7 (0.481–28.571)	0.250
Headache	15 (55.6)	30 (58.8)	1.059 (0.704–1592)	0.813
Postop outcomes				
Persistent syrinx†	14 (100)	39 (97.1)	0.972 (0.917–1.028)	1.000
Cervical	11 (78.6)	31 (77.5)	0.986 (0.716–1.359)	1.000
Thoracic	9 (64.3)	29 (72.5)	1.127 (0.073–1.742)	0.397
Lumbar	1 (7.1)	1 (5.0)	0.700 (0.069–7.143)	1.000
Headache improvement†	8 (53.3)	27 (90)	1.686 (1.035–2.747)	0.009
Complete resolution	7 (46.7)	21 (70)	1.5 (0.832–2.702)	0.193
Regression	1 (6.7)	6 (20)	3 (0.396–22.727)	0.395
No significant change	4 (26.7)	3 (10)	0.375 (0.096–1.464)	0.199
Progression	3 (20)	0 (0)	0.0737 (0.004–1.342)	0.032

* Relative risk calculated as Grade I versus Grade 0.

† Percentages are calculated out of patients for whom the condition was present preoperatively only.

for age and sex. The pB–C2 line grade was independently associated with preoperative presence of thoracic syrinx, postoperative MSD, absolute change in MSD, absolute change in MSD/CD ratio, and headache improvement. The multivariate models for presence of a syrinx located at any location ($p = 0.073$, $R^2 = 0.120$) or a cervical syrinx ($p = 0.077$, $R^2 = 0.113$) did not quite reach statistical significance, although there was a strong trend. Postoperative MSD/CD ratio did not vary significantly with pB–C2 line grade after controlling for age and sex. After adjusting for age and sex, the odds ratio of headache improvement for Grade I compared with 0 increased from 7.8 to 101. This model accounted for 49.2% of the variance in headache resolution.

Discussion

The pB–C2 Line in CM-I

The pB–C2 line (Fig. 1) was initially developed by Grabb et al. to study ventral brainstem compression in children and young adults with CM-I.⁶ In that study, the pB–C2 line length ranged from 3 to 12 mm. Encroachment was categorized as low (< 6 mm), medium (6–9 mm), and high (> 9 mm). No statistically significant difference was observed with symptomatology across these groups, although eye abnormalities trended with increasing pB–C2 line length. The authors suggested that patients with pB–C2 lines longer than 9 mm were more likely to require anterior decompression. In our series only a single patient had a pB–C2 line longer than 9 mm, and this patient did not undergo anterior decompression. Compared with our population, the mean pB–C2 line was longer (3.5 vs 7 mm) in the Grabb cohort, and more patients presented with medium- and high-grade encroachment.

A later study of pB–C2 lines in children with CM-I

found a correlation between pB–C2 line length and odontoid angulation.¹⁵ The pB–C2 line length ranged from –2 mm to 11 mm (mean approximately 4.6 mm) in CM-I patients. In controls, the pB–C2 line ranged from –3 to 4.8 mm (mean 2.9 mm). This study demonstrated posterior odontoid angulation in 84% of patients with CM-I compared with 10% in healthy controls. There was increasing pB–C2 line length with more posterior inclination of the odontoid process, as one would expect. However, unlike the present study, the authors did not find a correlation between retroflexion or pB–C2 line length and symptoms or postoperative outcome.

These prior studies support our delineation of the Grade I pB–C2 line at ≥ 3 mm, as this length is longer than the mean in asymptomatic individuals, yet shorter than the measurement in patients with brainstem compression. We hypothesize that CSF flow would be disturbed prior to brainstem compression, which is supported by the fact that a shorter pB–C2 line length was observed as a risk factor for syringomyelia compared with brainstem compression. However, we emphasize that Grade I pB–C2 correlates with syringomyelia in the setting of CM-I, and by itself it may not be pathological.

A recent study of normative measures of the pB–C2 line and odontoid angulation in 150 healthy adults found that the odontoid process is longer and more posteriorly inclined, with a greater pB–C2 line in this population.¹⁰ The mean pB–C2 line length in this population was 6.5 mm. In contrast to the present study, there was no statistically significant difference in size between sexes, although there was a slight trend toward increased length in men (6.7 vs 6.2 mm, $p = 0.066$), which is the reverse of the relationship we have observed in pediatric CM-I. There was also no difference in length between 18- to 50-year-old and 51- to

FIG. 2. Upper: Magnetic resonance images obtained in a 16-year-old boy with a Grade 0 pB–C2 line (2 mm) and a 6-mm cervical syrinx. Two months postoperatively, the syrinx is unchanged in size. **Lower:** Magnetic resonance images obtained in a 13-year-old boy with a Grade I pB–C2 line (6 mm) and a 12-mm cervical syrinx. Four months postoperatively, the syrinx has decreased to 1 mm at maximum diameter.

89-year-old patients. The authors suggested that changes in skull base angulation during normal development induce compensatory angulation of the C-2 body, leading to greater posterior inclination of the odontoid process. They

concluded that, whereas such measurements of odontoid process angulation are useful in evaluating children with CM-I, these measurements may have less applicability in adults. Based on the limited understanding of the ana-

TABLE 7. Multivariate analysis of select clinical variables: linear regression*

Factor	Variable	Beta	p Value
Postop MSD (mm)	Age	-0.052	0.717
	Sex	-0.052	0.725
	pB–C2 line	-0.051	0.003
	F (3,43) = 3.915, p = 0.015, R ² = 0.215		
Postop change in MSD (mm)	Age	0.191	0.157
	Sex	0.307	0.035
	pB–C2 line	0.519	0.001
	F (3,42) = 6.209, p = 0.001, R ² = 0.307		
Postop MSD/CD ratio	Age	0.072	0.613
	Sex	-0.067	0.653
	pB–C2 line	-0.179	0.238
	F (3,51) = 0.511, p = 0.676, R ² = 0.029		
Absolute change in MSD/CD ratio	Age	0.205	0.134
	Sex	0.258	0.074
	pB–C2 line	0.468	0.002
	F (3,43) = 5.327, p = 0.003, R ² = 0.271		

* For each dependent variable, female sex and Grade 0 pB–C2 line are used as reference categories.

TABLE 8. Multivariate analysis of select clinical variables: logistic regression*

Factor	Variable	Odds Ratio	p Value
Preop syrinx	Age	0.999	0.990
	Sex	1.834	0.277
	pB–C2 line	4.098	0.017
	$\chi^2 (3) = 6.951, p = 0.073, R^2 = 0.120$		
Preop cervical syrinx	Age	1.042	0.516
	Sex	1.225	0.688
	pB–C2 line	3.199	0.033
	$\chi^2 (3) = 6.874, p = 0.077, R^2 = 0.113$		
Preop thoracic syrinx	Age	0.971	0.642
	Sex	0.652	0.390
	pB–C2 line	3.675	0.018
	$\chi^2 (3) = 8.129, p = 0.043, R^2 = 0.133$		
Headache improvement	Age	0.695	0.030
	Sex	4.936	0.135
	pB–C2 line	101.1	0.007
	$\chi^2 (3) = 17.44, p = 0.001, R^2 = 0.492$		

* For each dependent variable, female sex and Grade 0 pB–C2 line are used as reference categories.

tomical changes of this region over time, we would agree, and we highlight that our findings presented here must be taken in the context of a maturing odontoid process in the pediatric population.

Our study reaffirms some findings in earlier reports, but also introduces new objective data to assist with the pre- and postoperative evaluation of patients with CM-I. Specifically, this is the first study to associate a symptomatic outcome with such radiological measurements of the craniocervical junction. Similar to previous studies, we did not observe any relationship between odontoid angulation and preoperative symptoms. However, we have shown that pB–C2 line grade correlates well with syrinx burden and improvement of both syrinx and headache postoperatively. Patients with Grade I pB–C2 lines were 51% more likely to have a syrinx than those with Grade 0 pB–C2 line, and when present, had greater syrinx reduction. Patients with Grade 0 pB–C2 lines essentially had no postoperative change in syrinx size. Patients with Grade I pB–C2 lines were also 69% more likely to have headache resolution than those with Grade 0 pB–C2 lines.

What Is the Origin of Syringomyelia in CM-I?

The exact mechanism for the development of syringomyelia in CM-I has remained unclear, although several hypotheses abound. A consistently observed feature is the disruption of normal CSF pulsations. An early explanation, the water-hammer theory, proposed that increased pulse pressure from fourth ventricle or foramen magnum outlet flow directs CSF into the central canal.⁴ Tubbs et al. hypothesized that posterior odontoid inclination results in posterior inclination of the brainstem at the level of the obex, opening up the foramen cecum and diverting greater egress of CSF flow into the central canal.¹⁵ Their findings that the obex–McRae line length correlated with degree of inclination, coupled with an overall shorter distance in patients with CM-I, often below the foramen

magnum, support this hypothesis. We were surprised to find that the obex was far less displaced in our population, much closer to that of the controls in the prior study by Tubbs and colleagues. The shortest measured obex–McRae line distance in any of our patients was 3 mm. In addition, there was no significant relationship between obex displacement and syringomyelia in our population ($p > 0.05$).

The piston theory suggests that excessive downward tonsil motion elevates systolic CSF pressure, compressing the cord and propelling spinal subarachnoid CSF into the central canal.^{8,9} We expect that in this setting the patients with a distant focal stenosis within the spinal canal would be at an increased risk for syringomyelia as a result of a pressure differential between the subarachnoid space cisterns and the central canal. While we found no difference in cerebellar tonsil descent between patients with and without a syrinx, this retrospective study was limited in its inability to record and measure tonsil position changes with CSF pulsations.

Others have alternatively posited that a syrinx is produced by cord distension from the extracellular space via the Venturi effect at a site of focal stenosis, which produces cavitation and propagation of the syrinx.⁷ A focal stenosis at the craniocervical junction might increase the frequency of cervical and upper thoracic syringes by this mechanism, which is consistent with our finding that the frequency of cervical and thoracic syringes was higher in the Grade I group. Still, others have suggested that decreased compliance of the posterior spinal veins in the setting of a compressed spinal subarachnoid space impairs resorption of extracellular fluid and therefore forms a syrinx.¹¹ This is also hypothetically consistent with the stenosis observed with ventral canal encroachment via the odontoid process. While we cannot say for sure by which mechanism syringomyelia is generated in CM-I regardless of pB–C2 line grade, it is likely that this phenomenon is

multifactorial, attributing to a combination of several of these proposed mechanisms.

Does Ventral Canal Compression Disrupt CSF Flow and Predispose to Syringomyelia?

Our observation of an increased preoperative incidence and postoperative resolution of syrinx in patients with Grade I pB–C2 lines suggests a tentative role for ventral

encroachment ≥ 3 mm in the pathogenesis of syrinx. Ventral encroachment by the odontoid process may contribute to the disruption of CSF flow pulsations implicated in syringomyelia. Surgical decompression of the craniocervical junction relieves obstructive velocity disturbances and restores normal CSF flow.^{2,12,13} Using cine phase-contrast MRI, McGirt et al. showed that the presence of a preoperative decrease in both ventral and dorsal CSF flow at the

FIG. 3. Illustrations. **A:** A Grade 0 pB–C2 line with unchanged syrinx after PFDD. **B:** A Grade I pB–C2 line with a significantly reduced syrinx postoperatively. The insets demonstrate the pB–C2 line, drawn perpendicular to a line drawn from basion to inferoposterior C-2 vertebral body, at the posterior extent of the odontoid tip. Copyright David Fisher. Published with permission. Figure is available in color online only.

craniocervical junction correlated with better response to decompression in pediatric patients with CM-I.¹² Patients with ventral canal compression may therefore respond particularly well to surgical decompression, and as such, a Grade I pB–C2 line may be a predictor of positive postoperative outcomes (Fig. 3).

We hypothesize that the syrinx in patients with Grade 0 pB–C2 lines may be of a different structural origin. While likely multifactorial, stenosis elsewhere in the spinal canal or other mechanisms of CSF flow abnormalities as described above may contribute to syringomyelia in these patients. Although patients with Grade I pB–C2 lines were more likely to have a syrinx in general, when present, the relative distributions of syrinx locations within the spine were comparable across groups ($p > 0.05$). Within this study there was no other obvious reason why patients with Grade 0 pB–C2 lines would be less likely to have a syrinx and less likely to have syrinx and headache resolution. The descent of tonsils was comparable across groups. Obex displacement might be a rational cause for syrinx formation outside of overt bony anomalies, although we did not observe such a difference.

Despite our lack of finding another developmental source of the syrinx in patients with Grade 0 pB–C2 lines, a structural anomaly outside the craniocervical junction would be an attractive way to explain why PFDD essentially had a lesser effect on the syrinx in these patients. The mean absolute reduction in MSD was only 0.2 mm. Our preliminary analysis suggests that PFDD is not as efficacious for patients with Grade 0 pB–C2 lines presenting with syrinx or headache. This radiological measurement may inform identification of patients who are likely to respond well to PFDD, thereby guiding physician counsel to patients and families seeking treatment. In addition, the debate over duraplasty continues, and measurements such as these may impart a predictor of surgical success as prospective trials investigating best surgical practice move forward.

Limitations

The results herein must be interpreted in the context of several study limitations. First, this was a retrospective study; therefore, the bias and data deficiencies inherent to any retrospective study must be considered. Only patients who underwent decompression were evaluated, introducing surgical candidate selection bias. However, we feel the benefit of a single-center study is such that it allows us to adequately assess the uniformity of the cohort, and what is lost in generality is gained in specificity. There was a statistically significant difference in ages between the pB–C2 line groups, with patients with Grade I pB–C2 lines being older. Khaleel et al. have demonstrated that pB–C2 line length is generally longer in healthy adults than in healthy children; however, trends in adult CM-I patients have not been assessed.¹⁰ While age could be a confounder of results, we know of no literature implying such but recognize this as a limitation of the work inherent in its retrospective nature. However, after controlling for age and sex, pB–C2 line grade was independently associated with thoracic syrinx burden and postoperative outcomes. The imaging in this study was reviewed by only a single neuroradiologist; a stronger study would have included another independent

reviewer along with a calculated interrater reliability. This reviewer, however, was at least blinded to patient clinical status. Finally, there was a lack of uniformity with which pre- and postoperative clinical assessments were documented in patient records. To address this problem, beginning in 2013 our institution has implemented a standardized Chiari assessment, which includes patient-reported quality of life measures as well as the recently validated Chicago Chiari Outcome Scale.^{1,16}

Conclusions

We found that patients with a pB–C2 line greater than or equal to 3 mm were more likely to have a syrinx preoperatively, and, when present, these patients had a greater likelihood of absolute syrinx reduction postoperatively. We also found that these patients were more likely to have headache improvement. These findings suggest that patients with Grade 0 pB–C2 lines are less likely to experience syrinx and headache resolution from decompressive surgery with duraplasty than those with Grade I pB–C2 lines. However, a Grade I pB–C2 line represents a predictor of positive postoperative outcome in select patients. These measurements may be useful in counseling patients and should help direct further prospective studies of preoperative radiological measurements and surgical outcomes in CM-I.

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Conception and design: all authors. Acquisition of data: Ladner, Dewan, Day, Tomycz. Analysis and interpretation of data:

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Supplemental Information

Previous Presentation

A portion of the findings herein were previously presented at the 42nd Annual Meeting of the AANS/CNS Section on Pediatric Neurological Surgery on December 3, 2013, in Toronto, Ontario, Canada.

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