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ORIGINAL ARTICLE

A new supportive approach in the diagnosis of Chiari malformation type 1 in pediatric patients

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Abstract

Purpose Chiari malformation type 1 (CM-1) is a posterior fossa anomaly characterized by herniation of the cerebellar tonsils from the foramen magnum (FM). This study compares FM, medulla spinalis (MS), and herniated cerebellar tonsils ratios by making area measurements from axial plane MRI in CM-1 patients and the control group.

Methods Our study evaluated 30 pediatric patients with CM-1 and 30 people in the control group. The lengths of the McRae line, twining line, and clivus line were measured on the posterior cranial fossa evaluation. The areas of FM (A_{FM}), MS (A_{MS}), and herniated cerebellar tonsils ($A_{TONSILS}$) were measured by axial images.

Results As a result of area measurements obtained from axial cross-sectional MRI, a statistically significant difference was found between CM-1 patients and the control group. According to the results of the ROC analysis, if an individual's A_{MS}/A_{FM} value is above 17.9% or the $A_{TONSILS}/A_{FM}$ value is above 18.4%, it can be interpreted as a CM-1 patient.

Conclusion It will be easier to diagnose the patient with the new approach we obtained from axial MR images in addition to sagittal MR images. This method can be a guide in some cases when the surgeons are undecided.

Keywords Chiari malformation · Foramen magnum · McRae line · Posterior cranial fossa

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Introduction

Chiari malformation type 1 (CM-1) is an idiopathic disease described as a herniation of the cerebellar tonsils 5 mm or greater below the foramen magnum (FM) [1, 2]. Although many theories have been put forward to explain the etiology of CM-1, the cause is still unknown [2]. CM-1 has been estimated to occur in 1 in 1000 births. Cerebellar tonsils herniate into the upper cervical spinal canal. In 60% of the cases, the tonsils are at the level of the C1 vertebra, rarely below C2 [3]. Patients have no clinical findings in cases where herniation of the tonsils from FM is less than 3 mm, but clinical findings occur when this value exceeds 5 mm in CM-1. The most common symptoms (63%) are upper cervical and suboccipital headaches and neck pain [4, 5].

In clinical studies, CM-1 is associated with occipital bone dysplasia, and patients have craniovertebral junction anomalies with decreased volume of the posterior cranial fossa (PCF). It was reported that various volume measurements, length, diameter, area and angle measurements in the sagittal direction are performed in patients with CM-1 [6–14].

The measurement of FM diameters or areas can be needed to determine some clinical conditions and the diagnosis of various diseases that develop in this area [15]. Depending on the types of Chiari malformation (CM), FM dimensions increased in size as observed in patients with CM, and some others do not [16, 17]. Especially, different theories arise in CM-1 regarding the different dimensions of the FM [18–21]. Sagittal MRI is used to perform the necessary evaluations for a CM-1 diagnosis. In this study, it was aimed to develop a new supportive approach diagnostic method in radiology by comparing FM, medulla spinalis (MS) and herniated cerebellar tonsils, ratios by making area measurements from axial cross-sectional MRI in CM-1 patients and a control group. Furthermore, elaborating on axial MRI scan measurements for CM-1 patients can contribute to an important degree to a greater understanding of this condition given the pathological neurological crowding is often very well identifiable on axial MRI scans.

Methods

Participants

In this study, the measurements obtained from MR images of 30 randomly selected patients who applied to the Erciyes University Faculty of Medicine Department of Neurosurgery with headache complaints. Although the herniation amount was 5 mm or more in 27 of these 30 patients, this herniation was less than 5 mm in 3 of them. Twenty-seven patients were diagnosed with CM-1 by conventional methods (by sagittal plane MRI) but 3 patients were with symptoms suggestive for CM-1 (sleep apnea, headache exacerbated by the Valsalva maneuver) with MRI not conclusive for CM-1. However, considering the clinical complaints, these 3 patients were diagnosed with CM-1 and operated after the evaluation and measurements. All 30 patients were symptomatic and all of these 30 patients were operated. Thirty healthy individuals were included in the study as the control group. The age range of both groups was 10–18.

MRI protocol

Cranial MRs were performed using a 1.5 Tesla Siemens Aera scanner (Siemens, Germany). T1-weighted 3D magnetization-prepared rapid gradient sequence MPRAGE was used to obtain from the sagittal plane, slice thickness = 1.0 mm. The axial images were created by multiplanar reconstruction from sagittal plane T1-weighted 3D volume rendering images. From the midsagittal cross-sectional view at the level of the McRae line, joining the inner faces of the basion and opisthion poles of FM, herniated cerebellar tonsils length were measured in millimeters as shown in Fig. 1.

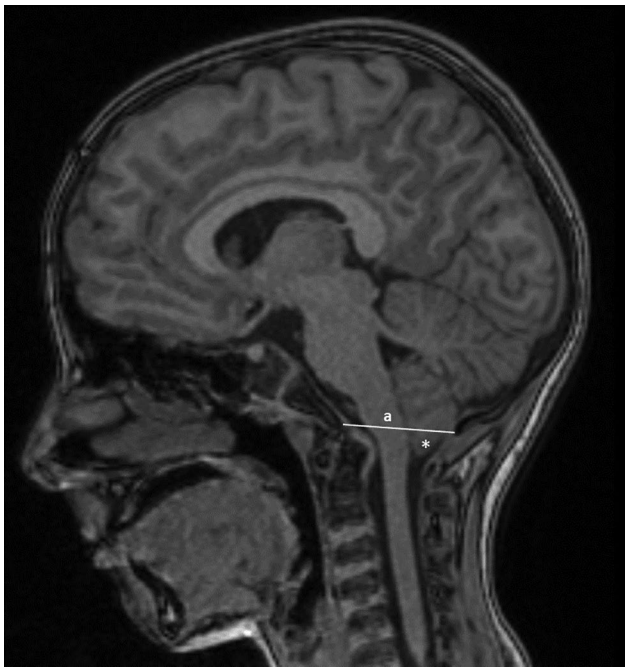

Fig. 1 Mid-sagittal section MR image. a, McRae line. *Herniated cerebellar tonsils

Area measurements

Areas of FM (A_{FM}), MS (A_{MS}), and herniated cerebellar tonsils ($A_{TONSILS}$) were measured from the same level axial cross-sectional images shown in Fig. 2. Although FM area measurements are calculated using the Radinsky formula (A = 1/4 × FM length × FM width) [21], independently using computer imaging software [10, 15] and using the formula πr^2 [22] both in CM-1 patients in the literature, FM area was automatically measured on axial images created by multiplanar reconstruction from sagittal plane images in our study.

We created the relationship between MS and FM, TONSILS and FM by calculating the percentages of A_{MS}/A_{FM} and $A_{TONSILS}/A_{FM}$ respectively.

Linear measurements of the PCF

The lengths of McRae line, twining line and clivus length were measured from midsagittal plane in MRI (shown in Fig. 3). McRae line joins the inner faces of the basion and opisthion pole of FM. The twining line connects the tuberculum sella to internal occipital protuberence. Clivus length, between the apex of the dorsum sellae and basion, shows the height of the PCF. We used axial cross-sectional view through the McRae line to evaluate the A_{FM}, A_{MS}, and $A_{TONSILS}$ in our study. All of linear measurements were taken the head in Frankfurt horizontal plane.

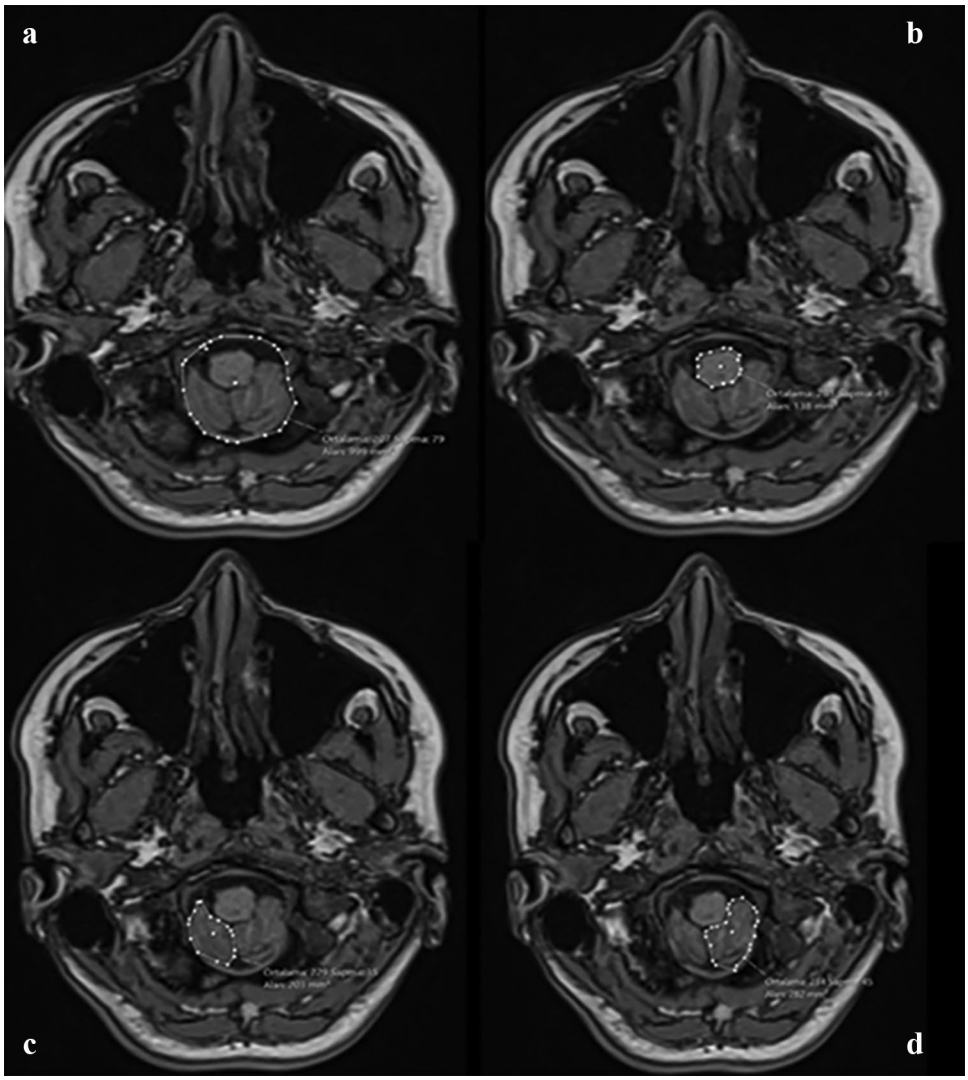

Fig. 2 Axial cross-sectional view through the McRae line. **a**, foramen magnum area; **b**, medulla spinalis area; **c**, right cerebellar tonsil area; **d**, left cerebellar tonsil area

Statistical analysis

Histogram and q-q plots were examined; the Shapiro–Wilk test was applied to test the data's normality. The Levene test was used to assess variance homogeneity. Pearson χ^2 analysis was used to compare the differences between groups for categorical variables, or the Mann–Whitney *U*, and Student *t*-tests were used for continuous variables. ROC analysis was applied to identify the predictive ability of A_{MS}/A_{FM} and $A_{TONSILS}/A_{FM}$ on the CM-1 diagnosis. The area under ROC (receiver operating characteristic) curves was calculated with 95% confidence intervals and compared with each other using DeLong's test. For each marker, cut-off values were determined using the Youden index. Using these cut-off values for each marker, sensitivity, specificity, positive and negative predictive values were calculated with 95% confidence intervals. The sample size of the study was calculated using the G* Power 3. 1. 9. 6 (Frans Foul, Universitat Kiel, Germany) program and the effect size as 0.8, alpha of 0.05. The analysis was conducted using SPSS 22.0 version software. A *p*-value of less than 5% was considered statistically significant.

Results

There were 15 males and 15 females in the CM-1 and control groups, with a mean age of 11.9 and 12.9 respectively. There was no statistically difference between the two groups regarding age ($p > 0.05$). At the end of the 6-month follow-up, it was determined that pre-op clinical findings had vanished in 30 of the 30 operated patients.

Area and length measurements

The FM shapes of all participants were oval. A_{FM}, A_{MS}, left cerebellar tonsil area, right cerebellar tonsil area, $A_{TONSILS}$,

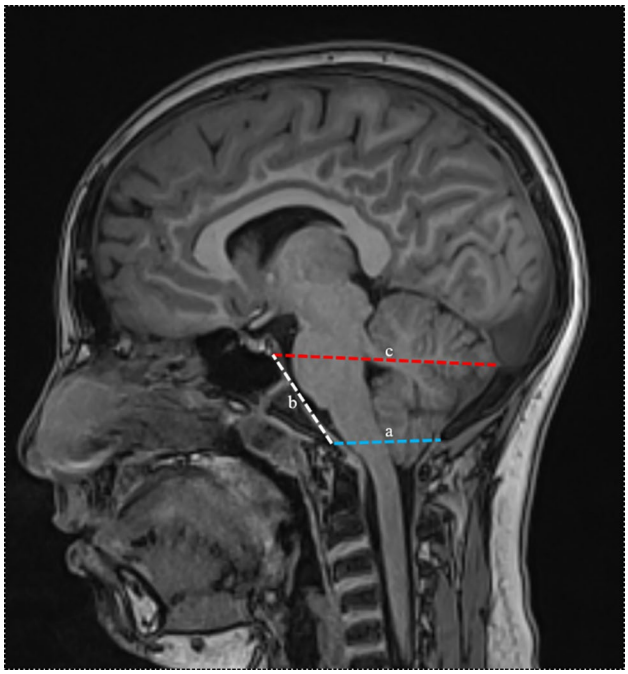

Fig. 3 Mid-sagittal section view. a, McRae line; b, clivus length; c, twining line

$A_{TONSILS}/A_{FM}$(%), A_{MS}/A_{FM} (%), herniated cerebellar tonsils length and twining line length variables are statistically significant between the CM-1 and control groups ($p<0.05$). In the CM-1 group, the mean values of herniated cerebellar tonsils length, A_{MS}/A_{FM} (%), A_{FM} and A_{MS} were significantly higher than those of the control group. In the CM-1 group, the median values of left and right cerebellar tonsil areas, $A_{TONSILS}$, and $A_{TONSILS}/A_{FM}$ (%) were significantly higher than the control group. The mean value of the twining line in the control group was significantly higher than the CM-1 group. The McRae line and clivus lengths variables were not statistically significant between the CM-1 and control groups ($p>0.05$) shown in Table 1.

In the CM-1 group, there was a positive correlation and statistical significance between $A_{TONSILS}/A_{FM}$ (%) and herniated cerebellar tonsils length variables ($r=0.657$, $p<0.01$). In the control group, a statistically significant negative correlation and moderate agreement were found between the A_{MS}/A_{FM} (%) and McRae line length variables ($r=-0.564$, $p<0.01$).

A ROC analysis was performed to determine whether there is a diagnostic cut-off value for detecting CM-1 disease. As a result of ROC analysis, it was determined that A_{MS}/A_{FM} (%) and $A_{TONSILS}/A_{FM}$ (%) values have a diagnostic value in the diagnosis of CM-1 (Table 2, shown in Fig. 4). It was detected that the area under the curve for A_{MS}/A_{FM} (%) on the ROC curve is statistically significant (AUC: 0.72, CI. %: 0.56–0.86, $p<0.001$). It was detected that the area under the curve for $A_{TONSILS}/A_{FM}$ (%) on the ROC curve was also statistically significant (AUC: 1.0, CI. %: 0.89–1.0, $p<0.001$).

According to the Youden index, the optimal cut-off value for A_{MS}/A_{FM} was 17.87% and for $A_{TONSILS}/A_{FM}$ was 18.44%. Namely, if an individual's A_{MS}/A_{FM} is above 17.87% or $A_{TONSILS}/A_{FM}$ is above 18.44%, this individual can be interpreted as a CM-1 patient. The sensitivity and specificity values calculated for the 17.87% and 18.44% cut-off points show that both A_{MS}/A_{FM} and $A_{TONSILS}/A_{FM}$ have a diagnostic value on CM-1 (Table 2).

Although symptomatic and operated three patients not diagnosed CM-1 with length measurements (3.3, 3.5, and 4.5 mm) from sagittal MRI, can be diagnosed with CM-1 via the cut-off value of A_{MS}/A_{FM} we have created from axial MRI in our study (A_{MS}/A_{FM} percentages of 20.3, 25.1, and 31.6, respectively). Also, via the cut-off value of $A_{TONSILS}/A_{FM}$ we have created, these three patients can be diagnosed with CM-1 ($A_{TONSILS}/A_{FM}$ percentages of 28.7, 37.6, and 39.9, respectively).

Table 1 Results of area and length values in patient and control groups

Variables	Groups		*p*
	CM-1 group ($n=30$)	Control group ($n=30$)	
FM area (mm^2)	731.4 ± 118.1	603.9 ± 92.5	< 0.001*
MS area (mm^2)	151.5 ± 39.1	103.5 ± 17.9	< 0.001*
A_{MS}/A_{FM} (%)	20.8 ± 4.2	17.4 ± 3.5	0.002*
Left cerebellar tonsil area (mm^2)	175.0 (122.0–217.0)	0.0 (0.0–0.0)	< 0.001*
Right cerebellar tonsil area (mm^2)	220.5 (186.2–238.5)	0.0 (0.0–3.7)	< 0.001*
Total cerebellar tonsil area (mm^2)	397.5 (311.2–448.7)	0.0 (0.0–1.5)	< 0.001*
$A_{TONSILS}/A_{FM}$ (%)	54.74 (43.9–59.0)	0.0 (0.0–1.5)	< 0.001*
Herniated cerebellar tonsils length (mm)	7.7 ± 1.1	0.1 ± 0.2	< 0.001*
McRae line (mm)	36.7 ± 3.1	36.7 ± 3.5	0.947
Twining line (mm)	92.7 ± 5.6	96.8 ± 4.2	0.002*
Clivus length (mm)	39.1 ± 5.3	41.3 ± 5.6	0.121

FM foramen magnum, *MS* medulla spinalis

Data are expressed as mean ± standard deviation and median (1st quarter–3rd quarter). *$p<0.05$

Table 2 ROC analysis results and diagnostic statistics of A_{MS}/A_{FM} and $A_{TONSILS}/A_{FM}$ markers

Variables	AUC	CI. 95%	Sensitivity (%) (CI. 95%:L-U)	Selectivity (%) (CI. 95%:L-U)	*p*
$A_{MS}/A_{FM} > 17.87\%$	0.72	0.56–0.86	73.3	60.0	< 0.001
$A_{TONSILS}/A_{FM} > 18.44\%$	1.0	0.89–1.0	100	100.0	< 0.001

AUC area under curve, *ROC* receiver operating characteristic

The statistics are given with 95% confidence interval

In our study, whereas 90% of the patients who showed symptoms according to the classical method (sagittal MRI) were CM-1 patients, this rate was 100% with our new method (axial MRI). In this context, the reliability of our study is higher than the reliability of the classical diagnosis method.

Discussion

The dimensions of the FM are clinically important such as the posterior cranial fossa dimensions because the vital structures that pass through it can be subjected to compression.

Many reports for CM-1 mentioned that the mean age of the patients admitted to the clinics was between 5 and 71 [6, 9, 11, 23]. Our study was performed in the pediatric group, the mean age of the control group was 12.9, and the mean age of the patients with CM-1 was 11.9. No studies in the literature found cerebellar tonsil areas on axial cross-sectional images in pediatric CM-1 patients. In studies on the length of herniated cerebellar tonsils into the spinal canal in CM-1 cases, sagittal plane MRI of patients in the Chiari group reported that the length of tonsillar herniation was 5 mm and more [1, 6, 9, 24]. In the study conducted by Elster et al. [1] on the MRI of 68 patients, they found that 30% of patients with herniated cerebellar tonsils less than 5 mm were asymptomatic. In our study, all patients were symptomatic. Except for the results of three patients with symptomatic findings, the length measurements (mean 7.7 mm) of

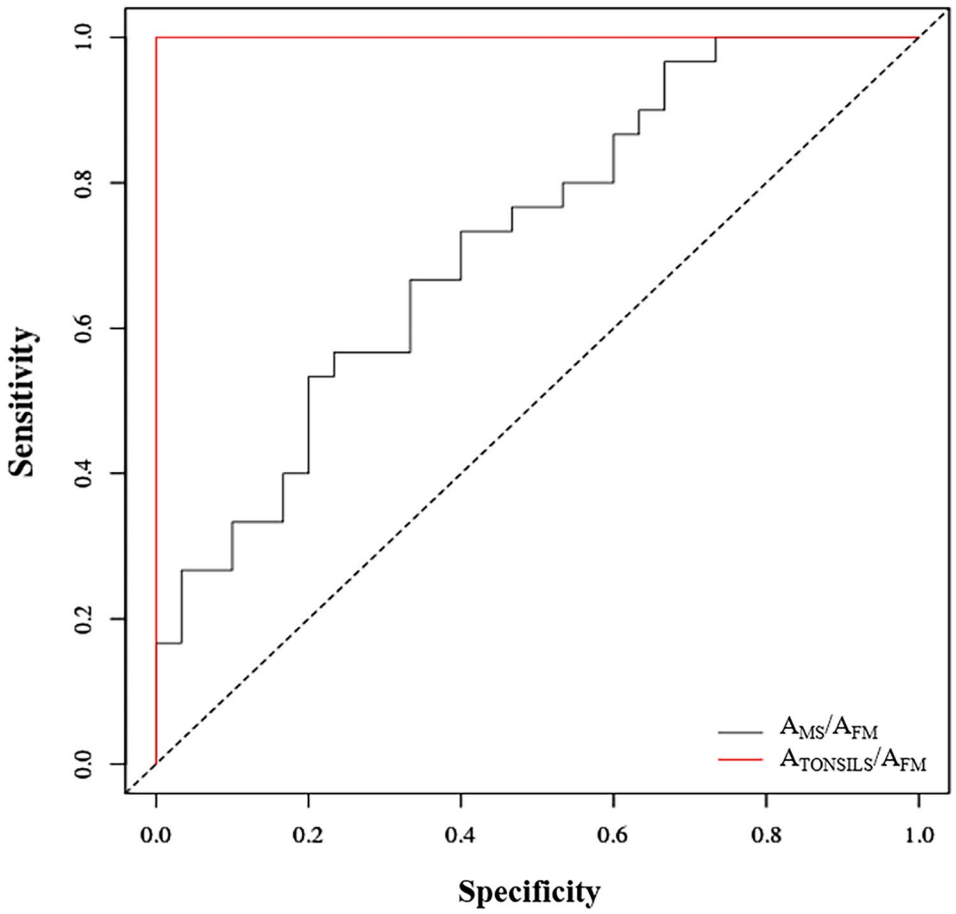

Fig. 4 ROC curve

the herniated cerebellar tonsils of the patients were like the sagittal measurements in the literature.

Although there have been studies in the literature on the effect of tonsillar herniation on the cerebrospinal fluid flow rate in CM-1 patients [25–27], there have been no studies on the effect of tonsillar herniation on the medulla spinalis area (A_{MS}). The results of A_{MS} measurements were 103.5 ± 17.9 mm^2 in the control group and 151.5 ± 39.1 mm^2 in the CM-1 group in our study. A_{FM}, A_{MS}, and A_{MS}/A_{FM} variables were statistically significant between the CM-1 and control groups ($p < 0.05$). The reason why we found more A_{MS} in the CM-1 group compared to the control group may be due to the large size of the A_{FM} in the CM-1 group. No studies have been found in the literature to compare our results with theirs.

In 1982, Teixeria conducted an initial study of sex estimation based on FM size and created a formula for area calculation of FM 40 skeletons [28]. After this study, new studies were conducted by increasing the number of cases and extending the measured criteria [13, 29–31].

The FM area and dimensions have differed in the Chiari subtypes [16–22]. Kruyff et al. [16] and Basaran et al. [21] found the FM area increased in CM-2 patients compared with the control group, while Tubbs et al. [17] describe the FM as decreased in size in CM-0 patients. Some studies have been conducted on FM area, diameter, and volume measurements in CM-1 patients [10, 15, 18, 19, 22]. According to the study of Milhorat et al. [10] and Basaran et al. [21] on adult patients with CM-1, the FM area was smaller than the control group. Ulutabanca et al. [19] have stated that size of FM in CM-1 patient to be significantly higher aspect ratio compared to a normal. According to literature information, the width, length, and area of FM vary in CM-1 [10, 19]. Similar to Ulutabanca et al. [19], the FM area was higher in the CM-1 group than control group in our study (CM-1 group: 731.4 ± 118.1 mm^2, control group: 603.9 ± 92.5 mm^2). As a result of this, the large area of FM may lead to the formation of CM-1.

Although in some studies the McRae line was found to be higher in patients with CM-1 compared to the control group [6, 14, 25, 32, 33], some studies [9, 10, 20] found no difference between the McRae line lengths in CM-1 patients and the control group. The findings of the McRae line in both studies are consistent with our data. In the present study, the McRae line gives information about the length of FM, which was found to be 36.7 ± 3.5 mm in the control group and 36.7 ± 3.1 mm in the CM-1 group.

We found the clivus length to be 41.3 ± 5.6 mm and 39.1 ± 5.3 mm, respectively, in the control and CM-1 groups. There was a difference between the two groups, but this difference was not statistically significant ($p > 0.05$). In studies in the literature, the results of the CM-1 group were found to be smaller than the control group [6, 8, 9, 14, 20, 32, 33]. Our results are compatible with the studies in the literature.

The twining line was lower in the CM-1 group compared to the control group in our study. This decrease in the CM-1 group was statistically significant ($p = 0.002$). Our results were consistent with other studies [10, 32, 33], except by Alkoç et al. [6].

We found that clivus and twining line lengths were shorter in CM-1 patients compared to the control group. We think that the shortness of these linear measurements of the PCF in patients will cause the formation of this malformation.

Conclusion

Although CM-1 was not diagnosed in patients with tonsillar herniation less than 5 mm in sagittal MR images, these patients may also have symptoms. Considering such patients, it will be easier to diagnose the patient with the cut-off values and new approach we obtained from axial MR images in addition to sagittal MR images. This method can be a guide in some cases when the surgeons are undecided. Evaluating the accuracy and reliability of the method may need a bigger number of patients and case controls to assess its reliability.

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Author contribution The authors confirm contribution to the paper as follows:

Conception or design of the work: Burcu Kamaşak, İbrahim Suat Öktem, Kenan Aycan. Data collection: Burcu Kamaşak, İbrahim Suat Öktem. Data analysis and interpretation: Burcu Kamaşak, Zehra Filiz Karaman, Funda İpekten. Drafting the article: Burcu Kamaşak, Tufan Ulcay, İbrahim Suat Öktem. Critical revision of the article: Ahmet Küçük, Tufan Ulcay, İbrahim Suat Öktem. Supervision: İbrahim Suat Öktem, Kenan Aycan. All authors (Burcu Kamaşak, Tufan Ulcay, Ahmet Küçük, Zehra Filiz Karaman, Funda İpekten, İbrahim Suat Öktem, Kenan Aycan) reviewed the results and approved the final version of the manuscript.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Ethics approval This study was approved by the Erciyes University Ethical Board (2018–372) as well as the Scientific and Technological Research Council and has been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its later amendments. The written informed consent was obtained from each participant.

References

1. Elster AD, Chen MY (1992) Chiari I malformations: clinical and radiologic reappraisal. Radiology 183:347–353. https://doi.org/10.1148/radiology.183.2.1561334
2. Greenberg MS (1994) Handbook of neurosurgery. Florida, Greenberg Graphics, pp 154–157

3. Iskandar BJ, Oakes W (1999) Chiari malformations. In: Pollack FI, Albright A, Adelson PD (eds) Principles and practice of pediatric neurosurgery. Thieme, pp 165–184
4. Loukas M, Noordeh N, Shoja MM et al (2008) Hans Chiari (1851–1916). Childs Nerv Syst 24:407–409. https://doi.org/10.1007/s00381-007-0535-y
5. Steinbok P (2004) Clinical features of Chiari I malformations. Childs Nerv Syst 20:329–331. https://doi.org/10.1007/s00381-003-0879-x
6. Alkoc OA, Songur A, Eser O et al (2015) Stereological and morphometric analysis of MRI Chiari malformation type-1. J Korean Neurosurg Soc 58:454–461. https://doi.org/10.3340/jkns.2015.58.5.454
7. Bagci AM, Lee SH, Nagornaya N, Green BA, Alperin N (2013) Automated posterior cranial fossa volumetry by MRI: applications to Chiari malformation type I. AJNR Am J Neuroradiol 34:1758–1763. https://doi.org/10.3174/ajnr.A3435
8. Gad KA, Yousem DM (2017) Syringohydromyelia in patients with Chiari I malformation: a retrospective analysis. AJNR Am J Neuroradiol 38:1833–1838. https://doi.org/10.3174/ajnr.A5290
9. Karagoz F, Izgi N, Kapicioglu Sencer S (2002) Morphometric measurements of the cranium in patients with Chiari type I malformation and comparison with the normal population. Acta Neurochir (Wien) 144:165–171. https://doi.org/10.1007/s007010200020
10. Milhorat TH, Nishikawa M, Kula RW, Dlugacz YD (2010) Mechanisms of cerebellar tonsil herniation in patients with Chiari malformations as guide to clinical management. Acta Neurochir (Wien) 152:1117–1127. https://doi.org/10.1007/s00701-010-0636-3
11. Odaci DE, Bahadir A, Yildirim S et al (2005) Volume estimation using the cavalieri principle on computerized tomography and magnetic resonance images and its clinical application: review. Turkiye Klin J Medical Sci 25:421–428
12. Oral S, Kucuk A, Tümtürk A, Çiftçi M, Menkü A (2016) Measuring posterior fossa with neuronavigation in chiari type 1 malformation patients and the relation between syrinx cavity and posterior fossa volume. J Neurological Sci (Turkish) 34. https://doi.org/10.24165/jns.8782.15
13. Shepur MP, Magi M, Nanjundappa B et al (2014) Morphometric analysis of foramen magnum. Int J Anat Res 2:249–255
14. Taştemur Y, Sabanciogullari V, Salk İ, Sönmez M, Cimen M (2017) The relationship of the posterior cranial fossa, the cerebrum, and cerebellum morphometry with tonsiller herniation. Iran J Radiol 14: e13461. https://doi.org/10.5812/iranjradiol.24436
15. Furtado SV, Thakre DJ, Venkatesh PK, Reddy K, Hegde AS (2010) Morphometric analysis of foramen magnum dimensions and intracranial volume in pediatric Chiari I malformation. Acta Neurochir 152(2):221–227
16. Kruyff E, Jeffs R (1966) Skull abnormalities associated with the Arnold Chiari malformation. Acta Radiol Diagn (Stockh) 5:9–24
17. Tubbs RS, Elton S, Grabb P, Dockery SE, Bartolucci AA, Oakes WJ (2001) Analysis of the posterior fossa in children with the Chiari 0 malformation. Neurosurgery 48(5):1050–1054. https://doi.org/10.1097/00006123-200105000-00016
18. Shuman WH, DiRisio A, Carrasquilla A et al (2022) Is there a morphometric cause of Chiari malformation type I? Analysis of existing literature. Neurosurg Rev 45:263–273. https://doi.org/10.1007/s10143-021-01592-4
19. Ulutabanca H, Acer N, Küçük A, Dogan S, Tümtürk A, Kurtsoy A, Sagıroglu A, Bilgen M (2015) Chiari type I malformation with high foramen magnum anomaly. Folia Morphol (Warsz) 74(3):402–406
20. Wang S, Huang Z, Xu R, Liao Z, Yan Y, Tang W, Xia Y (2020) Chiari malformations type I without basilar invagination in adults: morphometric and volumetric analysis. World Neurosurg 143:e640–e647
21. Basaran R, Efendioglu M, Senol M, Ozdogan S, Isik N (2018) Morphometric analysis of posterior fossa and craniovertebral junction in subtypes of Chiari malformation. Clin Neurol Neurosurg 169:1–11. https://doi.org/10.1016/j.clineuro.2018.03.017
22. Iqbal S, Robert A, Mathew D (2017) Computed tomographic study of posterior cranial fossa, foramen magnum, and its surgical implications in Chiari malformations. Asian J Neurosurg 12(3):428–435. https://doi.org/10.4103/1793-5482.175627
23. Roberts N, Puddephat MJ, McNulty V (2000) The benefit of stereology for quantitative radiology. Br J Radiol 73:679–697. https://doi.org/10.1259/bjr.73.871.11089458
24. Meadows J, Kraut M, Guarnieri M, Haroun RI, Carson BS (2000) Asymptomatic Chiari type I malformations identified on magnetic resonance imaging. J Neurosurg 92:920–926. https://doi.org/10.3171/jns.2000.92.6.0920
25. Alperin N, Loftus JR, Oliu CJ et al (2014) Magnetic resonance imaging measures of posterior cranial fossa morphology and cerebrospinal fluid physiology in Chiari malformation type I. Neurosurgery 75:515–522. https://doi.org/10.1227/NEU.0000000000000507
26. Badie B, Mendoza D, Batzdorf U (1995) Posterior fossa volume and response to suboccipital decompression in patients with Chiari I malformation. Neurosurgery 37:214–218. https://doi.org/10.1227/00006123-199508000-00004
27. Nishikawa M, Sakamoto H, Hakuba A, Nakanishi N, Inoue Y (1997) Pathogenesis of Chiari malformation: a morphometric study of the posterior cranial fossa. J Neurosurg 86:40–47. https://doi.org/10.3171/jns.1997.86.1.0040
28. Teixeira WR (1982) Sex identification utilizing the size of the foramen magnum. Am J Forensic Med Pathol 3:203–206. https://doi.org/10.1097/00000433-198209000-00003
29. Gapert R, Black S, Last J (2009) Sex determination from the foramen magnum: discriminant function analysis in an eighteenth and nineteenth century British sample. Int J Legal Med 123:25–33. https://doi.org/10.1007/s00414-008-0256-0
30. Murshed K, Cicekcibasi A, Tuncer I (2003) Morphometric evaluation of the foramen magnum and variations in its shape: a study on computerized tomographic images of normal adults. Tr J Med Sci 33
31. Raghavendra Babu YP, Kanchan T, Attiku Y, Dixit PN, Kotian MS (2012) Sex estimation from foramen magnum dimensions in an Indian population. J Forensic Leg Med 19:162–167. https://doi.org/10.1016/j.jflm.2011.12.019
32. Houston JR, Eppelheimer MS, Pahlavian SH, Biswas D, Urbizu A et al (2018) A morphometric assessment of type I Chiari malformation above the McRae line: a retrospective case-control study in 302 adult female subjects. J Neuroradiol 45:23–31. https://doi.org/10.1016/j.neurad.2017.06.006
33. Sekula RF, Jannetta PJ, Casey KF et al (2005) Dimensions of the posterior fossa in patients symptomatic for Chiari I malformation but without cerebellar tonsillar descent. Cerebrospinal Fluid Res 2:11. https://doi.org/10.1186/1743-8454-2-11