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Original Article

Cerebrospinal Fluid Flow Analysis in Prepontine Cistern, Foramen Magnum and 5th Cervical Spine Levels: Temporal and Spatial Patterns at MR Imaging in Volunteers and in Patients with Chiari I Malformation

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Abstract

Background and Purpose: The neurological signs and symptoms in Chiari I malformation patients are related to cerebrospinal fluid (CSF) flow obstruction at the foramen magnum. Previous studies show significantly higher peak CSF velocity at the foramen magnum level in these patients than in the normal population. However, recent studies report no significant difference of peak CSF velocity at the foramen magnum between symptomatic and asymptomatic Chiari I groups and suggested further studies of CSF flow outside the foramen magnum for better patient classification. The purpose of this study was to evaluate and compare CSF flow patterns in Chiari I patients and in healthy controls at the prepontine cistern, foramen magnum, and 5th cervical spine (C5) levels.

Methods: Five patients and ten healthy control volunteers were studied with a phase-contrast MRI at these levels through 20 phases of a cardiac cycle. The CSF flow patterns were analyzed for inhomogeneity using the flow velocity difference between the areas anterior and posterior to the spinal cord, the synchronous bidirectional flow, and the preferential flow direction.

Results: The peak systolic velocity means in the patients were higher than those in the controls for all three levels. However, statistical significance occurred only at the foramen magnum level. For all three levels, the flow spatial and temporal variations (flow nodes and jets and consecutive images with synchronous bidirectional flows) were more evident in the patients than in the controls.

Conclusion: No significant difference of the CSF flow occurs at the prepontine cistern and C5 levels between the patients and controls. Therefore, the CSF flow studies outside the foramen magnum may not be effective for patient evaluation

Introduction

The Chiari I malformation is a congenital hind-brain dysgenesis characterized by tonsillar ectopia, which is downward displacement of the cerebellar tonsils below foramen magnum or into the spinal canal. Multiple etiologies cause small posterior fossa relatively with the cerebellum. Chiari I patients may present with clinical findings related to brainstem compression, i.e., valsava maneuver-induced head-ache, ataxia or lower cranial nerve symptoms, or related to syringomyelia, i.e., pain, impaired tem-perature sensation or peripheral motor weakness[1,3].

However, about 1/3 of patients have no signs or symptoms related to the Chiari I malformation. In addition, clinical manifestations vary between patients with the similar amounts of tonsillar ectopia[2,4]. To our knowledge, neurological signs and symp-toms in Chiari I patients related to cerebrospinal fluid (CSF) flow obstruction at foramen magnum[1,12].

Previous studies of CSF flow in the foramen magnum with phase contrast magnetic resonance imaging (MRI) show more synchronous bidirectional flows of CSF flow in symptomatic Chiari I group and show significant higher peak CSF velocity at foramen magnum than that in normal population[7]. Furthermore, in Chiari I patients, the peak CSF velocity decreases after surgical treatment by craniocervical decompression[5-9]. Then, the alteration of the CSF flow patterns in Chiari I patients may be helpful in patient screening for surgical treatment and postoperative follow-up[11-15].

However, the recent study of Krueger KD et al.[15] shows no significant difference of the peak CSF velocity in the foramen magnum between symptomatic and asymptomatic Chiari I groups and suggests that CSF flow analysis outside the foramen magnum may be beneficial for evaluation of the Chiari I patients[15].

In our study, we compared difference of CSF flow patterns at MRI in Chiari I patients and healthy controls at the prepontine cistern, foramen mag-num, and 5th cervical spine (C5) levels.

Research question

Are there any differences in CSF flow pat-terns at the prepontine cistern, foramen magnum, and C5 levels at MRI in healthy controls and in patients with Chiari I Malformation?

Objective

To study variation in CSF flow patterns at the prepontine cistern, foramen magnum, and C5 levels through a cardiac cycle and throughout the sub-arachnoid space at MRI in healthy controls and in patients with Chiari I malformation.

Materials and Methods

Study design

Prospective case-control study between a Chiari I patient group and a healthy control group

Patients and Controls

Patients

Out patients with Chiari I malformation from the Departments of Neurosurgery, Neuromedicine, and Orthopedics of Ramathibodi hospital between November 2010 and October 2011 were included in our study. The inclusion and exclusion criteria were described below.

Inclusion criteria:

1. All of the patients who have been diag-nosed Chiari I malformation, as determined on the basis of T2-weighted sagittal MR image (tonsillar ectopia and/or peg like cerebellar tonsils). The

patients may have or may not have signs and symptoms of Chiari I malformation.

2. No history of claustrophobia or contraindications to MRI.

3. Completed informed consent.

Exclusion criteria:

1. Contraindication for 3-Tesla MRI.

2. Not completed informed consent or cancelled informed consent

Controls

Inclusion criteria:

1. All normal volunteers who are healthy and no present or previous spinal and neurologic problems or hypertension.

2. No cerebellar tonsils below the foramen magnum level from the T2-weighted sagittal MR image.

3. No history of claustrophobia or contraindications to MRI.

4. Completed informed consent.

The MRI protocol followed ethical rules and was approved by our institutional review board, and all patients were informed and gave their consents.

MRI protocol for CSF flow study:

- Flip angle = 20°
- Repetition time (msec)/ echo time (msec)= 7.4/5.5
- Slice thickness = 5 mm
- Field of view = 150 mm
- Matrix size = 256 x 256
- Encoding velocity = 10 cm/sec

Locations of the CSF flow study (Figure 1)

1. Axial plane perpendicular to the CSF space at the mid prepontine cistern level

2. Axial plane perpendicular to the CSF space at

2.1 The foramen magnum in controls, (the mid of the slice at the line between basion (anteriorly) and opision (posteriorly)

2.2 Just below the cerebellar tonsils in patient with Chiari I malormation

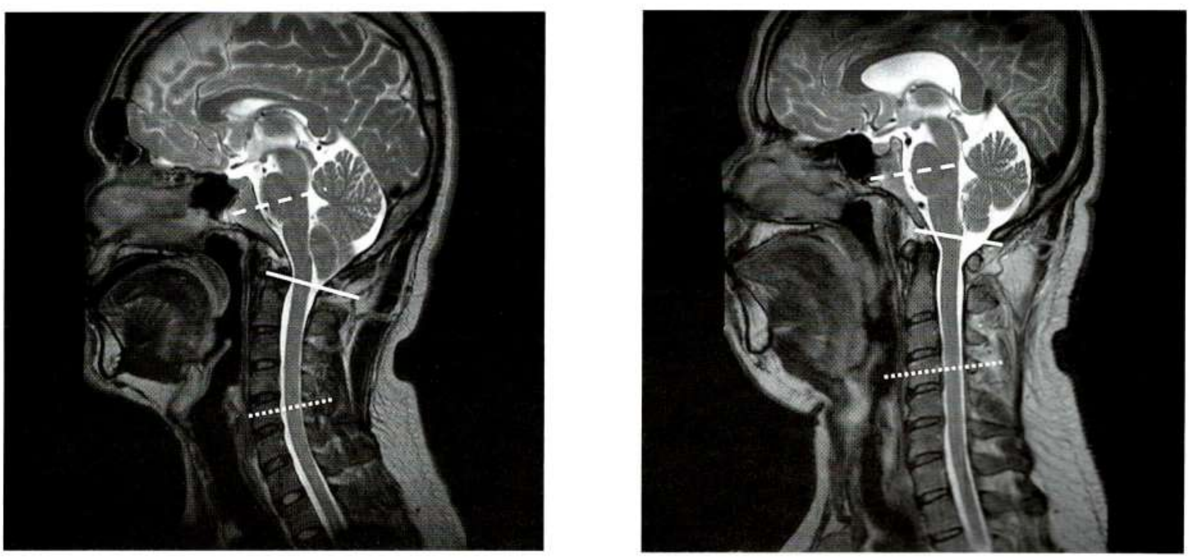


Fig.1 Axial planes are placed perpendicular to CSF space at the prepontine cistern, foramen magnum, and mid C5 levels (represented by dashed, solid, and dotted lines, respectively) on the T2-weighted images of a Chiai I patient (left) and of a healthy control volunteer (right).

3. Axial plane perpendicular to the CSF space at the mid C5 level

Total scan time was about 30-40 minutes and there was no intravenous contrast material administration.

Sample size

This study compared differences in CSF flow patterns at the prepontine cistern, foramen magnum, and C5 levels at MRI in healthy controls and in patients with Chiari I malformation.

For comparison between these two groups of data, the sample size was estimated by using estimated sample size for two-sample comparison of means, which were calculated from STATA statistical analysis program. In the previous study[10], the Chiari I patients had significant elevations of peak systolic velocity of the CSF in the foramen magnum. The average peak systolic velocity was 2.4 cm/sec (SD, 0.7) in the controls and was 3.1 cm/sec (SD, 1.0) in the Chiari I patients.

Then we set the difference between peak systolic velocity of the CSF in the foramen magnum between the controls and the Chiari I patients with statistically significant level at power = 0.800 and alpha = 0.0500.

Estimated sample size for two-sample comparison of means

Test Hypothesis: m1 = m2, where m1 is the mean in population 1 and m2 is the mean in population 2.

Assumptions:

Alpha = 0.0500 (two-sided)

Power = 0.8000

m1 = 2.4

m2 = 3.1

sd1 = 0.7

sd2 = 1.0

n2 / n1 = 2.00

Estimated required sample sizes:

n1 = 16

n2 = 32

Between November 2010 and October 2011, we estimated number of Chiari I patients that were included in the study about 5 persons. Then we recalculated estimated required sample sizes at the mean of peak systolic velocity of the Chiari I patient group at 3.5 cm/sec.

Estimated sample size for two-sample comparison of means

Test Hypothesis: m1 = m2, where m1 is the mean in population 1 and m2 is the mean in population 2

Assumptions:

Alpha = 0.0500 (two-sided)

Power = 0.8000

m1 = 2.4

m2 = 3.5

sd1 = 0.7

sd2 = 1.0

n2 / n1 = 2.00

Estimated required sample sizes:

n1 = 5

n2 = 10

Then, sample sizes in this study were 5 persons in the Chiari I patient group and 10 persons in the control group.

Data collection

Demographic data

The following demographic data, collected by interviewing or reviewing from the medical record, were recorded in data collection form.

- Age

- Gender
- Clinical presentation: sign and symptom of Chiari I malformation

CSF flow measurement and analysis

The patients and controls underwent imaging with a 3-Tesla MRI scan (Achiva; Philips medical systems, Best, the Netherlands). The T2-weighted sagittal images of the cervical spine in two groups were obtained for evaluation of tonsillar ectopia and syringomyelia by a neuroradiologist and a radiology resident. The lengths of the tonsillar ectopia in the Chiari I patient group were recorded.

The cardiac gated phase-contrast images were acquired at the prepontine cistern, foramen magnum, and C5 levels when the participant had achieved steady heart rate. The CSF flow measurement data were conduct with computer software analysis program of the Philips MRI scan. The images of 20 phases of a cardiac cycle were inspected to identify the subarachnoid space and the course of the vertebral arteries. The signal intensity within the subarachnoid space was assessed visually for the uniformity or inhomogeneity.

To measure velocity and flow volume of CSF of each voxel in the systolic and diastolic phases and to evaluate CSF flow pattern at the 3 levels, the CSF flow analysis computer program has been developed by a research scientist from the National Electronics and Computer Technology Center (NECTEC). A region of interest was manually placed to include the entire subarachnoid space (including the spinal cord), then the program removed the voxels that have absolute velocities less than 1.5 cm/s (in either caudad or cephalad directions) in all cardiac phases, indicating stationary tissue. In addition, the voxels that have all positive or all negative flow velocities in all cardiac phases, indicating vascular tissue, were also removed from the region of interest. By concensus, the investigators verify the region of interest by investigating the plots of the CSF velocities versus the cardiac phases to adjust some voxels in the regions of interest. The voxels exhibiting aliased velocities were corrected with the program. The peak systolic and diastolic velocities in the region of interest were demonstrated from color maps and surface contour plots of the CSF velocities.

The color maps and surface contour plots of the CSF velocities in both control group and patient group at three levels were analyzed for the following parameters:

1. Peak systolic velocity (PSV) and peak diastolic velocity (PDV) and their location in 6 locations of the subarachnoid space, i.e., anterior midline, anterior paramedian, posterior midline, posterior paramedian, anterolateral, and posterolateral regions
2. CSF flow in the anterior and the posterior subarachnoid space
3. Voxels that have velocity exceeded those in the adjacent region of the subaracnoid space by 100-200% (nodes) and 200-300% (jets), compared with voxels that exhibit total subaracnoid space
4. Presence of the synchronous bidirectional flow, i.e., flow images containing both cephalad and caudad flow in same image in two or more consecutive phases
5. Flow preferential direction: cephalad flow volume, caudad flow volume, and net flow volume in the subarachnoid space

Statistical analysis

Discontinuous variables, i.e., sex of patients or controls, symptoms and signs of patients will be summarized as counts and percentages. Continuous variables, i.e., age of patients or controls, velocity or flow volume of CSF will be summarized as range) and mean ± 1 standard deviation (SD) of the groups.

To test the significance of differences in the parameters between the patients and the controls, the comparison of the mean was performed using student t-test or Mann-Whitney test, with P-value ≤ .05 considered to indicate a statistically significant difference.

Fisher's exact test was used to test the significant difference in the presence of synchronous bidirectional flows in both groups.

Results

Patients and volunteers

The Chiari I group comprised 5 patients (3 men, 2 women; age range, 16-49 years; mean age, 36 years) who have been diagnosed with Chiari I malformation, as determined on the basis of T2-weighted sagittal MR images. The control volunteers groups included 10 normal volunteers (4 men, 6 women; age range, 23-51 years; mean age, 32.1 years) who have no evidence of tonsillar ectopia or gross posterior fossa abnormalities. The age difference between the two groups was not significant (P-value = 0.4934).

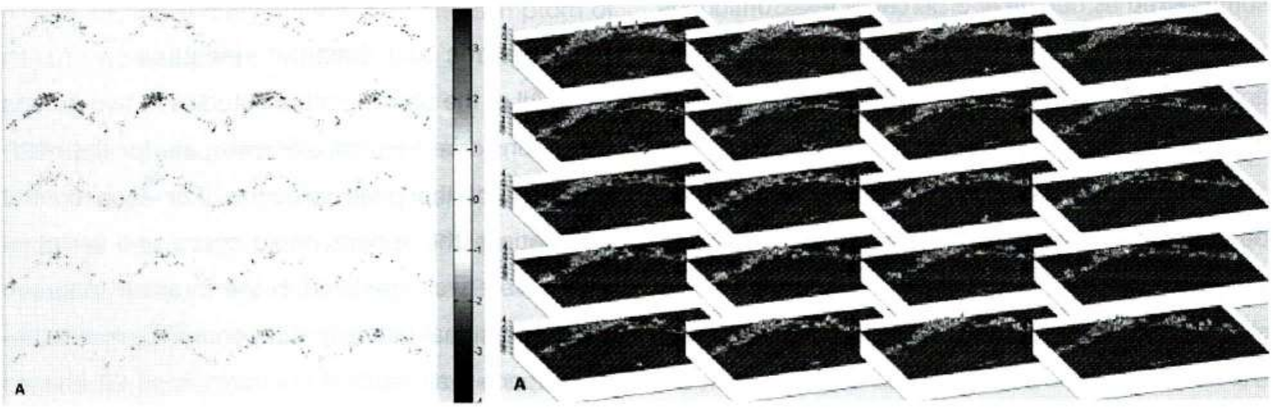
In Chiari I group, tonsillar herniation ranged from 4 mm to 16 mm (mean = 11 mm). One asymptomatic Chiari I patient had unilateral tonsillar herniation about 8 mm. Four patients had symptoms and/or signs that were attributed to Chiari I malformation. Three of these patients presented with valsava maneuver-induced headache and two of which had sensory deficit (paresthesia of the upper extremity). The other patient presented with scoliosis and syringomyelia seen on MRI.

Peak systolic and diastolic velocities

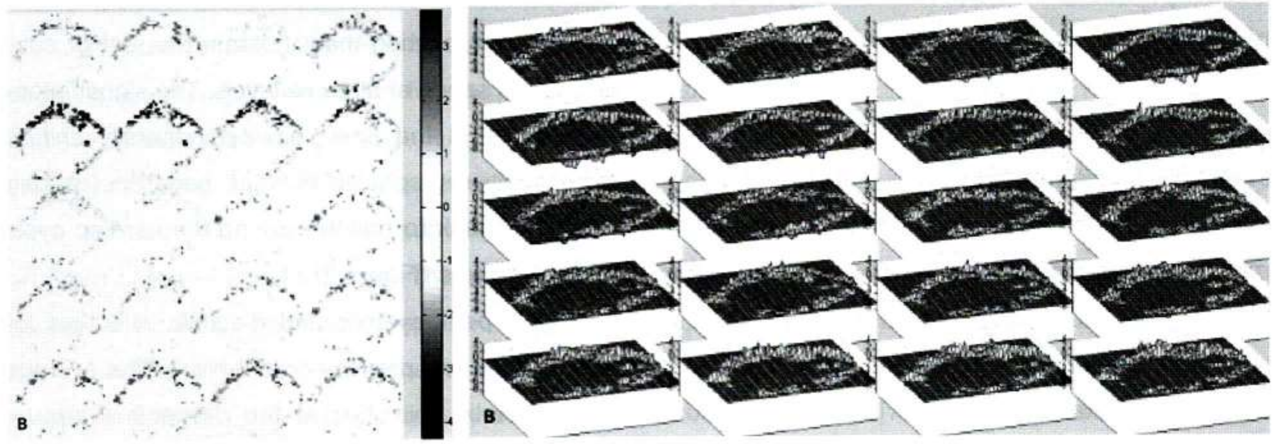
All of the phase-contrast studies of two groups were considered technically adequate for the measurement of the peak velocities. For each control and patient, the subarachnoid space and vertebral artery were well identified in the foramen magnum level. The signal intensity throughout the subarachnoid space was relatively uniform in all 20 images of the cardiac phases. In both Chiari I and control groups, slightly greater velocities of CSF flow were evident in the anterior subarachnoid space in a paramedian location than those in the rest of subarachnoid space at all three levels. The signal intensity (which is the flow velocity) generally shifted from positive (cephalad flow) to negative (caudad flow) and back to positive during the cardiac cycle in both groups (Figure 2).

The peak systolic and diastolic velocities for the controls are presented in Table 1. The average peak systolic velocities at the prepontine cistern, foramen magnum and C5 levels were 3.93 cm/s (SD, 0.87), 4.10 cm/s (SD, 0.51), and 7.29 cm/s (SD, 1.38), respectively, while the average peak diastolic velocities at these three levels were 3.58 cm/s (SD, 0.94), 3.42 cm/s (SD, 0.42), and 5.76 cm/s (SD, 1.66), respectively.

The peak systolic and diastolic velocities for the Chiari I patients are presented in Table 2. The average peak systolic velocities at the prepontine cistern, foramen magnum, and C5 levels were 4.54 cm/s (SD, 1.51), 7.33 cm/s (SD, 1.62), and 8.09 cm/s (SD,1.43), respectively, while the average peak diastolic velocities at these three levels were 3.54 cm/s (SD, 0.83), 3.65 cm/s (SD, 0.79), and 5.45 cm/s (SD,1.43), respectively.



(a)



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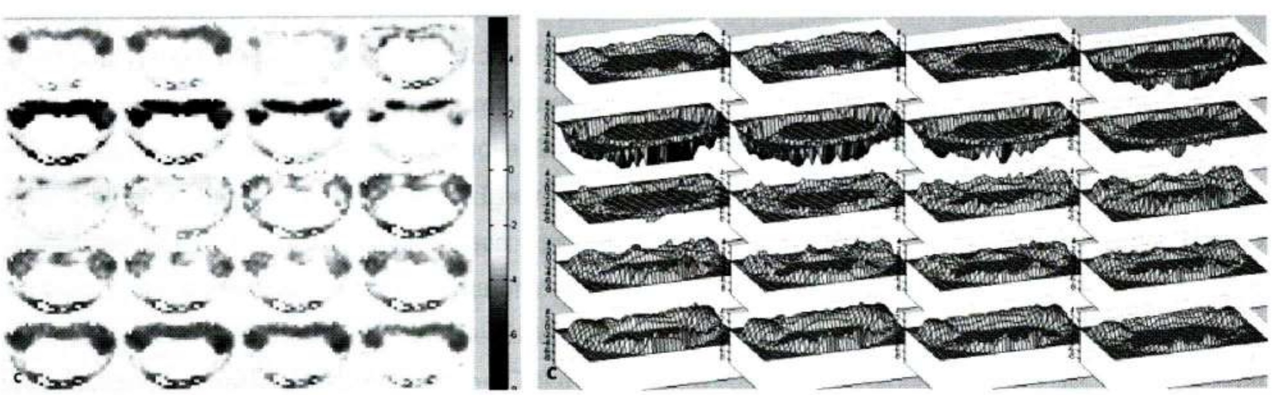

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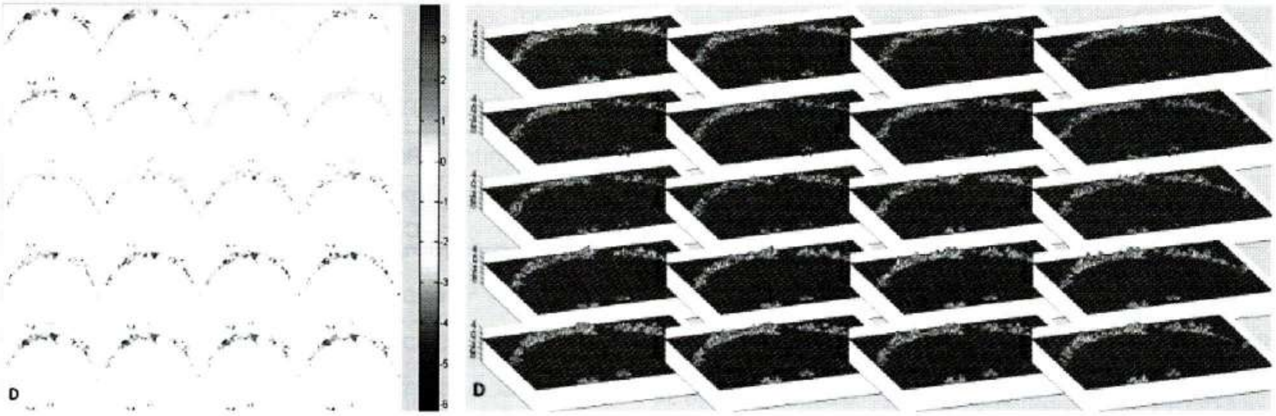

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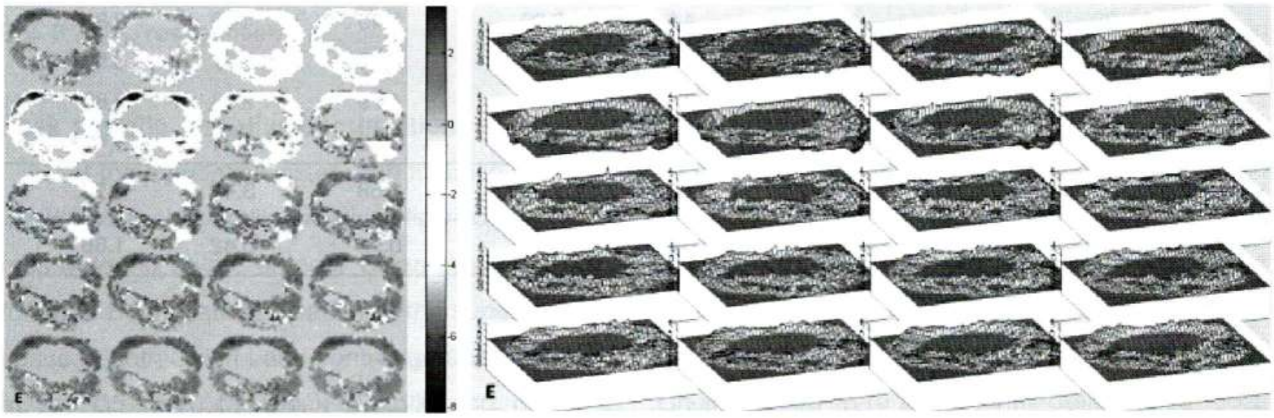

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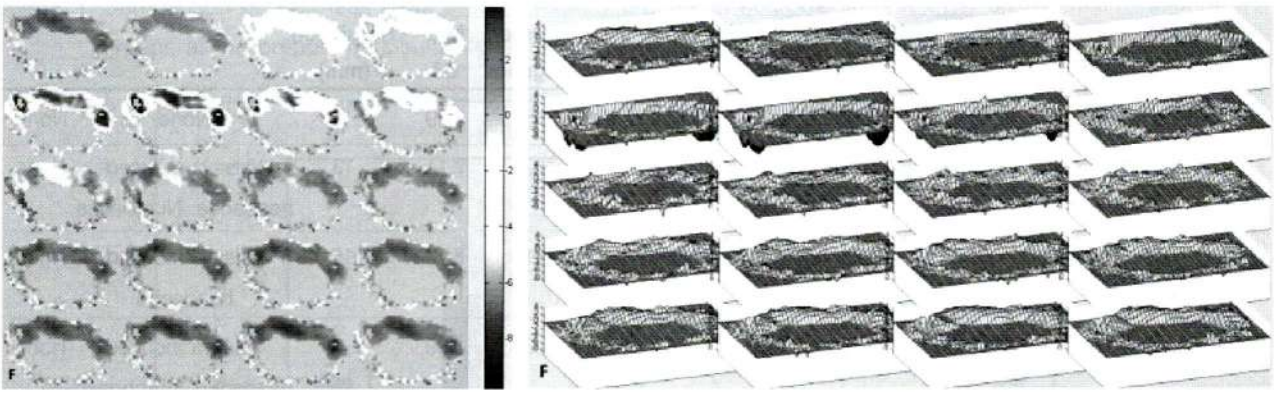

(f)

Fig.2 Color maps (left column) and surface contour plots (right column) of the CSF flow velocity during 20 cardiac phases (ordered from the left to the right and then the top to the bottom) in a control volunteer (A, B, and C) and a Chiari I patient (D, E, and F) at the prepontine cistern level (A and D), the foramen magnum level (B and E), and the C5 level (C and F). The CSF flow velocity is scaled from -8.0 to 4.0 cm/s as indicated by the colorbars and the vertical axis scales. The surfaces above the horizon plane show the cephalad flows and the surfaces below the horizon plane show the caudad flows.

Table 1 The age, sex, and peak systolic and diastolic velocities in the normal control volunteers.

No.	Age (years)	Sex	Peak Systolic Velocity (cm/s)			Peak Diastolic Velocity (cm/s)		
			Prepontine Cistern	Foramen Magnum	Mid C5	Prepontine Cistern	Foramen Magnum	Mid C5
1	51	female	3.35	3.83	8.55	4.00	3.40	5.85
2	35	male	4.19	4.13	7.31	2.88	3.33	8.36
3	34	male	3.86	3.77	8.06	3.30	3.53	5.85
4	30	female	3.21	3.94	7.81	2.66	3.54	5.10
5	30	female	2.71	4.02	4.71	2.47	3.81	4.03
6	23	female	3.28	3.81	8.54	3.15	3.12	4.80
7	28	female	4.64	4.91	8.09	5.40	4.09	8.88
8	24	female	4.05	4.35	8.00	3.79	3.67	5.50
9	37	male	5.78	3.31	5.03	4.79	2.53	3.80
10	29	male	4.26	4.97	6.76	3.32	3.21	5.40
Mean	**32.10**		**3.93**	**4.10**	**7.29**	**3.58**	**3.42**	**5.76**
SD	**8.01**		**0.87**	**0.52**	**1.38**	**0.94**	**0.42**	**1.66**

Table 2 The age, sex, and peak systolic and diastolic velocities in the Chiari I patients, including the information of the tonsillar herniation length (mm), signs/symptoms, and syrinx existance.

No.	Age (years)	Sex	Peak Systolic Velocity (cm/s)			Peak Diastolic Velocity (cm/s)			Tonsillar Herniation (mm)	Signs / Symptoms	Syrinx
			Prepontine Cistern	Foramen Magnum	Mid C5	Prepontine Cistern	Foramen Magnum	Mid C5			
1	30	male	5.49	6.58	8.39	4.11	3.52	5.09	7	None	None
2	48	female	2.68	5.88	5.96	2.64	3.24	7.11	13	Valsava induced headache, Numbness	None
3	37	female	3.23	6.23	8.51	2.67	3.13	6.79	16	Valsava induced headache	None
4	49	male	6.21	8.22	9.89	3.86	3.32	3.89	4	Valsava induced headache, Numbness	None
5	16	male	5.07	9.75	7.72	4.43	5.06	4.38	15	Scoliosis	Syrinx
Mean	**36.00**		**4.54**	**7.33**	**8.09**	**3.54**	**3.65**	**5.45**	**11.00**		
SD	**13.69**		**1.51**	**1.62**	**1.43**	**0.83**	**0.80**	**1.44**	**5.24**		

The peak systolic velocity at the foramen magnum in the Chiari I group was significantly higher than that in the control group (P = 0.0001). The peak systolic velocities at the prepontine cistern and the C5 levels in the Chiari I group were also higher than those in the control group but not statistically significant (P = 0.3398 and P = 0.3103). However, the peak diastolic velocities at the prepontine cistern, foramen magnum, and C5 levels between the Chiari I and control groups are not significantly different (P = 0.9464, P = 0.4701 and P = 0.7329, respectively).

Peak systolic and diastolic locations

At the prepontine cistern and foramen magnum levels, the peak systolic and diastolic velocities were mostly found at the anterior paramedian location, followed by the lateral location of the subarachnoid space in both Chiari I and control groups. However, at the C5 level, the peak systolic and diastolic velocities were mostly found at the lateral location of the subarachnoid space in both Chiari I and control groups. Only one control has the peak systolic velocity at the C5 level at the anterior paramedian location (Table 4).

Flow nodes and jet areas

On each image, the voxels exhibiting velocities exceeding the mode of the velocities in the subaracnoid space on that image by 100-200% were defined as nodes and those by 200-300% were defined as jets. The area of nodes or jets was then calculated in a percentage compared to the total area of the subarachnoid space on that image.

At the foramen magnum level, the node and jet areas in both cephalad and caudad directions in the Chiari I group were generally greater than those in the control group (as shown in Table 5). The node and jet areas in the cephalad direction in the Chiari I group were significantly greater than those

Table 3 Comparison of the mean peak systolic velocity and mean peak diastolic velocity of the Chiari I and control groups at the prepontine cistern, foramen magnum, and C5 levels.

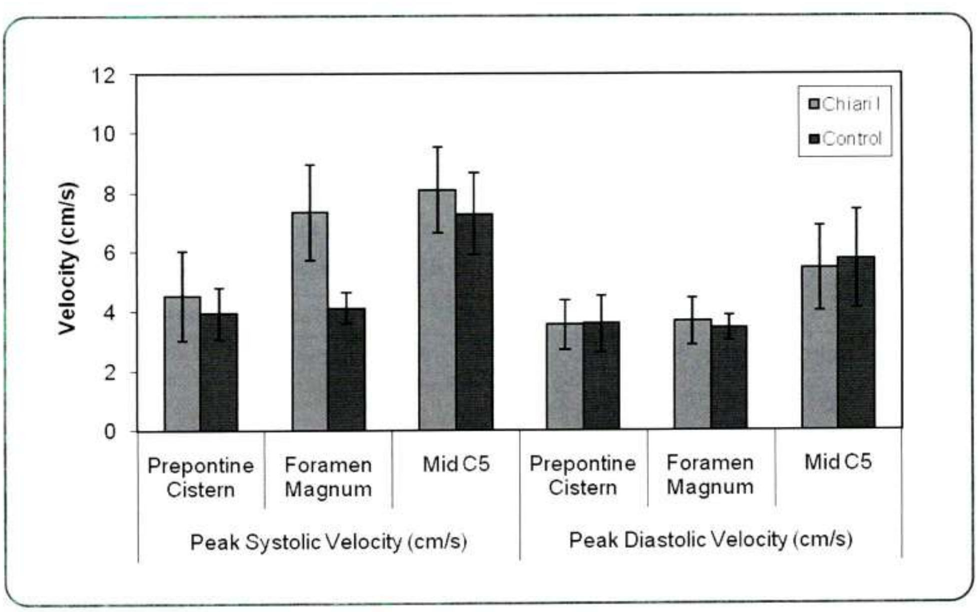

Table 4 The number of the Chiari I patients and the control volunteers categorized by their locations of the peak systolic and diastolic velocities in the subarachnoid spaces.

Location	Number of Subjects											
	Peak Systolic Velocity						Peak Diastolic Velocity					
	Prepontine Cistern		Foramen Magnum		Mid C5		Prepontine Cistern		Foramen Magnum		Mid C5	
	Chiari I	Contorl	Chiari I	Contorl	Chiari I	Contorl	Chiari I	Contorl	Chiari I	Contorl	Chiari I	Contorl
Anterior midline	-	-	-	-	-	-	-	-	-	-	-	-
Anterior paramedian	4	8	3	6	-	1	4	9	3	6	-	-
Posterior midline	-	-	-	-	-	-	-	-	-	-	-	-
Posterior paramedian	-	-	-	-	-	-	1	-	-	-	-	-
Anterolateral	1	2	2	4	5	9	-	1	2	4	5	10
Posterolateral	-	-	-	-	-	-	-	-	-	-	-	-

Table 5 The node and jet areas in percentage according to the subarachnoid at the prepontine cistern, foramen magnum, and C5 levels in the Chiari I patients and the control volunteers.

Node and Jet Areas in Subarachnoid Space	Prepontine Cistern			Foramen Magnum			Mid C5		
	Chiari I	Contorl	P-value	Chiari I	Contorl	P-value	Chiari I	Contorl	P-value
Cephalad									
Node (%)	14.54	15.62	0.807	16.98	6.72	**0.037**	9.54	11.81	0.803
Jet (%)	7.95	9.45	0.540	4.36	1.02	**0.020**	9.99	15.04	0.519
Caudad									
Node (%)	17.33	13.24	0.392	15.41	7.77	0.066	2.28	8.41	0.184
Jet (%)	5.99	4.20	0.354	13.61	1.99	**0.004**	13.63	7.64	0.662

in the control group, i.e., the node areas in the Chiari I and control groups are 16.98% and 6.72%, respectively, P = 0.0373, while the jet areas are 4.36% and 1.02%, respectively, P = 0.0200. In the caudad direction, the jet area in the Chiari I group was also significantly greater than that in the control group, i.e., 13.61% and 1.99%, respectively, P = 0.0036. The node area in the caudad direction of the Chiari I was greater than in the control group, however, it was not statistically significant, i.e., 15.41% and 7.77%, respectively, P = 0.0662.

At the prepontine cistern and C5 levels, there were no significant difference of the node and the jet areas in the cephalad and caudad directions in both groups (Table 5).

Comparison of the flow in anterior and posterior subarachnoid spaces

At the foramen magnum and the C5 levels, the cephalad and caudad flows were founded mostly in the anterior subarachnoid space in both groups.

Synchronous bidirectional flows

Synchronous bidirectional flows, i.e., simultaneous cephalad and caudad flows, were evident in both groups at all three levels. Using Fisher's exact test, the presence of synchronous bidirectional flows in both groups were not statistically different in all levels (Table 6). However, in the Chiari I group, there were more consecutive images recognized as synchronous bidirectional flows than in the control group at all three levels. In two groups, bidirectional flows were found mainly at the transitional cardiac phases from the cephalad to caudad flows or from the caudad to cephalad flows.

Preferential direction of the flow

For the variations in the flow rate over the cardiac cycles, we defined the cumulative flow through a voxel as the sum of the flow volume at that voxel over all 20 cardiac phases. The sum of the cumulative flow over all voxels in the region of interest was the net cumulative flow. The positive or negative value of the net cumulative flow assumably indicated the preferential flow direction, i.e., the cephalad or caudad flow, respectively.

At the foramen magnum, the all preferential flow directions in the Chiari I group were in the caudad (negative) direction. It was significantly different (P-value = 0.044) from the preferential flow directions of the controls, 6 of which in the cephalad (positive) direction and the other 4 of which

Table 6 The absence/presence of the synchronous bidirectional flow and the number of consecutive cardiac phases containing the synchronous bidirectional flow at the prepontine cistern, foramen magnum, and C5 levels in the Chiari I patients and the control volunteers.

Synchronus Bidirectional Flow	Prepontine Cistern			Foramen Magnum			Mid C5		
	Chiari I	Control	P-value	Chiari I	Control	P-value	Chiari I	Control	P-value
Presence (persons)	5	7	0.505	5	8	0.524	5	9	1
Absence (persons)	0	3		0	2		0	1	
Mean Number of Presence Phases	11.2	4.28	**0.007**	6.6	3.875	**0.042**	6.2	3.11	**0.008**
Range	7 to 20	2 to 8		3 to 10	2 to 7		4 to 9	2 to 5	

Table 7 The number of the Chiari I patients and the control volunteers possessing the preferential flow in the caudad and cepalad directions at the prepontine cistern, foramen magnum, and C5 levels.

Preferential Flow Direction	Prepontine Cistern			Foramen Magnum			Mid C5		
	Chiari I	Control	P-value	Chiari I	Control	P-value	Chiari I	Control	P-value
Caudad (persons)	4	5	0.58	5	4	**0.044**	2	5	1
Cephalad (persons)	1	5		0	6		3	5	

in the caudad direction. However, in the prepontine cistern and C5 levels, the preferential flow directions in the Chiari I and control groups were not significantly difference (P-value = 0.580 and 1.000, respectively) (Table 7).

Discussion

The focus of this research is on both the temporal and spatial variation of the CSF flow at MRI in Chiari I patients and healthy controls.

In control group, the peak systolic and diastolic velocities at the prepontine cistern level are not significantly different from those at the foramen magnum level. These values at the C5 level are higher compared to those at the prepontine cistern and foramen magnum levels.

In Chiari I group, the peak systolic velocity tends to increase progressively from the superior to inferior levels, i.e., from the prepontine cistern level to the foramen magnum level and to the C5 level. The peak diastolic velocities at the prepontine cistern and foramen magnum levels are not significantly different; however, it increases at the C5 level. In addition, there is no significant relation between the length of tonsillar herniation and the peak velocity at the foramen magnum in the Chiari I group. This finding supports the result from the previous study that isolated finding of tonsillar herniation is of limited prognostic utility and must be considered in the context of clinical and radiographic data[4].

At the foramen magnum level, we found a significant increase in the peak systolic velocity in the Chiari I group compared to the control group. However, there is no significant difference in the peak diastolic velocity between the two groups. This finding is similar to the previous studies[4,10]. The results support the hypothesis that the presence of the tonsils in the foramen magnum alters the CSF flow patterns due to the CSF flow obstruction.

Difference in section location at the foramen magnum in volunteers and just below cerebellar tonsils in Chiari I patients has been thought to diminish differences in CSF velocities between patient and control groups[7]. In our study, we found that the CSF velocities tend to increase from superiorly to inferiorly (prepontine cistern down to C5 level). So, CSF velocities at just below cerebellar tonsils may not be significantly lower than those at the foramen magnum, and this should not affect the result.

However, at the prepontine cistern and C5 levels, the peak systolic and diastolic velocities are not significantly different between the two groups. The finding implies that the altered CSF flow from the cerebellar tonsils at the foramen magnum in the Chiari I group does not influence the CSF flow at the level above or below the foramen magnum.

For the location of the peak velocity at the foramen magnum level, in our study both the peak systolic velocity and the peak diastolic velocity are mostly found at the anterior paramedian location of the subarachnoid space, followed by the lateral location. In contrast to the previous studies[4,10], the peak systolic velocity and the peak diastolic velocity are found only at the anterior paramedian location.

We find the number of consecutive images of the synchronous bidirectional flows in the Chiari I group is higher than that in the control group in all three levels. In addition, the areas of nodes and jets are much larger in the Chiari I group at the foramen magnum level, compared to the control group. These suggest that the CSF flow in the Chiari I group is more inhomogeneous than that in the control group, agreeing with the previous studies[7,10].

Significant preferential CSF flow in caudad direction at the foramen magnum in the Chiari I group found the our study supports theory of CSF obstruction at the foramen magnum as a pathophysiology of syringomyelia[12].

Limitation of study

The result of this study is limited to the Philips 3T MRI scanner and the provided software to evaluate the phase contrast MR images for the velocity of the CSF flow. The partial volume artifact on the image pixels due to the thick slice thickness and the pixel value interpolation from the image reconstruction could also impair the results. In addition, the investigators' decisions on the segmentation of the ROI could bias the results. The result of this study is also based on a small number of Chiai I patients and normal control volunteers. Therefore, further data collection from large population should be obtained for adequate information for conclusion.

Conclusion

There is significantly higher degree of peak systolic velocity and the inhomogeneity of the CSF flow at the foramen magnum level in the Chiari I group compared to the control group. There is no significant difference in the quantitative analysis of the CSF flow at the prepontine cistern and C5 levels between the Chiari I group and the control group. Then, CSF flow studies outside the foramen magnum may not be useful enough for evaluation and differentiation between symptomatic and asymptomatic Chiari I patients. Conclusion about relationship between the CSF flow patterns and the clinical deficits in association with Chiari I malformations requires additional data from larger population.

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