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Quantitative assessment of physiological cerebrospinal fluid flow in the cervical spinal canal with 3.0T phase-contrast cine MRI☆

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Abstract

A total of 50 healthy volunteers aged between 18 and 54 years underwent phase-contrast cine MRI to assess cerebrospinal fluid flow characteristics in different regions of the vertebral canal. The results revealed that the cerebrospinal fluid peak flow velocity and peak flow rate in the systolic phase were significantly greater than those in the diastolic phase at the same level in the subarachnoid space of the cervical spinal canal. The ventral peak flow velocity and peak flow rate were significantly greater than the post-lateral peak flow velocity and flow rate, while there were no differences between left and right post-lateral subarachnoid peak velocity and flow rate. Moreover, there were no significant differences in peak flow velocity and peak flow rate between the systolic and diastolic phases, ventral, right post-lateral or left post-lateral peak flow velocity and peak flow rate at the same level in the subarachnoid space of the cervical spinal canal among different age groups (18–24, 25–34, 35–44, ≥ 45 years).

Key Words

magnetic resonance imaging; phase-contrast; cerebrospinal fluid; vertebral canal; subarachnoid space; flow velocity; neural regeneration

Abbreviations

CSF, cerebrospinal fluid; PC-MRI, phase-contrast cine MRI

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INTRODUCTION

Cerebrospinal fluid (CSF) circulation is regarded as the third circulatory system in human body. CSF circulation has been studied since the 1940s[1] using invasive methods, which can alter physiological environment of the CSF. MRI studies of the CSF have been conducted since the 1980s, focusing on morphology only[2]. Application of phase-contrast cine MRI (PC-MRI) enables CSF quantitation. PC-MRI combines MR phase contrast and electrocardiogram-gating, involving fluid phase displacement and the time to acquire related fluid waveforms, velocity and flow rate. PC-MRI studies have initially been used in quantitative studies of blood flow[3]. However, this technique can also non-invasively, accurately measure CSF flow direction and velocity, in the absence of contrast medium. PC-MRI is particularly sensitive to slow flows[4-9]. Previous PC-MRI examinations have mainly focused on intracranial CSF flow[10-17], and few data are available regarding intraspinal CSF. The present study utilized PC-MRI to observe CSF circulation characters in different cervical spinal canal regions in healthy volunteers of different ages.

RESULTS

Quantitative analysis and baseline data of participants

A total of 76 volunteers undergoing physical examinations were selected, and 26 with intraspinal and intracranial lesions confirmed by MR were excluded. Therefore, a total of 50 participants were included in the final analysis. The baseline data are listed in Table 1.

Table 1 Baseline data of participants

Age group (year)	*n*	Sex (Male/female, *n*)	Median age (year)
18–24	15	8/7	20.1
25–34	13	5/8	30.2
35–44	14	5/9	40.4
≥45	8	4/4	50.3

Differences in CSF peak flow velocity and peak flow rate in the systolic and diastolic phases at C_{2-3} levels among different age groups

A multiple-sample rank sum test showed that CSF peak flow velocity and peak flow rate of systolic phase or diastolic phase at C_{2-3} levels were similar among different age groups, but the CSF peak flow velocity and peak flow rate were greater in the systolic phase compared to the diastolic phase ($P < 0.05$; Table 2).

Table 2 Cerebrospinal fluid peak flow velocity and peak flow rate in the systolic and diastolic phases at C_{2-3} levels among different age groups

Age group (year)	*n*	Systolic phase		Diastolic phase	
		Peak flow velocity (cm/s)	Peak flow rate (mL/s)	Peak flow velocity (cm/s)	Peak flow rate (mL/s)
18–24	15	2.05±1.31[a]	3.03±2.18[a]	1.10±1.12	1.64±1.36
25–34	13	1.95±1.58[a]	3.08±1.46[a]	1.02±0.94	1.45±1.05
35–44	14	2.11±1.75[a]	2.77±2.20[a]	1.16±1.07	1.52±1.26
≥45	8	2.14±1.59[a]	3.16±2.41[a]	1.21±1.27	1.79±1.19

Data were expressed as mean ± SD. Multiple-sample Kruskal-Wallis tests were used to compare peak flow velocity and peak flow rate in the systolic phase and diastolic phase, ventral, right post-lateral and left post-lateral peak flow velocity and peak flow rate at C_{2-3} levels among different age groups.

Mann-Whitney *U* tests were used to compare peak flow velocity and peak flow rate of systolic phase and diastolic phase, ventral, right post-lateral and left post-lateral peak flow velocity and peak flow rate between any two groups.

[a]$P < 0.05$, *vs.* diastolic phase. Peak flow rate = peak flow velocity × C_{2-3} subarachnoid space area.

CSF in the heart systolic phase exhibited white hyperintensity, flowing from head to foot but CSF in the diastolic phase exhibited black hypointensity, flowing from foot to head. Therefore, vertebral canal CSF exhibited oscillating movement in one cardiac cycle. The higher flow velocity in the systolic phase than the diastolic phase indicates CSF net flow from head to foot (Figure 1).

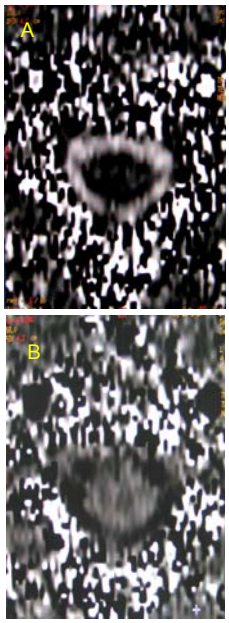

Figure 1 Cerebrospinal fluid flow in the vertebral canal on phase-contrast cine MRI.

(A) White areas represent cerebrospinal fluid flow from head to foot.

(B) Black areas represent cerebrospinal fluid flow from foot to head.

Differences in CSF ventral, right post-lateral and left post-lateral peak flow velocity and peak flow rate at C_{2-3} levels among different age groups

The multiple-sample rank sum test revealed that CSF ventral, right post-lateral and left post-lateral peak flow velocity and peak flow rate were similar among different groups, but the ventral peak flow velocity and peak flow rate were significantly greater than the left and right post-lateral peak velocity and flow rate ($P < 0.05$).

Moreover, there were no significant differences between the left and right post-lateral peak flow velocity and peak flow rate (Table 3), indicating that the vertebral canal ventral CSF circulation dynamic was significantly greater than the post-lateral.

Table 3 Cerebrospinal fluid peak flow velocity and peak flow rate in different regions at C_{2-3} levels among different age groups

Age group (year)	*n*	Ventral		Right post-lateral		Left post-lateral	
		Peak flow velocity (cm/s)	Peak flow rate (mL/s)	Peak flow velocity (cm/s)	Peak flow rate (mL/s)	Peak flow velocity (cm/s)	Peak flow rate (mL/s)
18–24	15	4.03±0.84	1.73±1.42	1.95±1.12[a]	0.36±0.24[a]	1.90±1.42[a]	0.42±0.25[a]
25–34	13	3.68±1.57	1.56±0.72	1.69±1.17[a]	0.42±0.22[a]	1.58±1.24[a]	0.40±0.12[a]
35–44	14	3.76±1.10	1.86±0.83	1.70±1.54[a]	0.43±0.32[a]	1.65±1.58[a]	0.54±0.11[a]
≥45	8	3.85±1.05	1.61±0.65	1.62±1.54[a]	0.35±0.12[a]	1.82±1.39[a]	0.46±0.32[a]

Data were expressed as mean ± SD. Multiple-sample Kruskal-Wallis tests were used to compare peak flow velocity and peak flow rate of systolic phase and diastolic phase, ventral, right post-lateral and left post-lateral peak flow velocity and peak flow rate at C_{2-3} levels among different age groups. Mann-Whitney *U* tests were used to compare peak flow velocity and peak flow rate of systolic phase and diastolic phase, ventral, right post-lateral and left post-lateral peak flow velocity and peak flow rate between any two groups.

[a]$P < 0.05$, *vs.* ventral. Peak flow rate = peak flow velocity × C_{2-3} subarachnoid space area corresponding to ventral, right post-lateral and left post-lateral.

DISCUSSION

PC-MRI can provide an accurate quantitative measure of vertebral canal ventral CSF flow velocity and direction. This technique has several advantages including non-invasion and rapid scanning, in the absence of patient preparation, contrast medium or X-ray radiation. In particular, rapid PC-MRI scanning takes only seconds to acquire real-time CSF flow velocity[18]. The present results revealed no significant differences in CSF peak flow velocity and peak flow rate of systolic phase or diastolic phase at C_{2-3} levels among different age groups in the 50 healthy adults. Therefore, values of cervical spinal canal CSF flow were obtained in the normal range. The ventral CSF peak flow velocity and peak flow rate were significantly greater than the post-lateral, while there were no differences in these measures between left and right post-lateral subarachnoid. These results indicate that the vertebral canal ventral CSF circulation dynamics were significantly greater than the post-lateral dynamics. Consistent with previous results[19], the present findings revealed that in normal adults, vertebral canal CSF exhibited oscillating movement. That is, CSF flowed from head to foot in the systolic phase, but from foot to head in the diastolic phase. In addition, flow velocity in the systolic phase was found to be higher than in the diastolic phase, indicating CSF net flow from head to foot.

In summary, the present study revealed normal values of cervical spinal canal CSF physiological flow patterns and velocity. These findings can be used in future studies of lesion-induced abnormal vertebral canal CSF circulation.

SUBJECTS AND METHODS

Design

A clinical neuroimaging comparison study.

Time and setting

The experiment was performed at the MR Laboratory, Second Hospital of Hebei Medical University, China between October 2010 and October 2011.

Subjects

A total of 50 healthy adults undergoing physical examinations at the Second Hospital of Hebei Medical University were selected and subjected to MR. Informed consent was obtained from all participants. Cranial, cervical, thoracic, lumbar spinal T_2-weighted imaging horizontal axial and sagittal plane scanning excluded intracranial and intraspinal lesions. In addition, we excluded participants with arrhythmia. The final 50 subjects included 22 males (44%) and 28 females (56%), with a mean age of 36.3 ± 18.2 years (age range 18–54 years). Subjects were assigned to four age groups: 18–24 years (*n* = 15), 25–34 years (*n* = 13), 35–44 years (*n* = 14), and ≥45 years (*n* = 8).

Methods

PC-MRI

GE Signa EXCITE 3.0T HD MR apparatus (GE, Fairfield, Connecticut, USA) was used with a spine coil. Scanning was performed while subjects lay in a supine position. We instructed participants to avoid deep breathing and swallowing during scanning. First, routine cervical spinal sagittal and horizontal axial plane scanning were performed using fast-recovery fast

spin-echo scanning. The parameters were as follows: repetition time/echo time/number of excitations/flip angle, 2 400–2 500 ms/ 110–120 ms/4/90°; slice thickness, 3 mm; gap interval, 0.5 mm; field of view, 26 cm × 26 cm; matrix, 380 × 256. Gating was conducted and PC-MRI scanning was performed at C_{2-3} levels, with the location line vertical to the vertebral canal subarachnoid CSF flow (Figure 2).

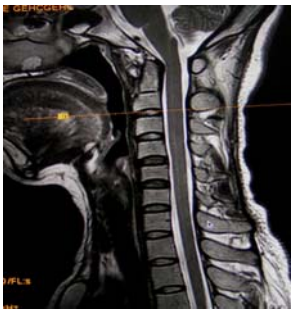

Figure 2 Cervical phase-contrast cine-MRI sagittal plane images. The location line (brown yellow) was vertical to the vertebral canal cerebrospinal fluid flow at C_{2-3} levels.

The parameters were as follows: repetition time/echo time/number of excitations/flip angle, 12 ms/6.2 ms/1/20°; slice thickness, 3 mm; gap interval, 0 mm; field of view, 16 cm × 16 cm; matrix, 256 × 128. Velocity encoding was set at 20 cm/s. Head to foot was considered as the positive direction, shown as white on the phase plot, while foot to head was considered the negative direction, shown as black on the phase plot. The entire scanning period lasted 10 minutes. Each cardiac cycle was equally divided into 30 phases. PC-MRI scanning images were post-processed to obtain cervical spinal canal real-time flow velocity in one cardiac cycle at C_{2-3} levels. Briefly, the obtained images were amplified to an appropriate size, and the window width and position were adjusted until the contrast of cervical subarachnoid space and surrounding structure was clearest. Two imaging physicians carefully drew the range of the vertebral canal subarachnoid space using a trackball to include the entire region containing CSF, while excluding regions free of CSF. Real-time CSF flow velocity in every phase of one cardiac cycle and flow waveform during the entire cardiac cycle was obtained following computerized post-processing, and the maximum value was considered as the peak flow velocity (Figures 3, 4). Peak flow rate (mL/s) = peak flow velocity (cm/s) × cervical spinal canal subarachnoid space area (cm^2). The cervical spinal canal is triangular, so we divided it into ventral, right and left post-lateral sections, by drawing a horizontal line parallel to the posterior ventral subarachnoid space. The area in front of the line was regarded as the ventral part, and the area behind the line was considered the post-lateral part. Two physicians with imaging experience carefully drew the range of ventral, right and left post-lateral subarachnoid space using a trackball, and CSF flow velocity was obtained in every phase of each cardiac cycle and flow waveform during the entire cardiac cycle (Figures 5, 6). Peak flow rate (mL/s) = peak flow velocity (cm/s) × area of region of interest (cm^2).

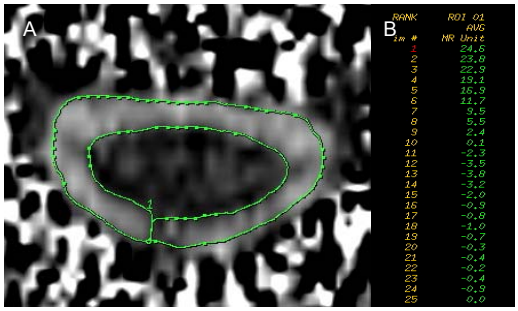

Figure 3 Cervical phase-contrast cine-MRI horizontal axial scanning of real-time velocity of cerebrospinal fluid in region of interest (ROI) and each phase.

(A) Green lines included the ROIs.

(B) Real-time flow velocity corresponding to each ROI (mm/s). Rank represents phase.

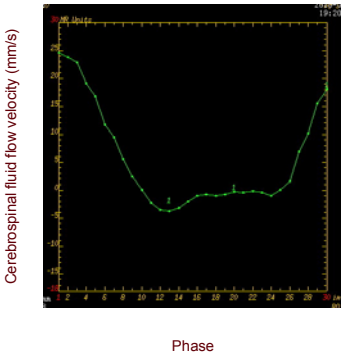

Figure 4 Flow waveform of cervical spinal canal cerebrospinal fluid in one cardiac cycle.

Each cardiac cycle was divided into 30 phases. Green number 1 represents cerebrospinal fluid flow curves in green region of interest 1 in Figure 3.

Statistical analysis

Data were analyzed using SAS V8 software (SAS Institute Inc., Cary, NC, USA). Measurement data were expressed as mean ± SD. A rank sum test was used because the flow velocity values followed a non-normal distribution.

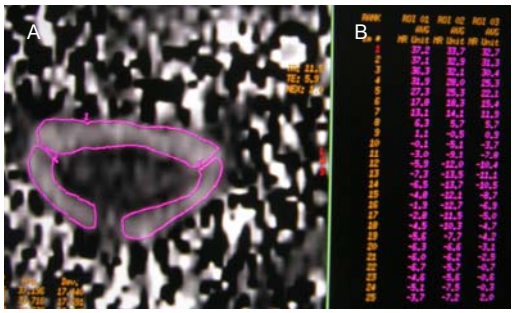

Figure 5 Cervical phase-contrast cine-MRI horizontal axial scanning of real-time flow velocity of cerebrospinal fluid in each phase in ventral, right and left post-lateral subarachnoid space at C_{2-3} levels.

(A) 1: Ventral; 2: right post-lateral; 3: left post-lateral

(B) Real-time flow velocity corresponding every region of interest (mm/s); rank represents phase.

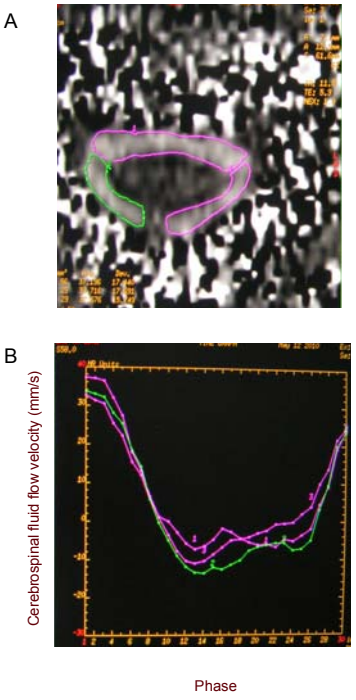

Figure 6 Cervical phase-contrast cine-MRI horizontal axial scanning of oscillating waveform of cerebrospinal fluid in every phase in ventral, right and left post-lateral subarachnoid space at C_{2-3} levels.

The 1, 2, and 3 in the right figure represent flow velocity curves of cerebrospinal fluid corresponding to region of interests (ROIs) 1, 2 and 3 in the left figure.

(A) 1: Ventral; 2: right post-lateral; 3: left post-lateral.

(B) X-ray: 30 phases in one cardiac cycle; Y-axis: real-time flow velocity of cerebrospinal fluid.

The multiple-sample Kruskal-Wallis test was used to compare peak flow velocity and peak flow rate in the systolic and diastolic phases, ventral, right post-lateral and left post-lateral peak flow velocity and peak flow rate at C_{2-3} levels among different age groups. A value of $P < 0.05$ was considered statistically significant.

Mann-Whitney *U* test was used to compare peak flow velocity and peak flow rate in the systolic and diastolic phases, ventral, right post-lateral and left post-lateral peak flow velocity and peak flow rate between each pair of two groups. A value of $P < 0.05$ was considered statistically significant.

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Conflicts of interest: None declared.

Ethical approval: This study received permission from the Medical Ethics Committee of Second Hospital, Hebei Medical University, China.

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