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

Hua Shang, Huaijun Liu, Leka Yan, Jianming Lei, Caixia Cui, Hui Li

Department of Radiology, Second Hospital of Hebei Medical University, Shijiazhuang 050000, Hebei Province, China

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

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.

Differences in CSF peak flow velocity and peak flow rate in the systolic and diastolic phases at C2-3 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 C2-3 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).

Differences in CSF ventral, right post-lateral and left post-lateral peak flow velocity and peak flow rate at C2-3 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.
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. 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.

### DISCUSSION

### 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

### Table 3  Cerebrospinal fluid peak flow velocity and peak flow rate in different regions at C\(_{2-3}\) levels among different age groups

<table>
<thead>
<tr>
<th>Age group (year)</th>
<th>Ventral</th>
<th>Right post-lateral</th>
<th>Left post-lateral</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peak flow velocity (cm/s)</td>
<td>Peak flow rate (mL/s)</td>
<td>Peak flow velocity (cm/s)</td>
</tr>
<tr>
<td>18–24</td>
<td>4.03±0.84</td>
<td>1.73±1.42</td>
<td>1.95±1.12(^a)</td>
</tr>
<tr>
<td>25–34</td>
<td>3.68±1.57</td>
<td>1.56±0.72</td>
<td>1.69±1.17(^a)</td>
</tr>
<tr>
<td>35–44</td>
<td>3.76±1.10</td>
<td>1.86±0.83</td>
<td>1.70±1.54(^a)</td>
</tr>
<tr>
<td>≥45</td>
<td>3.80±0.05</td>
<td>1.61±0.65</td>
<td>1.62±1.54(^a)</td>
</tr>
</tbody>
</table>

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.
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 C2–3 levels, with the location line vertical to the vertebral canal subarachnoid CSF flow (Figure 2).

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 C2–3 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 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 (cm²).

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.
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 C2-3 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.

**Funding:** This study was supported by the Science and Technology Support Program of Hebei Province (Cervical spinal canal cerebrospinal fluid movement using 3.0TMR fast phase-contrast cine imaging), No. 112061179D.

**Author contributions:** Hua Shang provided, integrated and analyzed experimental data, conceived and designed the study, and wrote the manuscript. Huaijun Liu revised the manuscript and guided the experiments. Leka Yan contributed to statistical analysis, collected and integrated experimental data. Jianming Lei was in charge of funds. Caixia Cui provided technical and data support. Hui Li provided and integrated data.

**Conflicts of interest:** None declared.

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

**REFERENCES**


(Edited by Zhang ZQ, Miao YW/Su LL/Song LP)