Quantitative Flow Measurement of Cerebrospinal Fluids at Sylvian Aqueduct at 3 Tesla

Kezhou Wang[1], Xinjian Du[2], Wei Sun[3], Hagai Ganin[4], Yi Sui[4,5], Lauren Ostergren[1], Fady T. Charbel[6], William G. Bradley[7], and Xiaohong Joe Zhou[8,9]

[1]VasSol Inc., River Forest, IL, United States, [2]Neurosurgery, University of Illinois at Chicago, Chicago, IL, United States, [3]GE Healthcare, Waukesha, WI, United States, [4]Center for MR Research, University of Illinois Hospital & Health Sciences System, Chicago, IL, United States, [5]Department of Bioengineering, University of Illinois Hospital & Health Sciences System, Chicago, IL, United States, [6]University of Illinois at Chicago, Chicago, IL, United States, [7]Department of Radiology, UCSD Medical Center, San Diego, CA, United States, [8]Center for MR Research, University of Illinois at Chicago, Chicago, IL, United States, [9]Departments of Radiology, University of Illinois at Chicago, Chicago, IL, United States

Target Audience: Neuroradiologists, neurosurgeons, neurologists, pediatricians, and researchers who are interested in CSF flow.

Purpose: Flow quantification of cerebrospinal fluid (CSF) is important for diagnostic and therapeutic decisions in communicating hydrocephalus. Although phase contrast magnetic resonance (PCMR) imaging is typically used to measure blood flow in vessels[1], it can be adapted to quantifying CSF flow through the sylvian aqueduct. To accommodate the slow CSF flow, a low VENC value is commonly employed. This can however lead to a longer TE and worsened eddy current problems, which adversely affect the measurement accuracy. As such, imaging parameters must be optimized to obtain accurate and reliable CSF flow measurements. The purpose of this study was to develop and validate a robust PCMR method for quantifying CSF flow in human subjects, thereby paving the way for future clinical studies on patients with communicating hydrocephalus.

Methods: A Shelly flow phantom (CompuFlow 1000 MR, Shelly Medical Imaging Technologies, Toronto, Ontario, Canada) was first employed in the study. The flow phantom was positioned at the center of an 8-channel head coil on a 3T MRI scanner (General Electric Health Care, Waukesha, Wisconsin) and a polyethylene tube (8mm in diameter) was connected to a computer-controlled pump. The volumetric flow rate of the pump was selected between 60 and 240 ml/min, which corresponded to an average velocity of 1.98 to 7.96cm/s. At each of the four selected flow rates (Table 1), a PCMR scan was performed by systematically adjusting the following scan parameters: VPS (view per segment), NEX (number of excitations), number of phases per cardiac cycle, flip angle, and others. The PCMR images were analyzed using a commercial software package, NOVA (Non-invasive Optimal Vessel Analysis; VasSol Inc., River Forest, IL). Results from the PCMR measurements were compared with the known flow rate set on the Shelly pump. Following the phantom experiments, five healthy human subjects (2 males; 3 females; age range: $18 - 52$) were recruited under an approved IRB and scanned at the sylvian aqueduct with peripheral grating using the best protocol determined from the phantom study: slice thickness = 4.0mm, matrix = 224x160, FOV = 12cm, TR/TE = 11/5.2 ms, flip angle = 25°, VENC = 20 cm/s, and NEX = 4. To obtain accurate flow measurements, the imaging plane in the 2D PCMR acquisition needed to be normal to the flow direction. This was accomplished by first acquiring a volumetric image to highlight all CSF areas using a 3D FIESTA pulse sequence (Fig. 1a) with the following parameters: slice thickness = 0.8 mm, matrix = 440 x 256, FOV = 20cm, TR/TE = 6.5/2.0 ms, and flip angle = 30°. The 3D FIESTA images were processed on a NOVA workstation to display only the CSF areas, as shown in Fig 1b. From the 3D image, sylvian aqueduct was identified and a plane perpendicular to it was determined by NOVA, as shown by the yellow plane in Fig 1b. The geometric parameters defining the plane was automatically sent to the scanner and used for slice prescription in the subsequent 2D PCMR acquisition (Fig. 1c). Flow quantification based on the 2D PCMR image was accomplished using NOVA.

Table 1. Phantom Actual Flow Rate in Comparison with the Flow Rate from PCMR

Flow Rate (mL/min)	Avg Velocity (cm/s)	12 Phases (mL/min)				24 Phases (mL/min)			
		Min	Max	Avg	Error (%)	Min	Max	Avg	Error (%)
60	1.99	54.5	57.1	55.58	-7.36	54.7	56.5	55.37	-7.72
120	3.98	113	114	113.5	-5.41	112.1	115.3	113.5	-5.40
180	5.97	173.7	176.3	174.57	-3.01	172.1	175.5	174.0	-3.32
240	7.96	232.2	236.1	233.98	-2.51	218.2	236.8	232.7	-3.04

Results: The phantom study results are summarized in Table 1, where each row corresponds to a selected flow rate of the pump and shows the range of volumetric flow rate (minimum, maximum, and average) measured from PCMR at two numbers of "cardiac" phases: 12 and 24. Measurement error was reported as a percentage of the actual flow rate on the Shelly pump: error = $(V_{avg} - V_{actual})/V_{actual} \times 100\%$. A smaller error was observed at the faster flow rate, irrespective of the number of "cardiac" phases. After optimizing the protocol, all errors were confined within 8%.

In human subjects, the CSF flow through the aqueduct is dynamic and pulsatile. To accurately delineate the dynamic perspective of the CSF flow through both systolic and diastolic cycles, further optimization in human volunteers was conducted. A number of scans were performed by varying the VPS from 2 to 16, and number of cardiac phases from 12 to 40, and NEX from 2 to 4. The best results, judged by the flow waveforms in Fig. 2, were produced with the following parameters: VPS = 2 and number of cardiac phases = 40, NEX = 2, and scan time = 1'40". Using this optimized protocol, the net flow rates were determined to be 3.6 and 6.6 μL/cycle in two representative subjects, which corresponded to 388 and 712 mL/day, respectively. This was consistent with the normal CSF production rate of around 500 mL/day reported by Gideon[2]. In addition, the corresponding stroke volumes were found to be 22.8 and 21.3 μL/cycle, respectively, which were also consistent with the literature[3].
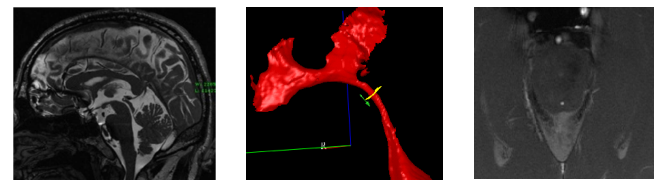

(a)FIESTA image   (b) Aqueduct Model   (c) 2D PC Image
Fig 1. (a) FIESTA image showing the CSF. (b) A 3D model of aqueduct with flow measurement location shown in yellow. (c) A 2D PCMR phase image perpendicular to aqueduct.
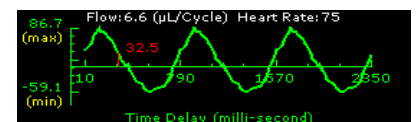

Fig 2. CSF flow waveform at the cerebral aqueduct through three cardiac cycles from a representative human subject.

Conclusions: In this study, several key parameters in a PCMR protocol have been optimized through phantom and human volunteer studies. The optimal PCMR protocol (VPS = 2, number of cardiac phases = 40, VENC = 20 cm/s, TR/TE = 11/5.2 ms, flip angle = 25°, etc.) has produced reliable and accurate CSF flow measurements at the cerebral aqueduct on humans. The method developed and validated in this study is expected to enable future quantitative CSF flow studies in patients with communicating hydrocephalus.

References: [1] M. Zhao, et al. *Magnetic Resonance Imaging*, vol. 18, pp. 697-706, 2000. [2] P. Gideon, et al. *Neuroradiology*, vol. 36(3), pp. 210–215, 1994. [3] W.G. Jr. Bradley, AJNR Am J Neuroradiol, vol. 19, pp. 1285-86, 1998.