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ORIGINAL ARTICLE

Retrospective Study

Assessment of superior mesenteric vascular flow quantitation in children using four-dimensional flow magnetic resonance imaging: A feasibility study

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Abstract

BACKGROUND
Four-dimensional (4D) flow magnetic resonance imaging (MRI) is used as a noninvasive modality for assessing hemodynamic information with neurovascular and body applications. The application of 4D flow MRI for assessment of bowel disease in children has not been previously described.

AIM
To determine feasibility of superior mesenteric venous and arterial flow quantitation in pediatric patients using 4D flow MRI.

METHODS
Nine pediatric patients (7-14 years old, 5 male and 4 female) with history or suspicion of bowel pathology, who underwent magnetic resonance (MR) enterography with 4D flow MR protocol from November 2022 to October 2023. Field strength/sequence: 3T MRI using 4D flow MR protocol. Flow velocity and peak speed measurements were performed by two diagnostic radiologists placing the region of interest in perpendicular plane to blood flow on each cross section of

superior mesenteric artery (SMA) and superior mesenteric vein (SMV) at three predetermined levels. Bland-Altman analysis, showed good agreement of flow velocity and peak speed measurements of SMV and SMA between two readers.

RESULTS

Mean SMV flow velocity increased from proximal to mid to distal (0.14 L/minute, 0.17 L/minute, 0.22 L/minute respectively). Mean SMA flow velocity decreased from proximal to mid to distal (0.35 L/minute, 0.27 L/minute, 0.21 L/minute respectively). Observed agreement was good for flow velocity measurements of SMV (mean bias -0.01 L/minute and 95% limits of agreement, -0.09 to 0.08 L/minute) and SMA (mean bias -0.03 L/minute and 95% limits of agreement, -0.23 to 0.17 L/minute) between two readers. Good agreement for peak speed measurements of SMV (mean bias -1.2 cm/second and 95% limits of agreement, -9.4 to 7.0 cm/second) and SMA (mean bias -3.2 cm/second and 95% limits of agreement, -31.4 to 24.9 cm/second).

CONCLUSION

Flow quantitation using 4D Flow is feasible to provide hemodynamic information for SMV and SMA in children.

Key Words: Four-dimensional flow magnetic resonance imaging; Superior mesenteric artery; Superior mesenteric vein; Bowel disease; Mesenteric vessel flow analysis

Core Tip: In this manuscript we assess use of four-dimensional (4D) flow magnetic resonance imaging (MRI) in superior mesenteric venous and arterial flow quantitation in pediatric patients. This retrospective study included 9 pediatric patients (7-14 years old, 5 male and 4 female) with history or suspicion of bowel pathology, who underwent MRI studies with 4D flow magnetic resonance protocol. In our study of pediatric patients, 4D flow MRI is feasible to provide quantitative superior mesenteric vein and superior mesenteric artery hemodynamic flow information.

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INTRODUCTION

Multiple imaging methods are currently available to obtain vascular flow measurements including Duplex ultrasound, contrast-enhanced ultrasound, contrast enhanced computed tomography (CT), and unenhanced and contrast-enhanced magnetic resonance imaging (MRI). Duplex ultrasound is one of the most readily available non-radiation tools to obtain vascular flow velocity information; however, this technique has limitations in patients of larger body habitus. While dynamic perfusion CT imaging provides high resolution and superior assessment of vascular images with evaluation of the abdominal visceral organs. It requires multiple phases for each study which increase risks of radiation exposure particularly for pediatric patients who are more sensitive to radiation. MRI also offers noninvasive techniques [including 2 dimensional (D) and 3D time of flight imaging] to acquire high image quality without use of ionizing radiation. Additionally, advanced applications have been developed to quantify accurate circulation including 4D flow MRI[1-9].

The 4D flow MRI is a volumetric time-resolved cine sequence enabling 3D velocity encoding with electrocardiographic gating[7]. Respiratory motion may affect 4D flow MRI quality, especially in the abdominal region, where diaphragmatic movement is a major factor causing limitation. Respiratory suppression techniques have been developed to improve sharpness of the imaging for decades; however, free-breathing 4D flow MRI has been reported[8]. Thus, respiratory gating for 4D flow MRI remains controversial[10].

The 4D flow MRI is widely used as a noninvasive alternative modality for assessing hemodynamic information of cardiovascular diseases. Although many studies have discussed flow velocities of the abdominal vessels in adults including normal ranges and abnormal measurements[1,3-6,11,12] as well as pelvic vasculature[12], less exploration in the pediatric population has been described[9].

The role of magnetic resonance (MR) enterography for detecting active bowel disease in children is well described[13,14]. The application of 4D flow in assessment of bowel pathology in children, however, has not to our knowledge been previously described. Feasibility of assessment of mesenteric circulation in children using 4D flow MRI has been demonstrated in a prior study[9]. This study focused on the flow pattern of mesenteric veins including portal (PV), superior mesenteric (SMV), and splenic, visceral arteries including the hepatic artery and splenic artery, as well as the inferior vena cava[9]. There has been prior literature describing assessment of superior mesenteric artery (SMA) flow by Doppler ultrasound to determine activity of Crohn's disease[15].

In this study we aim to assess the potential of SMV and SMA flow quantification in children utilizing 4D flow MRI. Secondarily, we aim to correlative assess these findings with endoscopic findings of active bowel disease by endoscopy in children.

MATERIALS AND METHODS

Study population

Institutional review board approval for retrospective correlation of imaging with other clinical parameters was obtained. The institutional review board number is 18-25412.

This study included 9 pediatric patients aged 18 years old and under, who underwent MR enterography with 4D flow MR protocol from November 2022 to October 2023. We retrospectively reviewed patients' clinical information and endoscopy findings from medical records.

MR protocol

All studies were conducted on 3T MRI scanners (GE Discovery MR750 and Discovery MR750w GEM; General Electric Healthcare, Waukesha, WI, United States) with software version DV27 using a 4D Flow MR protocol and a 32-channel cardiac coil as shown in Table 1.

Flow velocity measurement

Using flow analysis software (Tempus Pixel, Redwood Shores, CA, United States), velocity measurements were performed by two diagnostic radiologists (8 years and 4 years of experience). The flow velocities were measured by placing the region of interest in the perpendicular plane to the blood flow on each cross section of the SMA (Figure 1A) and SMV (Figure 1B). These parameters were a time integrated flow evaluation within the contour. The streamlines were demonstrated using Tempus Pixel software and applied as references for the accurate perpendicular plane (Figure 1C).

Statistical tests Statistical analysis was performed using MedCalc for Windows, version 22.014 (MedCalc Software, Ostend, Belgium). Agreement of flow velocity and peak speed measurements of SMV and SMA between two readers was calculated using Bland-Altman analysis (mean difference and limits of agreement).

RESULTS

Patients

Out study included 9 patients (5 male, 4 female). Median age was 13 years (range: 7-14 years). Bowel disease, which included Crohn's disease, ulcerative colitis (UC), and celiac disease was either present or suspected in all patients. Six patients were under medication while the other three were not on any medications. Patient characteristics are summarized in Table 2. Contrast was administered per the needs of the clinical protocol. Gadoterate meglumine (Dotarem®, Guerbet, Princeton, NJ, United States), a gadolinium contrast agent, was administered in eight patients. Only one patient performed a non-contrast MRI study. Seven patients underwent MR studies without sedation. Two patients were sedated.

In order to assess potential confounders related to time of day, we recorded when patients' scans were obtained. One patient was scanned in the morning (10:18 AM). Five patients were scanned in the afternoon (ranging between 12:21 PM and 5:19 PM). Three patients were scanned in the evening (ranging between 6:19 PM and 10:50 PM).

All results from MRI were correlated with endoscopy. Six patients showed no MR evidence of active inflammatory bowel disease which was concordant with normal findings in endoscopy. Two patients revealed unremarkable bowel appearances on MRI, while the time interval with endoscopy was over a week in both cases, two weeks in one case and two months in the other case, which probably caused discordance between these two investigations. One patient showed normal MR enterography without endoscopy performed at the same timeframe.

Quantitative assessment

Flow velocity and peak speed measurements are shown in Tables 3 and 4. Vascular assessment from MRI in comparison to endoscopy findings are shown in Table 5. Good agreement between two readers was observed for flow velocity measurements of SMV (mean bias -0.01 L/minute and 95% limits of agreement, -0.09 to 0.08 L/minute) as well as SMA (mean bias -0.03 L/minute and 95% limits of agreement, -0.23 to 0.17 L/minute). Similarly, there was a good agreement for peak speed measurements of SMV (mean bias -1.2 cm/second and 95% limits of agreement, -9.4 to 7.0 cm/second) and SMA (mean bias -3.2 cm/second and 95% limits of agreement, -31.4 to 24.9 cm/second) on Bland-Altman analysis. With respect to comparison of 4D flow velocities with endoscopy results, peak speed and flow velocity measurements for positive cases ranged between 11.15-19.33 cm/second and 0.11-0.33 L/minute for SMV, and 24.36-59.99 cm/second and 0.14-0.46 L/minute for SMA. For the negative group, the peak speed and flow velocity measurements ranged between 9.98-30.37 cm/second and 0.06-0.31 L/minute for SMV, and 11.64-85.19 cm/second and 0.11-0.83 L/minute for SMA.

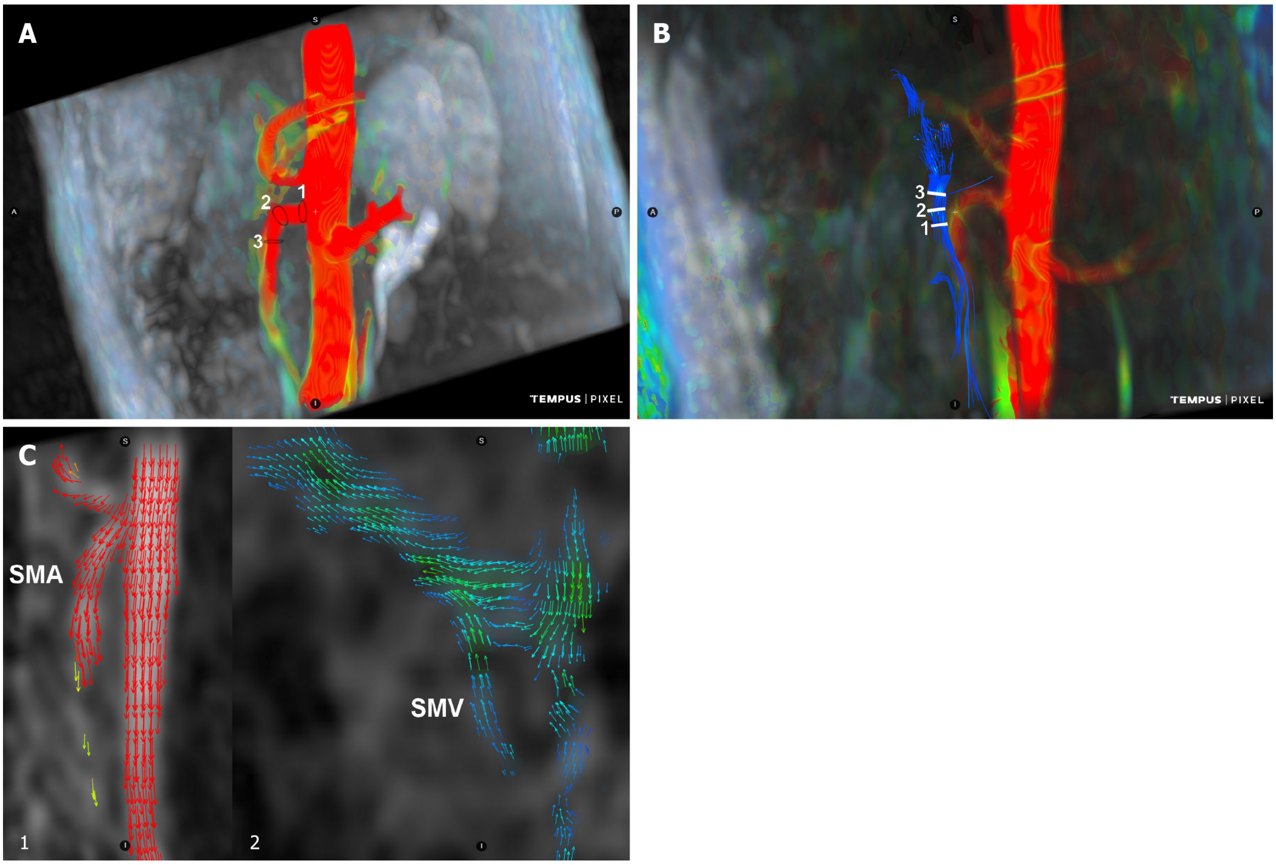

Figure 1 Flow velocity measurements of the superior mesenteric artery and superior mesenteric vein. A: Flow velocity measurements of the superior mesenteric artery. Regions of interest were placed in the perpendicular plane to the blood flow at proximal section (1), curved mid-section (2), and distal straight section before the first jejunal branching (3); B: Flow velocity measurements of the superior mesenteric vein. Regions of interest were placed in the perpendicular plane to the blood flow at the proximal section adjacent to the confluence of small venous tributaries (1), mid-section in between the proximal and distal sections (2), and distal section just below to the spleno-portal venous confluence (3); C: Tempus pixel web-based software demonstrating streamlines in the superior mesenteric artery (1) and superior mesenteric vein (2). The vectors were applied as references for the accurate perpendicular plane for flow velocity measurements. SMA: Superior mesenteric artery; SMV: Superior mesenteric vein.

DISCUSSION

In this study we aimed to determine feasibility of 4D flow quantitation of SMA and SMV flow in pediatric patients. We found good agreement for both peak velocity and peak speed measurements of SMA and SMV between our two readers. In comparison of 4D flow velocities with endoscopy results, there was no significant difference between the positive and negative cases.

The 4D flow MRI provides noninvasive hemodynamic quantitation of SMV and SMA and is feasible for detecting flow abnormality to bowel in children. We used a currently commercially available 4D flow MRI sequence in this study. There is prior literature discussing the role of 4D flow MRI to assess the PV system in children[9]. Additionally, there is also a study in the adult literature using 4D flow MRI to evaluate SMA flow dynamics[5]. In contrast, the study of small vessels in children has been limited.

There is a good agreement between two readers using 4D flow MRI to measure flow velocity and peak speed of SMV and SMA. The efficacy of 4D flow MRI compared with endoscopy reveals a good agreement in six patients. Two patients had a time interval between MRI and endoscopy over one week, which probably caused the discordance of these two investigations. One patient underwent an MRI study without endoscopy performed at the same period of time. Although the quantitative data of SMV and SMA were comparable to endoscopy findings, a limited small number of positive endoscopies impeded assessment for cut-off values to detect active bowel disease.

This feasibility study has limitations. The quantitative assessment was performed in 9 patients who underwent 4D flow MR protocol with clinical suspicion of IBD, Crohn's disease, UC, and celiac disease. Pediatric patients with very young age and those who could not tolerate the study without anesthesia were not eligible for the 4D flow protocol, causing a limited number of our cohort size of 9 patients. Secondly, the quality of MR enterography with 4D flow protocol was impacted by bowel movement. Therefore, measurements of tiny vessels were perplexing.

There is potential for future study of this technique with respect to assessment of disease activity in inflammatory bowel disease not only in pediatric, but also in adult patients. Further, this technique could be used for potential assessment in bowel ischemia, however, further study is needed to determine the overall generalizability of this application.

Table 1 Sequence parameters of four-dimensional flow magnetic resonance imaging

Parameter	4D flow MRI
Plane	Axial
FOV (mm)	280
Slice thickness (mm)	1.4
Number of slices	1
TR (millisecond)	4.4
TE (millisecond)	Min full
Flip angle (degrees)	15
Bandwidth/pixel (Hz)	1126.1
Matrix (phase × frequency)	148 × 148
Number of signal acquisitions	6.0
Acquisition time (second)	300-420
Slice resolution (%)	50.0
Voxel size (mm)	1.9 × 1.9 × 2.8
Velocity encoding (cm/second)	60

MRI: Magnetic resonance imaging; 4D flow: Four-dimensional flow; FOV: Field of view; TR: Repetition time; TE: Time to echo; Hz: Hertz.

Table 2 Patient characteristics

Median age, years (range)	13 years (7-14)
Gender	5 males; 4 females
Median body weight (kg)	53.5 (range: 24.5-93.4)
Heart rate (beats per minute), mean (SD)	88.4 (± 13.3)

Table 3 Dataset of flow velocity

Patient	Vessel (cm³/second)											
	SMVp		SMVm		SMVd		SMAp		SMAm		SMAd	
	DR1	DR2	DR1	DR2	DR1	DR2	DR1	DR2	DR1	DR2	DR1	DR2
1	3.33	3.33	3.67	3.83	4.67	4.17	3.50	4.50	2.67	1.83	1.67	3.00
2	1.67	1.83	2.83	2.00	3.67	2.83	2.50	2.17	2.50	2.00	2.50	2.33
3	2.17	2.33	2.50	3.17	3.33	2.50	13.50	14.00	8.00	9.17	4.17	9.83
4	2.50	3.33	2.67	3.50	3.00	4.33	5.17	4.33	3.83	3.00	2.00	3.00
5	3.00	3.33	3.50	4.83	5.67	5.33	6.83	8.50	5.17	5.33	2.33	3.00
6	1.00	1.67	1.50	1.50	2.17	2.17	2.67	2.50	2.50	2.17	2.17	2.83
7	1.00	1.33	1.00	0.83	1.83	1.67	2.17	4.33	3.50	4.83	1.00	2.50
8	2.50	1.50	4.00	3.83	5.17	5.17	8.67	5.83	8.67	6.67	3.33	6.67
9	2.00	3.50	3.17	3.17	4.17	3.33	7.33	6.50	5.33	4.67	4.00	5.50

SMVp: Proximal superior mesenteric vein; SMVm: Mid superior mesenteric vein; SMVd: Distal superior mesenteric vein; SMAp: Proximal superior mesenteric artery; SMAm: Mid superior mesenteric artery; SMAd: Distal superior mesenteric artery; DR1: First diagnostic radiologist; DR2: Second diagnostic radiologist.

Table 4 Dataset of peak speed

Patient	Vessel (cm/second)											
	SMVp		SMVm		SMVd		SMAp		SMAm		SMAd	
	DR1	DR2	DR1	DR2	DR1	DR2	DR1	DR2	DR1	DR2	DR1	DR2
1	11.77	11.99	11.78	13.29	18.02	20.78	53.01	65.90	40.69	50.29	23.38	53.56
2	11.08	11.21	14.85	13.41	17.17	18.42	59.80	56.78	45.79	74.18	48.28	51.87
3	12.90	12.98	18.97	20.81	17.43	18.42	90.74	79.63	29.80	29.97	21.75	27.86
4	11.22	14.64	8.67	11.29	11.07	11.14	16.02	18.51	14.64	14.47	9.29	13.98
5	22.17	16.49	17.20	16.09	14.17	15.52	66.60	50.40	60.87	47.34	25.11	23.61
6	16.81	28.16	23.87	23.95	32.47	28.27	56.81	52.33	59.58	37.92	42.00	28.70
7	10.08	10.77	11.59	8.40	13.27	12.77	40.59	48.46	44.21	44.37	24.45	30.95
8	20.00	15.69	14.39	14.52	19.46	20.91	59.19	62.66	63.63	61.72	35.27	48.48
9	12.85	15.64	13.20	26.90	25.01	31.46	78.80	81.18	77.28	76.15	37.77	81.73

SMVp: Proximal superior mesenteric vein; SMVm: Mid superior mesenteric vein; SMVd: Distal superior mesenteric vein; SMAp: Proximal superior mesenteric artery; SMAm: Mid superior mesenteric artery; SMAd: Distal superior mesenteric artery; DR1: First diagnostic radiologist; DR2: Second diagnostic radiologist.

Table 5 Dataset of endoscopy findings and vascular assessment

Patient	Gender	Age	Endoscopy	SMV (average)						SMA (average)					
				Velocity (cm^3/second)			Peak speed (cm/second)			Velocity (cm^3/second)			Peak speed (cm/second)		
				P	M	D	P	M	D	P	M	D	P	M	D
1	Female	13	Negative	3.33	3.83	4.50	11.88	12.54	19.40	4.00	2.33	2.33	59.46	45.49	38.47
2	Male	7	Not available	1.83	2.50	3.33	11.15	14.13	17.80	2.33	2.33	2.50	58.29	59.99	50.08
3	Female	11	Negative	2.33	2.83	3.00	12.94	19.89	17.93	13.83	8.67	7.00	85.19	29.89	24.81
4	Male	13	Negative	3.00	3.17	3.67	12.93	9.98	11.11	4.83	3.67	2.50	17.27	14.56	11.64
5	Male	12	Not available	3.17	4.17	5.50	19.33	16.65	14.85	7.67	5.33	2.67	58.50	54.11	24.36
6	Male	12	Negative	1.33	1.50	2.17	22.49	23.91	30.37	2.67	2.33	2.50	54.57	48.75	35.35
7	Female	11	Negative	1.17	1.00	1.83	10.43	10.00	13.02	3.33	4.17	1.83	44.53	44.29	27.70
8	Male	14	Negative	2.00	4.00	5.17	17.85	14.46	20.19	7.33	7.67	5.00	60.93	62.68	41.88
9	Female	14	Not available	2.83	3.17	3.83	14.25	20.05	28.24	7.00	5.00	4.83	79.99	76.72	59.75

SMV: Superior mesenteric vein; SMA: Superior mesenteric artery; P: Proximal section; M: Mid-section; D: Distal section.

CONCLUSION

In conclusion, in our study we demonstrate that 4D flow MRI is feasible for quantitative assessment of SMV and SMA flow in children, and that this can provide hemodynamic information as well as evaluate vascular morphology. This technique has the additional potential for a non-invasive method use to assess active bowel disease in pediatric patients. Larger population sized studies are required in the future to determine the overall clinical significance of this technique.

FOOTNOTES

Author contributions: Courtier J contributed to guarantor of the integrity of the entire study; Courtier J and Vakil P contributed to study concepts and design; Leesmidt K and Courtier J contributed to literature research; Verstraete S, Liu L, Durand R and Vakil P contributed to experimental studies/data analysis; Vakil P and Leesmidt K contributed to statistical analysis; All authors contributed to manuscript preparation and editing.

Institutional review board statement: Institutional review board approval for retrospective correlation of imaging with other clinical parameters was obtained, No. 18-25412.

Informed consent statement: This retrospective study was performed with institutional review board approval with informed consent requirements waived.

Conflict-of-interest statement: Jesse Courtier is founder and shareholder of Sira Medical (this is not mentioned or described in the manuscript). No other authors hold any real or potential conflicts of interest.

Data sharing statement: The data that support the findings of this study are available from UCSF. Restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request at jesse.courtier@ucsf.edu and with permission of UCSF.

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