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INNOVATIVE CLINICAL IMAGE

Assessing the Complicated Venous Hemodynamics and Therapeutic Outcomes of Budd-Chiari Syndrome with Respiratory-gated 4D Flow MR Imaging During the Expiratory and Inspiratory Phases

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A man in his 50s with Budd-Chiari syndrome diagnosed with the suprahepatic inferior vena cava (IVC) obstruction on CT was assessed using 4D Flow MRI before and after balloon angioplasty. 4D Flow MRI acquired in two respiratory phases, depicted complex hemodynamic and respiratory variability, and a jet stream at the narrowed channel of the membranous IVC. Post-interventional 4D Flow MRI showed that the IVC blood flow increased with corrected flow directions in the infrarenal IVC.

Keywords: *balloon dilation, Budd-Chiari syndrome, 4D Flow MRI, respiratory phases, inferior vena cava stenosis*

Introduction

Budd-Chiari syndrome is characterized by obstruction of the hepatic venous outflow from the intrahepatic veins (HVs) to the inferior vena cava (IVC) and right atrium.[1] Endovascular treatments, such as balloon angioplasty, stenting, and transjugular intrahepatic portosystemic shunt, are sometimes indicated.[1,2] The development of collateral blood vessels often complicates the hemodynamic situation. Further, the blood flow in the abdominal veins is affected by respiratory variability;[3] therefore, integrated hemodynamic assessment is essential before intervention.

Time-resolved 3D cine phase-contrast MRI (4D Flow MRI) enables noninvasive en-bloc 3D-blood-flow-velocity vector acquisitions.[4,5] Recently, the usefulness of 4D Flow MRI for assessing the indications for endovascular treatment and its outcomes has been reported; however, there are few reports regarding the assessment of the portal and venous systems.[6–8] For hemodynamic assessments of torso venous systems, care should be taken not to be affected by the respiratory cycle or Valsalva effect during breath-holding.[3] We present a case of Budd-Chiari syndrome with complex venous hemodynamics, in which 4D Flow MRI acquired in two respiratory phases (i.e., expiratory and inspiratory phases) was useful in assessing the hemodynamics, therapeutic indications, and treatment outcomes.

Case Presentation

A man in his 50s was diagnosed with Budd-Chiari syndrome during his annual check-up. He was referred to us, and dynamic contrast-enhanced CT (DCE-CT) suggested complete obstruction of all three main HV branches and IVC. Hepatic venous drainage into the IVC was done via a dilated accessory HV. Figure 1 shows a suspected complete membranous obstruction of the suprahepatic IVC (Fig. 1a) and the flow stagnation in the infrarenal IVC (Fig. 1b). Although his liver damage was mild, the development of collateral pathways, such as the lumbar venous-azygos pathway and subcutaneous veins, was also observed. Therefore, a transluminal angioplasty was planned to break the membranous obstruction followed by balloon dilatation, and 4D Flow MRI was scheduled for pre-interventional hemodynamic investigation.

The institutional review board approved the 4D Flow MRI study, and written informed consent was obtained from the patient. After > 6 h of fasting, the patient underwent 4D Flow MRI using a 3T MRI scanner (MAGNETOM Prisma; Siemens Healthineers, Erlangen, Germany) with two 18-ch

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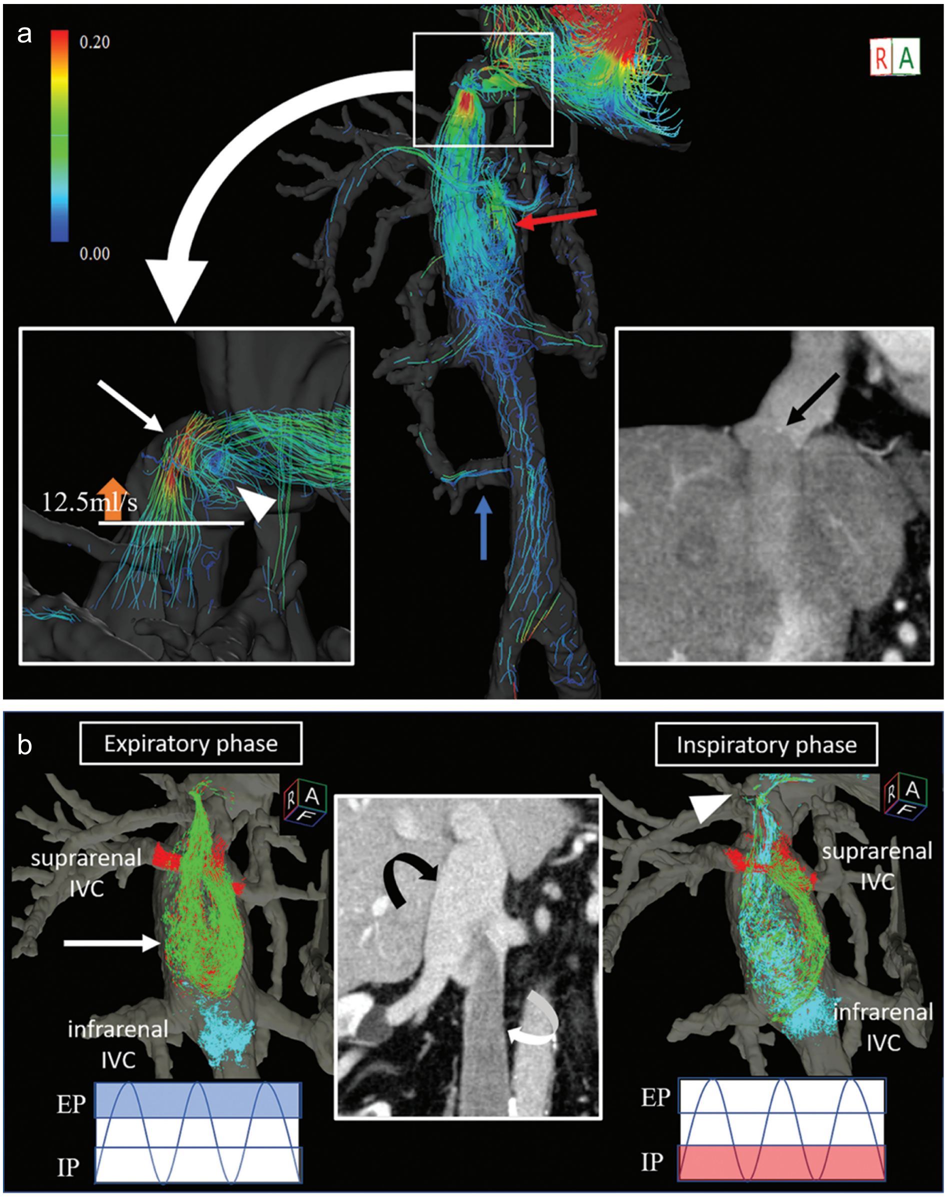

Fig. 1 Pre-interventional images of the IVC. (**a**) DCE-CT shows a suspected spotty-calcified membranous obstruction within the suprahepatic IVC (black arrow). The streamline of the whole abdomen 4D Flow MRI shows obstruction of the major three branches of the hepatic veins, a dilated accessory hepatic vein (red arrow), and dilated collateral veins (blue arrow). The streamline of the narrow segment shows high velocity on the right side of the stenosis (white arrow) and turbulent flow distal to the stenosis (arrowhead). IVC flow rate on the upstream side of the narrowing (measured at the line) was 12.5 mL/s. (**b**) Distinct opacity differences between supra- (black curved arrow) and infra-renal (white curved arrow) IVC on the DCE-CT was elucidated by 4D Flow MRI acquired in two respiratory phases under free-breathing. There were significant hemodynamic differences fluctuating to the respiratory cycle within the IVC. At the expiratory phase, a pathline shows vortex flow (arrow) in the dilated suprarenal IVC (green particles; from accessory hepatic vein) and stagnant blood flow in the infrarenal IVC (blue particles). At the inspiratory phase, however, a considerable amount of blood in the infrarenal IVC (blue particles) flow into suprarenal IVC, and this antegrade flow ultimately passes through the narrowed channel (arrowhead) into the right atrium together with the hepatic blood drainage (red particles; from intrahepatic venous branch). The pathline can track the movement of blood in the infra- and supra-renal IVC and the accessory hepatic vein, and thus delineates the trajectories that individual blood particles follow. These can be thought of as "recording" the path of blood movement over a certain period. Each respiratory waveform is not an actual measurement diagram but an imaginary diagram. DCE-CT, dynamic contrast-enhanced CT; EP, expiratory phase; IP, inspiratory phase; IVC, inferior vena cava.

phased-array coils. Prior to 4D Flow MRI, a 3D coronal DCE-MRI was obtained for morphological imaging, using 0.1 mmol/kg of gadobutrol (Gadovist; Bayer Yakuhin, Osaka, Japan) with an injection rate of 1 mL/s. Subsequently, a retrospective electrocardiogram-gated 4D Flow MRI with a respiratory navigator gate was conducted, including the entire

Table 1 4D flow MRI parameters.

	4D Flow MRI of the whole image			4D Flow MRI of stenosis	
	Pre EP	Pre IP	Post EP	Pre EP	Post EP
Orientation	Coronal			Axial	
TR/TE (msec)	70.68/3.1		66.24/2.73	65.28/2.65	64.32/2.57
Flip angle (degree)	8	8	8	8	8
No. of excitations	1	1	1	1	1
k-space segmentation	3	3	3	3	3
Temporal resolution (msec)	70.68		66.24	65.28	64.32
FOV (mm)	294 × 340			205 × 340	
Matrix	144 × 208			101 × 208	
Slice thickness (mm)/No. of slices	1.5/96	1.5/60	1.5/96	1.5/30	1.5/30
Voxel size (mm)	Reconstructed 1.4 × 1.4 × 1.5 Acquired 2.0 × 1.6 × 3.0			Reconstructed 1.6 × 1.6 × 1.5 Acquired 2.0 × 1.6 × 3.0	
VENC (cm/s)	50*		100	120	150
Pat	3			3	
Acceptance ratio (%)	72	41	78	73	92
Acquisition time (min)	22:56	24:11	22:03	5:32	4:19
Time frames (per R-R intervals)	10			10	
R-R intervals (msec)	1080	1010	1108	1027	1079
Gating	ECG, navigator			ECG, navigator	

*Aliasing artifacts have appeared. ECG, electrocardiogram; EP, expiratory phase; IP, inspiratory phase; VENC, velocity encoding.

abdomen or around the IVC membranous part, with the parameters listed in Table 1. For pre-interventional 4D Flow MRI, data samplings in two respiratory phases (i.e., expiratory and inspiratory phases) were employed to determine whether venous blood flow might fluctuate in the respiratory cycle. The expiratory phase was defined as the phase of decreased thoracic volume and the inspiratory phase as that of increased thoracic volume (Fig. 1b). The 4D Flow data set, segmented by morphological imaging, was post-processed and analyzed using flow analysis software (iTFlow; Cardio Flow Design, Tokyo, Japan).

Pre-interventional hemodynamic analysis using 4D Flow MRI demonstrated a high-velocity blood flow on the right side of the membranous part of the suprahepatic IVC, indicating incomplete membranous obstruction of the IVC (Fig. 1a). The dilated accessory HV merged the IVC downwards, and vortices were observed in the IVC. Notably, there were significant venous hemodynamic differences in the respiratory cycle within the IVC. In the expiratory phase, the pathline showed stagnant blood flow in the infrarenal IVC compared to the slow but antegrade flow of the suprarenal blood (Fig. 1b and Supplementary Movie 1). In the inspiratory phase, however, more antegrade flow in the IVC, including infrarenal blood, suprarenal blood, and accessory hepatic venous blood, ultimately passed through the narrowed channel and flowed into the right atrium (Fig. 1b and Supplementary Movie 2). The pre-interventional 4D Flow MRI provided details regarding the complex hemodynamic information, which were vital to predicting that there was no need to break through the membranous area, instead, to dilate the pore.

Based on this information, the right femoral vein was punctured and the guiding sheath (Parent Plus; Medikit, Tokyo, Japan) was advanced to the IVC. Digital subtraction angiography (DSA) from infrarenal IVC (Fig. 2a) showed that the IVC blood flowed to the collateral vein. In contrast, DSA just below the stenosis (Fig. 2b) showed an antegrade blood flow through the hole in the membranous area. These findings were similar to that of 4D Flow MRI. The guidewire was easily passed through the hole, and the blood pressure of the IVC was 10 mmHg, and that of the right atrium was 5 mmHg. Although the pressure disparity was mild at 5 mmHg, treatment was given to further improve blood flow in the IVC. The membranous hole was then dilated with a 12 × 40 mm balloon catheter (Armada; Abbott, Chicago, Illinois) (Fig. 2c). The pressure disparity was still 4 mmHg after dilation, due to mild

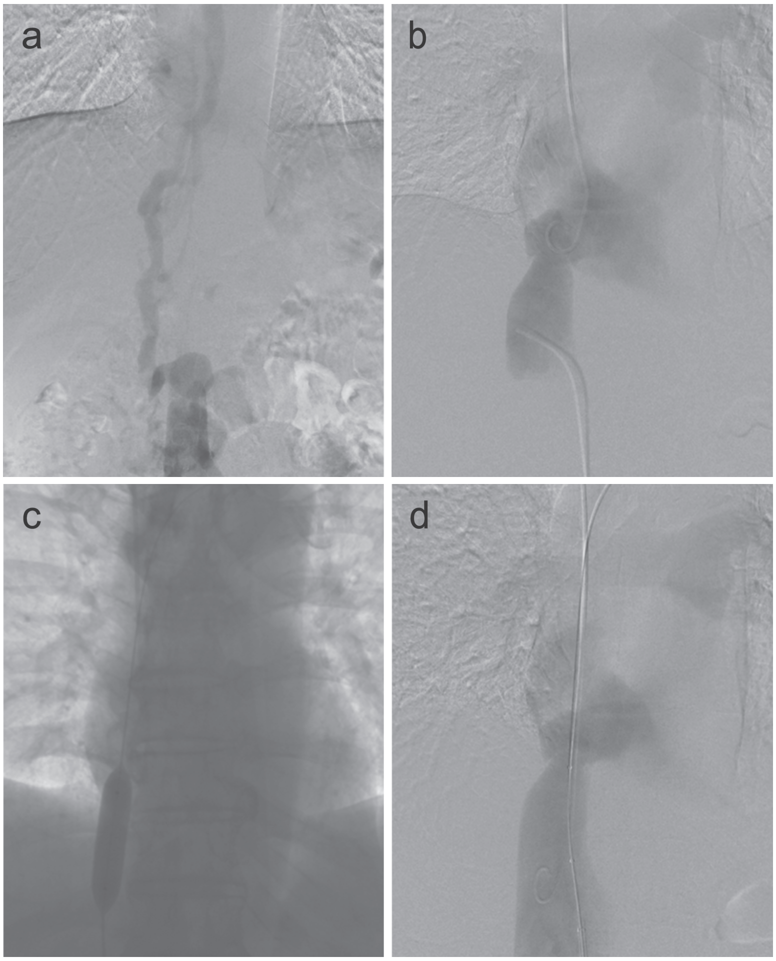

Fig. 2 DSA from the IVC before intervention (**a**) shows that the IVC blood flows to the collateral vein. In contrast, DSA from the suprahepatic IVC (**b**) shows an antegrade blood flow through the hole in the membranous area. These results are similar to the findings of 4D Flow MRI. Balloon dilation of the stenosis (**c**) and confirmation by DSA (**d**) show mild improvement in blood flow. DSA, digital subtraction angiography; IVC, infrarenal inferior vena cava.

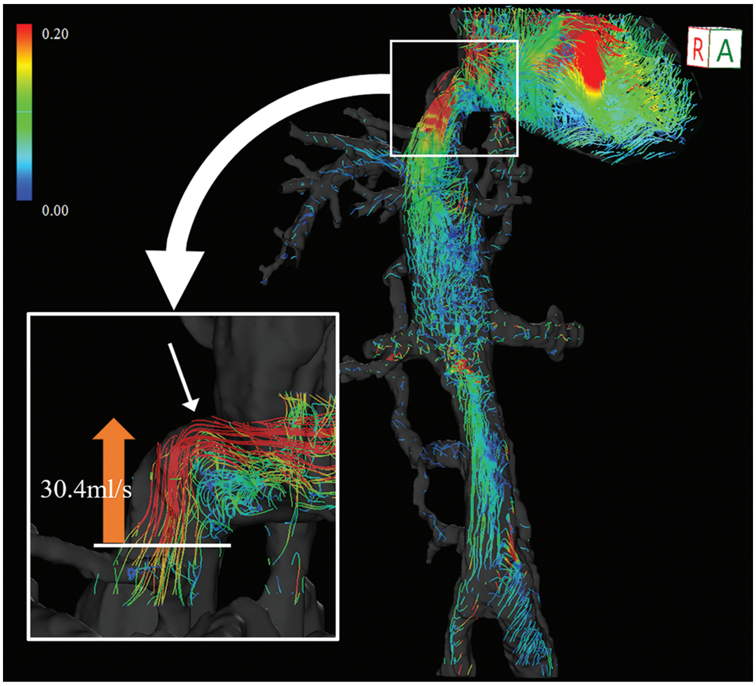

Fig. 3 Post-interventional 4D Flow MRI. The streamline of the whole abdomen and the narrow segment show high-velocity blood flow at the dilated but still somewhat narrowed portion (arrow). However, the IVC flow rate on the proximal side of the stenosis (measured at the line) increased to 30.4 mL/s, which was considered a therapeutic effect. In addition, IVC blood flow has changed antegrade. IVC, infrarenal inferior vena cava.

dilation to avoid causing IVC rupture; however, DSA after dilation showed a slight improvement in blood flow (Fig. 2d).

The next day, an expiratory phase 4D Flow MRI (Table 1) showed that the flow in the infrarenal IVC was successfully corrected in an antegrade fashion. The mean flow rate measured in the submembranous IVC, which did not show turbulence but laminar flow, increased from 12.5 mL/s to 30.4 mL/s after intervention (Fig. 3). Doppler ultrasonography (DUS) also showed a subsided jet flow through the narrowed channel with maximum velocity reduction from 150–200 cm/s to 60–100 cm/s, confirming the success of the treatment. Thereafter, the patient was followed-up as an outpatient without any problems.

Discussion

There are two patterns of Budd-Chiari syndrome: one in which the HVs are mainly occluded, and one in which the IVC is occluded or stenotic.[1] Since our patient had both complications, complicated hemodynamics were associated. Unlike DCE-CT, 4D Flow MRI readily depicts the jet stream through the narrowed channel in the membranous portion of the IVC and changes in blood flow due to respiratory phase.

Ultrasonography is the first choice in the hemodynamic assessment of Budd-Chiari syndrome and is suitable for repeated examinations; however, its shortcomings include relatively low intra- and inter-agreement, limited FOV, and limited visualization of deep-seated lesions.[1,2,8] Unlike DUS, 4D Flow MRI enables objective, comprehensive, and quantitative evaluation of the blood flow even after the patient leaves the MR suite, which is termed as retrospective flowmetry. In our case, there was turbulence near the stenosis, but 4D Flow MRI enabled accurate flowmetry by avoiding non-laminar flow. DUS, in contrast, did not allow depicting the entire lesion, so that only the flowmetry for the narrowed portion was done, whereas the portion was affected by the non-laminar flow, and thereby, an accurate flowmetry was deemed difficult. In addition, biphasic respiratory imaging (physiological inhale and exhale) during normal breathing in 4D Flow MRI allowed us to avoid the Valsalva effect. The application is sometimes critical in measuring the hemodynamics of the venous systems in the torso that is susceptible to the respiratory cycle (Fig. 1b and Supplementary Movies 1 and 2). In our case, CT alone could not explain the unusual hemodynamics in the IVC because DCE-CT was essentially not time-resolved (Fig. 1b). DSA is time-resolved; however, hemodynamics could be affected by the breath-holding, catheter position, or the injection rate of the contrast medium. 4D Flow MRI under normal breathing, on the other hand, was free of these effects, and the improvement in blood flow was clearly assessed.

This report has several limitations. First, the imaging time is relatively long because two imaging sessions are required to obtain the inspiratory and expiratory phases. This problem may be solved by using an acceleration method (e.g., employing the compressed sensing[9] or the spiral method).[10] Second, an IVC stenosis site has fast blood flow, and when velocity encoding (VENC) is applied to the site, the analysis accuracy of slow-flowing veins is reduced. To solve this problem, using dual-VENC may be useful.[11]

Conclusion

Inhale and exhale 4D Flow MRI allowed visual, quantitative, and objective evaluation of the physiological venous hemodynamics of Budd-Chiari syndrome. It assisted in treatment planning and post-treatment evaluation of Budd-Chiari syndrome, the hemodynamics of which are sometimes difficult to understand using CT.

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Conflicts of Interest

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Supplementary Information

Supplementary files below are available online.

Supplementary Movie 1

A cinema of pathline study at the phase-resolved expiratory-phase before intervention shows vortex flow in the dilated suprarenal IVC (green and red particles) and stagnant blood flow in the infrarenal IVC (blue particles). Green particles: derived from the dilated accessory hepatic vein; red particles, derived from intrahepatic veins; blue particles, derived from the infrarenal IVC. The pathline can track the movement of these blood in the infra- and supra-renal IVC and the accessory hepatic vein, thus delineating the trajectories that individual blood particles follow. The "pathline study" is a technique that can record the path of blood movement over a certain period of time.

Supplementary Movie 2

A cinema of pathline at the inspiratory phase before intervention shows a considerable amount of blood in the infrarenal IVC (blue particles) flow into the suprarenal IVC, and this antegrade flow ultimately passes through the narrowed channel into the right atrium together with the hepatic blood drainage (red and green particles). Green particles: derived from the dilated accessory hepatic vein; red particles, derived from intrahepatic veins; blue particles, derived from the infrarenal IVC. The "pathline study" can track the movement of these blood in the infra- and supra-renal IVC and the accessory hepatic vein, thus delineating the trajectories that individual blood particles follow.

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