Abdominal Applications of 4D Flow MRI

Abdominelle Anwendungen der 4D-Fluss-MRT

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ZUSAMMENFASSUNG

Hintergrund Die 4-dimensionale Fluss-Magnetresonanztomografie (4D-Fluss-MRT) erlaubt die zeitaufgelöste Darstellung und Quantifizierung des Blutflusses. Diese Übersichtsarbeit stellt die möglichen Anwendungen der 4D-Fluss-MRT zur nichtinvasiven Bildgebung der Hämodynamik im Abdomen zusammen.

Methode Diese Übersichtsarbeit basiert auf der Erfahrung der Autoren sowie einer aktuellen Literaturrecherche. Die Literaturrecherche wurde in der PubMed-Datenbank bezüglich abdomineller Anwendungen der 4D-Fluss-MRT im Dezember 2019 durchgeführt. Wir haben die Arbeit mit Abbildungen und Filmen klinischer Fälle aus unserer Institution illustriert.

Ergebnisse und Schlussfolgerung Die 4D-Fluss-MRT erlaubt die umfassende Beurteilung des abdominellen Blutflusses in verschiedenen Organsystemen und Gefäßterritorien. Die Ergebnisse neuerer Studien zeigen, dass die 4D-Fluss-MRT ein besseres Verständnis der veränderten Hämodynamik bei Patienten mit abdominellen Erkrankungen sowie die Überwachung des therapeutischen Ansprechens ermöglicht. Zukünftige Studien in größeren Kohorten sind nötig, um die 4D-Fluss-MRT in den klinischen Alltag zu integrieren.

Kernaussagen:

- Die 4D-Fluss-MRT ermöglicht eine umfassende Visualisierung der komplexen abdominellen Gefäßanatomie.
- Die 4D-Fluss-MRT ermöglicht die Quantifizierung der Geschwindigkeiten und der Flussraten in abdominellen Blutgefäßen.
- Die 4D-Fluss-MRT könnte zu einem besseren Verständnis der veränderten Hämodynamik bei unterschiedlichen abdominellen Erkrankungen beitragen.
- Weitere Studien zur Validierung der 4D-Fluss-MRT in der abdominellen Bildgebung sind vor der breiten Anwendung notwendig.

ABSTRACT

Background Four-dimensional flow magnetic resonance imaging (4D flow MRI) provides volumetric and time-resolved visualization and quantification of blood flow. This review presents an overview of possible applications of 4D flow MRI for non-invasive assessment of abdominal hemodynamics.

Method This review is based on the authors' experience and the current literature. A PubMed database literature research was performed in December 2019 focusing on abdominal applications of 4D flow MRI. We illustrated the review with exemplary figures and movies of clinical cases from our institution.

Results and Conclusion 4D flow MRI offers the possibility of comprehensive assessment of abdominal blood flows in different vascular territories and organ systems. Results of recent studies indicate that 4D flow MRI improves understanding of altered hemodynamics in patients with abdominal disease and may be useful for monitoring therapeutic response. Future studies with larger cohorts aiming to integrate 4D flow MRI in the clinical routine setting are needed.

Key Points:
- 4D flow MRI enables comprehensive visualization of the complex abdominal vasculature
- 4D flow MRI enables quantification of abdominal blood flow velocities and flow rates
- 4D flow MRI may enable deeper understanding of altered hemodynamics in abdominal disease
- Further validation studies are needed prior to broad distribution of abdominal 4D flow MRI

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Introduction

Four-dimensional flow magnetic resonance imaging (4D flow MRI) is a three-dimensional and time-resolved phase contrast imaging technique allowing characterization of blood flows within the entire vasculature [1–3]. 4D flow MRI enables the visualization of physiological and pathological flow patterns by registration of both morphology and velocity data [3–5].

4D flow MRI represents a development from the clinically established two-dimensional cine phase contrast magnetic resonance imaging (2D PCMRI). 2D PCMRI provides only single direction measurement of flow velocities on predefined 2D planes [6, 7]. The 2D plane has to be placed manually perpendicular to the vessel of interest during the MRI examination, which represents a major limitation of this technique. In contrast, 4D flow MRI enables off-line placement of analysis planes during post-processing for retrospective evaluation of blood flow parameters like flow rates and velocities in multiple vessels [8].

4D flow MRI also has several advantages over Doppler ultrasound, another clinically established and radiation-free imaging modality. Doppler ultrasound enables the measurement of flow velocities, whereby the calculation of flow rates is often based on assumptions resulting in possibly inaccurate quantification [4]. The main disadvantages of ultrasound examinations include the missing possibility to comprehensively image the complex abdominal vascular anatomy due to a limited acoustic window [4], reduced image quality e. g. in obesity or meteorism [9] and operator dependency [10]. In contrast, 4D flow MRI has shown strong repeatability [11] and reproducible results regarding the inter- and intra-reader agreement of blood flow quantification in the abdomen [12].

This review gives a brief introduction to the technique of 4D flow MRI and provides an overview regarding possible applications of 4D flow MRI for assessment of abdominal hemodynamics.

Technical considerations

4D flow MRI is a phase contrast MR imaging technique allowing for the three-dimensional visualization of time-dependent blood flow patterns. During the 4D flow MRI acquisition, a volumetric time-resolved velocity vector field is obtained by recording velocity data of the scanned volume in three spatial directions over the entire cardiac cycle [8].

Before the 4D flow MRI acquisition, several technical parameters have to be defined depending on the scientific or clinical question.

The velocity encoding sensitivity (venc) is a critical parameter and has to be adjusted correctly. The adjusted venc represents the highest measurable blood flow velocity. Velocities above the venc cause aliasing and velocities far below the venc lead to inaccurate measurements [13]. The venc should be set 10 % higher than maximum expected blood flow velocity [4]. Specific venc settings according to the targeted vasculature are shown in ▶ **Table 1**. Regarding the abdominal vasculature, we generally recommend venc settings of at least 100 cm/s for arterial vessels or 30–100 cm/s for (portal) venous vessels. Dual-venc 4D flow MRI strategies have recently been developed for an improved assessment of slow and high flow velocities within a single MRI acquisition [14].

Cardiac triggering is necessary to obtain a time-resolved flow signal, which is particularly important in arterial vessels due to the pulsatile blood flow. The temporal resolution has to be sufficient for an accurate characterization of changes in flow velocity over time, thus allowing for the correct assessment of peak velocities [4]. However, the temporal resolution should not be too fine in order to avoid an unnecessary increase of scan time. Regarding abdominal arteries, we generally recommend a temporal resolution of < 40 ms per timestep [4].

The spatial resolution should ideally amount to at least 5–6 isotropic voxels per vessel diameter [4]. However, in the case of a large field of view (e. g. entire abdomen), this recommendation might not be achievable for smaller vessels (e. g. hepatic artery) of only a few millimeters diameter within a reasonable scan duration.

The reproducibility using different temporal and spatial resolutions for the assessment of liver hemodynamics has been recently investigated in more detail [15]. The 4D flow MRI acquisition protocols included spatial resolutions with voxel sizes ranging from $2.4 \times 2.0 \times 2.4\ mm^3$ to $2.6 \times 2.5 \times 2.6\ mm^3$ and temporal resolutions ranging from ~60 ms to ~80 ms (approximately 12–9 timeframes per heart cycle). A lower resolution in space and time resulted in lower blood flow velocities, most notably in arterial vessels but also in the portal venous system [15].

Respiratory motion during the 4D flow MRI acquisition causes artifacts like blurring and/or ghosting, resulting in reduced image quality and inaccurate flow measurements. Respiratory gating is required to reduce breathing artifacts. Gating strategies include self-gating techniques, respiratory bellows, and navigator gating [16–18]. In the case of navigator gating, we recommend placement of the navigator window on the diaphragm/liver interface with a gating window of ~6 mm. This results in acquisition efficiencies of usually ~50 % for regular breathing patterns [4]. How-

▶ **Table 1** Acquisition parameters of 4D flow MRI in different abdominal regions. Ao = abdominal aorta, CT = celiac trunk, HA = hepatic artery, SA = splenic artery, SMA = superior mesenteric artery, RA = renal artery, PV = portal vein, SV = splenic vein, SMV = superior mesenteric vein, TIPS = transjugular intrahepatic portosystemic shunt, AV = azygos vein (AV), n. s. = not specified, ind. opt. = individually optimized from preceding 2D PCMRI.

▶ **Tab. 1** 4D-Fluss-MRT-Akquisitionsparameter entsprechend der untersuchten abdominellen Regionen. Ao = Aorta abdominalis; CT = Truncus coeliacus; HA = Arteria hepatica; SA = Arteria splenica; SMA = Arteria mesenterica superior; RA = Arteria renalis; PV = Vena portae; SV = Vena splenica; SMV = Vena mesenterica superior; TIPS = transjugulärer intrahepatischer portosystemischer Shunt; AV = Vena azygos; n. s. = nicht spezifiziert; ind. opt. = individuell angepasst mittels vorheriger 2D-PC-MRT.

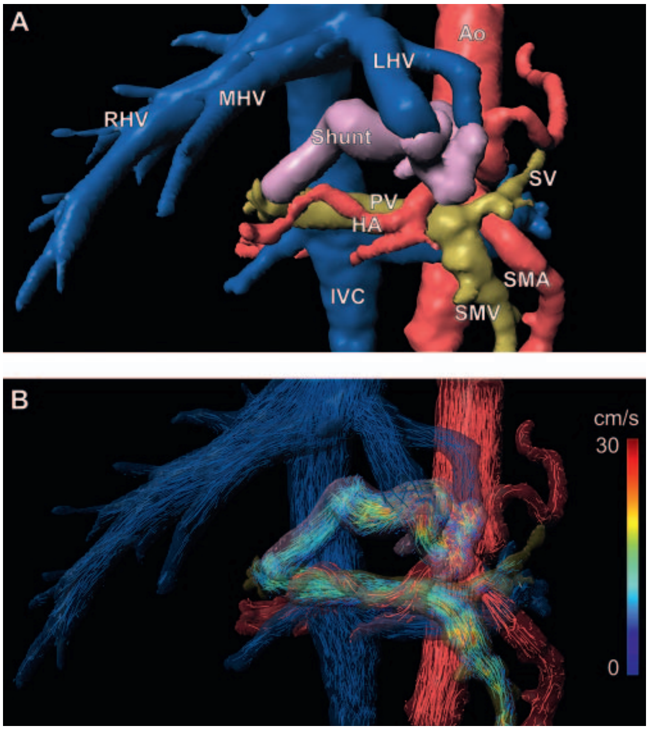
author	structure of interest	venc (cm/s)	spatial resolution (mm^3)	temporal resolution	scan duration (min)
liver and portal venous system					
Stankovic et al. 2010 [33]	PV, SV, SMV	50	1.6 × 2.1 × 2.4	44.8 ms	16–23
Stankovic et al. 2013 [39]	SV, SMV, PV, CT, SA, HA, SMA	100	1.7 × 2.1 × 2.4	62.4 ms	~13
Roldàn-Alzate et al. 2013 [32]	PV, SV, SMV, Ao, HA	60/100	1.4 × 1.4 × 1.4	14 timeframes per heart cycle	10–12
Roldàn-Alzate et al. 2015 [40]	Ao, AV, HA, PV, SMA, SMV, SV	100/120	1.25 × 1.25 × 1.25	14 timeframes per heart cycle	12
Stankovic et al. 2015 [46]	SV, SMV, PV, CT, HA, SA, SMA, TIPS	100	2.4 × 2.1 × 2.6	80 ms	~9
Bannas et al. 2016 [25]	SMV, SV, PV, TIPS	60/80/120	1.25 × 1.25 × 1.25	14 timeframes per heart cycle	~12
Owen et al. 2018 [45]	TIPS	225	2.38 × 1.33 × 3.00	10 timeframes per heart cycle	10–20
Motosugi et al. 2019 [42]	PV, SV, SMV, AV	30	1.25 × 1.25 × 1.25	14 timeframes per heart cycle	~10
kidneys and renal arteries					
Wentland et al. 2013 [11]	Ao, RA	150	1.32 × 1.32 × 1.32	16 timeframes per heart cycle	~11
Motoyama et al. 2017 [55]	Transplant RA	ind. opt.	1.25 × 1.25 × 1.25	20 timeframes per heart cycle	~9.5
abdominal aorta and mesenteric arteries					
Sughimoto et al. 2016 [63]	Ao	n. s.	0.55 × 0.55 × 5.0	20 timeframes per heart cycle	15–20
Siedek et al. 2018 [66]	Ao, CT, SMA	≤ 300 (ind. opt.)	1.5 × 1.5 × 1.5	24 timeframes per heart cycle	5–15

ever, for irregular breathing patterns, the efficiency can drop below 20 %, resulting in up to five times longer scan durations [19, 20]. The long acquisition time hampers the implementation of this technique in the clinical setting. Recently, respiratory motion corrected 4D flow MRI sequences with predictable scan times and large geometrical coverage were proposed, which may help to integrate 4D flow MRI into the clinical routine [21].

4D flow MRI enables the assessment of blood flows without the need of contrast media. This advantage allows the investigation of patients with renal insufficiency without the risk of nephrogenic systemic fibrosis. Of note, the administration of contrast media means higher flip angles can be used to increase signal-to-noise ratio [4]. A steady-state blood pool can be achieved with the gadolinium-based intravascular contrast agent gadofosveset trisodium [22–25]. Other gadolinium-based contrast media with faster blood pool clearance result in varying blood signal intensities over time and the possible effects on accuracy of flow measurements are not yet fully explored [4].

4D flow MRI data analysis

4D flow MRI offers the possibility to evaluate blood flow off-line retrospectively during post-processing. A three-dimensional angiogram can be segmented from the 4D flow MRI data for visual analyses of the vascular anatomy (▶ **Fig. 1A**, ▶ **Video 1A**). Velocity-coded angiograms can be obtained for each timeframe and are visualized as pathlines or streamlines within the vessel lumen [1] (▶ **Fig. 1B**, ▶ **Video 1B**).



▶ **Fig. 1** 4D flow MRI-based visualization of hemodynamics in the upper abdomen of a 75-year-old man with a spontaneous porto-systemic shunt in the left liver lobe. **A** Segmented 4D flow MR angiograms. Veins are indicated in blue, arteries in red, and the portal circulation in yellow. The shunt is indicated in purple. **B** Velocity-weighted 4D flow MRI shows velocity distribution in the portal circulation, which is indicated by color-coded pathlines. Note that no flow is observed in the right portal vein due to the steal phenomenon of the shunt in the left liver lobe. Red and blue pathlines indicate flow in the arterial and venous system, respectively. Ao = abdominal aorta, HA = hepatic artery, SA = splenic artery, SMA = superior mesenteric artery, PV = portal vein, SV = splenic vein, SMV = superior mesenteric vein, RHV/MHV/LHV = right/middle/left hepatic vein.

▶ **Abb. 1** 4D-Fluss-MRT zur Visualisierung der Hämodynamik im Oberbauch eines 75-jährigen Mannes mit spontanem portosystemischem Shunt im linken Leberlappen. **A** Segmentiertes 4D-Fluss-MR-Angiogramm. Venen und Arterien sind blau bzw. rot dargestellt, das portalvenöse System ist gelb dargestellt. Der Shunt ist in lila dargestellt. **B** 4D-Fluss-MRT-basierte Pathlines zur farbkodierten Darstellung der Flussgeschwindigkeiten im portalvenösen System. Man beachte den fehlenden Fluss in der rechten Pfortader, bedingt durch das Steal-Phänomen des Shunts im linken Leberlappen. Rote und blaue Pathlines zeigen den Fluss im arteriellen bzw. venösen System. Ao = Aorta abdominalis; HA = Arteria hepatica; SA = Arteria splenica; SMA = Arteria mesenterica superior; PV = Vena portae; SV = Vena splenica; SMV = Vena mesenterica superior; RHV/MHV/LHV = rechte/mittlere/linke Vena hepatica.

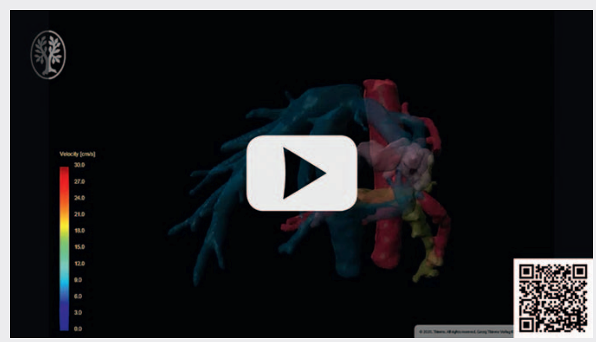
Pathlines allow time-resolved visualization of the temporal evolution of blood flow over the cardiac cycle by illustrating the trace that fluid particles would follow from their origin [26]. Streamlines represent the velocity vector field in a given moment, thus enabling us to identify specific flow patterns like helices and vortices [26].

OP-VIDEO

▶ **Video 1A** Three-dimensional angiogram of the abdominal vasculature segmented from the 4D flow MRI data for visual analyses of the anatomy.

▶ **Video 1A** Die Erstellung eines 3-dimensionalen Angiogramms mithilfe der 4D-Fluss-MRT erlaubt die anatomische Darstellung der abdominellen Gefäßstrukturen.

OP-VIDEO



▶ **Video 1B** 4D flow MRI-derived angiograms with velocity-weighted pathlines within the vessel lumen visualize the blood flow.

▶ **Video 1B** 4D-Fluss-MRT-basierte geschwindigkeitskodierte Angiogramme mit Pathlines innerhalb der Gefäßlumina visualisieren den Blutfluss.

Quantitative flow analyses are obtained by placing arbitrary analysis planes using the 4D flow MRI-derived angiograms for correct orientation. 4D flow MRI-derived analyses of time-resolved flow velocities and flow rates are made equivalent to 2D phase contrast flow measurements: a local acceleration of flow velocity indicates a stenosis and a reduced flow rate indicates a reduced blood supply of the downstream organ [1]. If spatial resolution suffices to visualize a reliable flow profile within the vessel lumen, helical and vortical flows, flow eccentricity, and wall shear stress (WSS) can be evaluated [13]. The evaluation of these 4D flow MRI-derived parameters is being performed using different commercially available or custom-built analysis tools. However, standardized analysis procedures have not been established yet.

Standardization of algorithms and comparison of different analysis tools is still needed and requires further comparative studies.

4D flow MRI provides a comprehensive assessment of blood flows within reasonable scan times (▶ **Table 1**). Shortening of the acquisition time might be achieved e. g. using acceleration techniques such as compressed sensing [27]. Multi-venc techniques might enable the flow evaluation of slow and fast flow velocities in a single MRI acquisition [28]. However, since 4D flow MRI is not integrated into clinical routine workflow yet, the analysis of 4D flow MRI data is still time-consuming due to the large amount of acquired data and the lack of standardization in post-processing.

Validation of 4D flow MRI

The validity of 4D flow MRI measurements has been investigated in several studies [11, 12, 15, 29–34]. In vivo reference methods include Doppler ultrasound, 2D PCMRI and computational fluid dynamics [33, 35]. In vitro, additional methods like laser Doppler anemometry or particle image velocimetry can serve as a reference [4].

A recent phantom study using a pulsatile flow phantom assessed the accuracy of 4D flow MRI in terms of flow rate and velocity using a flowmeter and 2D PCMRI as the standard of reference [29]. The study demonstrated that 4D flow MRI is accurate for the quantification of the mean flow rate. However, the maximal velocity is slightly lower in 4D flow MRI than that derived by 2D PCMRI. Of note, a variation of the venc up to three times greater than the maximal flow velocity did not influence the results [29]. Similar conclusions were drawn in a 4D flow MRI phantom study evaluating blood flows across a stenosis [30]. A flowmeter and computational fluid dynamics served as standard of reference for flow rate and flow velocity, respectively. The flow rate was measured accurately in the proximal and distal regions of the stenosis. However, there was also an underestimation of post-stenotic peak velocities [30].

Experimental in vivo blood flow measurements of the ascending aorta obtained simultaneously by 4D flow MRI and by an invasive flow probe were compared in a swine study. 4D flow MRI enabled accurate measurement of aortic flow rates [31]. In another porcine model, 4D flow MRI was compared in vivo to invasive flow measurements obtained by perivascular ultrasound in the abdominal vasculature (portal vein, splenic vein, hepatic artery, renal arteries) [12]. Perivascular ultrasound and 4D flow MRI showed good agreement regarding the abdominal blood flow rates. Furthermore, intra- and inter-reader comparison revealed excellent correlation [12].

Regarding abdominal imaging in humans, the internal consistency based on the conservation of mass and the repeatability of 4D Flow MRI was investigated [11]. The abdominal aorta and renal arteries were imaged two times in healthy volunteers. Repeatability was investigated by comparison of 4D flow MRI-derived measurements from both examinations. Internal consistency was tested by the comparison of in-flow (suprarenal aorta) and out-flow (sum of infrarenal aorta, left renal artery and right renal artery). Both repeated measurements and in-flow vs. out-flow measurements did not demonstrate significant differences [11].

Similar results were obtained for 4D flow MRI-derived flow rates in the portal venous system [15, 32]. Excellent correlations were observed between the sum of flow rates in the superior mesenteric vein (SMV) and splenic vein vs. the portal vein, as well as between the flow rates in the portal vein vs. the sum of the left and right portal vein branch [32]. Only small errors were observed in the arterial system when comparing flow rates in the celiac trunk with the sum of the flow rates in the splenic and hepatic artery (left gastric artery was neglected) [15]. Direct comparison of 4D flow MRI with 2D PCMRI and Doppler ultrasound as standard of reference was performed in the portal vein. Mean and peak velocities did not differ significantly. 4D flow MRI-derived velocities revealed moderate correlation compared to 2D PCMRI [33].

However, a recent 4D flow MRI study comparing flow volumes derived from different MR scanners found significant differences regarding accuracy and precision in humans [34]. Therefore, further large-scale studies addressing the reproducibility of 4D flow MRI in the abdomen using different MRI scanners and/or different acquisition techniques (e. g. Cartesian or radial imaging) are needed.

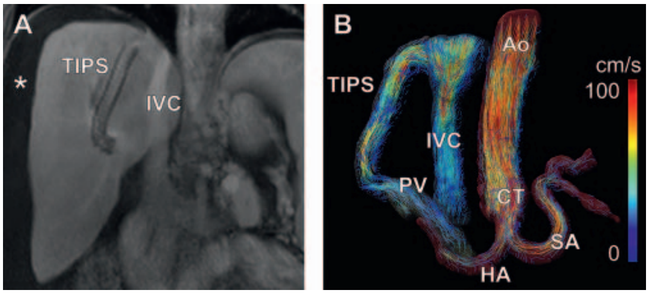
Abdominal applications of 4D flow MRI

4D flow MRI provides a non-invasive visualization and quantification of flows in the entire abdominal vasculature with a single examination. We expect that the implementation of 4D flow MRI in the clinical routine and larger clinical studies will further improve the understanding of abdominal pathologies. Several 4D flow MRI studies in different disease settings have been performed to date (▶ **Table 1**). Below, we present an overview regarding possible applications of 4D flow MRI for non-invasive assessment of abdominal hemodynamics in different diseases.

Liver and portal venous system

Different quantitative MRI methods have been used to evaluate chronic liver pathologies, such as steatosis [36], fibrosis, or cirrhosis [37, 38]. In patients with liver cirrhosis, 4D flow MRI allows to evaluate splanchnic blood flows in the arterial, venous, and portal venous system [32, 33, 39]. Mesenteric and portal hemodynamics depend on the ingestion of food due to physiological postprandial vasodilation, which results in increased mesenteric blood flow [40]. Therefore, we recommend performing 4D flow MRI acquisitions of the abdominal vasculature after the patient has fasted for ≥ 3 hours.

A recent 4D flow MRI study compared splanchnic blood flow directly after a standardized meal and after fasting for five hours in healthy individuals as well as in cirrhotic patients with portal hypertension [40]. Postprandially, significant increases in blood flow were observed in both groups in the portal vein, SMV, superior mesenteric artery, and supraceliac aorta. However, in contrast to healthy subjects, blood flow significantly decreased in patients with portal hypertension in the splenic vein and the hepatic artery, while flow rate increased in the azygos vein. [40]. The flow in the azygos vein is correlated with gastro-esophageal varices [41]. Therefore, the feasibility of 4D flow MRI to measure blood flow alterations in these vessels holds promise for the evaluation of portal hypertension, especially regarding the treatment of gastroesophageal varices [40].



▶ **Fig. 2** **A** Coronal T1-weighted MRI of a 57-year-old woman after transjugular intrahepatic portosystemic shunt (TIPS) placement. Note the not yet resolved ascites (asterisk). **B** 4D flow MRI-derived velocity-weighted pathline visualization of blood flow in the portal vein (PV) and TIPS stent. Flow in the inferior vena cava (IVC), aorta (Ao) and celiac trunk (CT) is also visualized by velocity-weighted pathlines. Note the accelerated flow in the TIPS stent.

▶ **Abb. 2** **A** Koronare T1-gewichtete MRT der Leber einer 57-jährigen Patientin nach Implantation eines transjugulären intrahepatischen portosystemischen Shunts (TIPS). Der Aszites ist noch nicht vollständig regredient (Asterisk). **B** Die 4D-Fluss-MRT-basierte Flussvisualisierung mittels geschwindigkeitskodierter Pathlines zeigt den Blutfluss in der Pfortader (PV) und eine Flussbeschleunigung im TIPS. Der Blutfluss in der Vena cava inferior (IVC), der Aorta (Ao) und im Truncus coeliacus (CT) ist ebenfalls mittels geschwindigkeitskodierter Pathlines dargestellt.

Portal hypertension in liver cirrhosis is associated with the development of gastroesophageal varices [8]. Recently, the stratification of variceal bleeding risk using 4D flow MRI has been investigated in 23 patients with liver cirrhosis [42]. Endoscopy was performed as standard of reference to grade the bleeding risk of those varices. In four of the 15 patients with endoscopy-confirmed varices, 4D flow MRI was able to visualize these vessels directly. Since the varices were not measurable in each 4D flow visualization, indirect measures of portosystemic collateral blood flow were evaluated. In this small study cohort, patients with high bleeding risk varices had a portal venous flow lower than the sum of the flow in the SMV and the splenic vein (sensitivity 100 %, specificity 94 %) and an increased flow rate in the azygos vein (sensitivity 100 %, specificity 62 %) [42].

The implantation of a transjugular intrahepatic portosystemic shunt (TIPS) represents a therapeutic option in these patients. The TIPS stent represents a bypass from the portal system to the systemic circulation, with the aim to lower portal pressure and consecutively to reduce the risk for variceal hemorrhage and to resolve ascites [43, 44]. 4D flow MRI enables the non-invasive monitoring of hepatic blood flow before and after TIPS implantation [25] (▶ **Fig. 2**, ▶ **Video 2**). Portal venous flow increased significantly after TIPS implantation and ascites resolved in most patients. In one individual, 4D flow MRI helped to identify arterioportal shunting, explaining the patient's refractory ascites despite TIPS implantation [25].

4D flow MRI may also be used to assess TIPS dysfunction (i. e. stenosis) by detection of focal turbulence and abnormal velocities [45, 46]. A recent feasibility study aiming to detect TIPS dysfunction included 16 patients with a successfully performed 4D flow MRI [45]. Qualitative and quantitative flow properties (i. e. flow abnormalities like focal turbulence and peak velocities, respectively) were separately evaluated in each patient. Clinical follow-up or, when available, venography served as reference standard. Three patients with TIPS dysfunction were correctly detected by 4D flow MRI due to focal turbulence and abnormal velocities. 4D flow MRI correctly excluded flow abnormalities in seven patients without TIPS dysfunction. However, six patients without TIPS dysfunction had discordant 4D flow results demonstrating flow alterations [45]. These results indicate that further studies are needed to establish more specific 4D flow MRI criteria for monitoring TIPS function. These 4D flow MRI-derived criteria might then help guiding TIPS revision strategies in non-responding TIPS-patients with persistent ascites.

OP-VIDEO

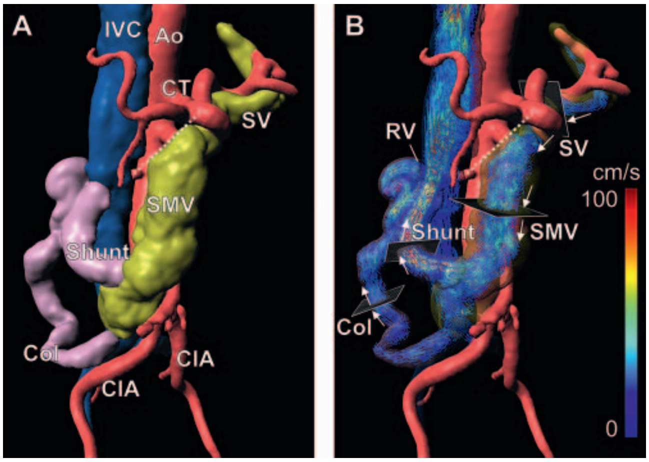
▶ **Video 2** 4D flow MRI for non-invasive monitoring of hepatic blood flow after TIPS implantation.

▶ **Video 2** Die 4D-Fluss-MRT ermöglicht die Darstellung der hepatischen Hämodynamik nach TIPS-Implantation.

4D flow MRI may also be useful in patients with severe complications of portal hypertension where TIPS implantation is not possible. We treated a patient with portal hypertension and refractory ascites due to portal vein thrombosis. Surgical implantation of a mesocaval stent graft between the SMV and the inferior vena cava (IVC) was performed to lower the portal pressure. Postoperative 4D flow MRI revealed a large spontaneous portosystemic mesorenal collateral between the SMV and the right renal vein (RV). 4D flow MRI not only allowed to confirm the patency of both the spontaneous mesorenal collateral (SMV-RV) and the implanted mesorenal shunt (SMV-IVC) but also quantification of flow rates (▶ **Fig. 3**, ▶ **Video 3A, B**).

In liver transplantation, 4D flow MRI may improve surgical planning through visualization of patient-specific hemodynamics. A recent study in living liver donors demonstrated that 4D flow MRI can support predicting the patient-specific response to altered post-surgery flow in the remaining liver lobe induced by resection of the donated liver lobe [47].

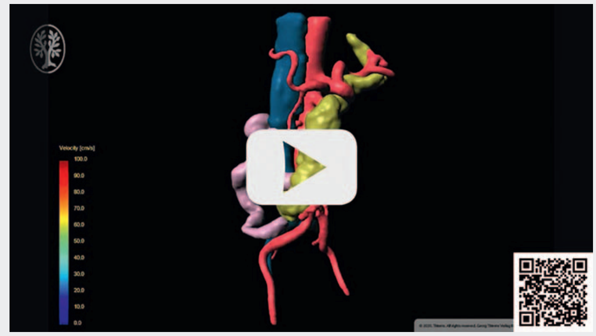
The usefulness of 4D flow MRI for blood flow assessment in complex postsurgical vascular anatomy has been recently highlighted in a patient with renoportal anastomosis after liver transplantation [48]. In the case of portal vein thrombosis renoportal



▶ **Fig. 3** 4D flow MRI of the entire abdominal vasculature in a 54-year-old man with thrombosis of the portal vein and both portosystemic spontaneous collateral and surgical shunt. **A** Note the missing portal vein in the segmented 4D flow MRI-derived angiogram due to complete portal vein thrombosis. Begin of the thrombosis is indicated by the dotted line, which begins at the venous confluence of the superior mesenteric vein (SMV) and splenic vein (SV). Note the large spontaneous mesorenal collateral (Col), originating from the SMV and draining into the right renal vein (RV). Since portal vein thrombosis precluded placement of a TIPS stent, a mesocaval shunt was surgically implanted, draining blood from the SMV into the inferior vena cava (IVC) in order to lower portal hypertension. Aorta (Ao), celiac trunk (CT), and right and left common iliac arteries (CIA) are also shown. **B** Velocity-weighted 4D flow MRI reveals reversed blood flow within the SMV draining into the spontaneous mesorenal collateral and surgical mesocaval shunt.

▶ **Abb. 3** 4D-Fluss-MRT bei einem 54-jährigen Patienten mit Pfortaderthrombose und portosystemischer spontaner mesorenaler Kollaterale sowie einem implantierten mesocavalen Shunt. **A** Die Pfortader ist im Angiogramm aufgrund der Thrombose nicht abgrenzbar. Die Thrombose beginnt unmittelbar an der Konfluenz von Vena mesenterica superior (SMV) und Vena splenica (SV) und ist durch die weiße Linie gekennzeichnet. Eine spontane mesorenale Kollaterale (Col) besteht zwischen der SMV und der rechten Nierenvene (RV). Zur Senkung des portalvenösen Drucks wurde operativ ein mesocavaler Shunt von der SMV in die Vena cava inferior angelegt (IVC). Aorta (Ao), Truncus coeliacus (CT) sowie rechte und linke Arteria iliaca communis (CIA) sind ebenfalls dargestellt. **B** Die 4D-Fluss-MRT-basierten geschwindigkeitskodierten Pathlines zeigen eine Flussumkehr in der SMV mit Abfluss in die spontane mesorenale Kollaterale und den operativ angelegten mesocavalen Shunt.

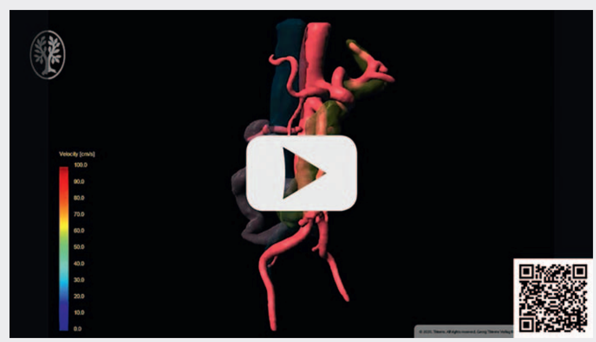
OP-VIDEO



▶ **Video 3A** 4D flow MRI-derived angiogram in a 54-year-old man with complete thrombosis of the portal vein and both portosystemic spontaneous mesorenal collateral and surgical mesocaval shunt.

▶ **Video 3A** 4D-Fluss-Angiogramm eines 54-jährigen Patienten mit vollständiger Pfortaderthrombose und portosystemischer spontaner mesorenaler Kollaterale sowie implantiertem mesorenalem Shunt.

OP-VIDEO



▶ **Video 3B** Velocity-weighted 4D flow MRI reveals reversed blood flow within the SMV draining into the spontaneous mesorenal collateral and surgical mesocaval shunt.

▶ **Video 3B** Die Flussvisualisierung mittels 4D-Fluss-MRT zeigt eine Flussumkehr in der SMV und Abfluss über die spontane mesorenale Kollaterale und den operativ angelegten mesocavalen Shunt.

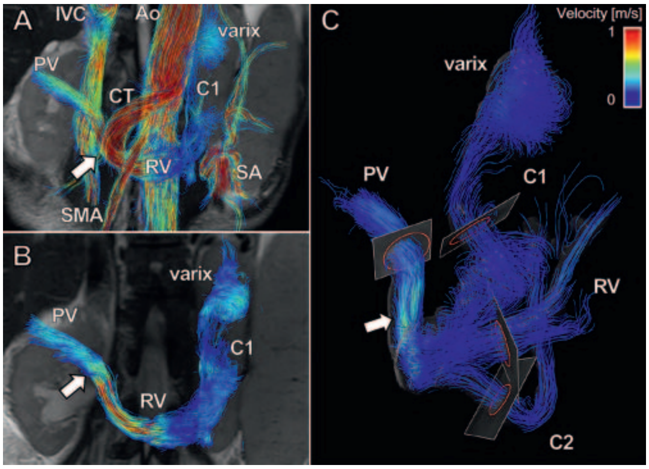
anastomosis is a surgical technique to preserve blood flow to the liver graft [49]. This patient suffered from variceal bleeding after renoportal anastomosis. 4D flow MRI enabled the measurement of splanchnic blood flows, which was not accessible by other imaging techniques. An orthograde flow was observed in the renoportal anastomosis, thus considering the risk for recurrent variceal bleeding to be low and avoiding secondary surgery (▶ **Fig. 4**, ▶ **Video 4**) [48].

Spleen

4D flow MRI-derived blood flow analyses may improve the diagnostic assessment of hypersplenism. Hypersplenism, as a complication of liver cirrhosis and portal hypertension, might lead to severe consequences such as thrombocytopenia [50]. Anatomic imaging combined with 4D flow MRI-based assessment of splenic blood flow and portosystemic shunts enabled the non-invasive determination of the clinical relevance of splenomegaly in patients with cirrhosis and suspected thrombocytopenia [51].

Kidneys and renal arteries

4D flow MRI enables the evaluation of renal perfusion with strong repeatability of flow measurements [11]. Stenoses of renal arteries may cause hypertension and renal failure [52]. However, the hemodynamic significance of a moderate renal artery stenosis might not



▶ **Fig. 4** 4D flow MRI-based visualization of portal hemodynamics after liver transplantation with renoportal anastomosis in a 49-year-old woman. Velocity-encoded 4D flow MRI reveals patency of the renoportal anastomosis (arrow) between the left renal vein (RV) and the portal vein (PV) that secures blood flow to the liver graft. **A** Oblique anterior view shows velocity distribution also in the inferior vena cava (IVC), aorta (Ao), celiac trunk (CT), superior mesenteric artery (SMA), and splenic artery (SA). **B** Isolated visualization of orthograde helical flow in a large esophageal varix that drains via a collateral (C1) into the renal vein. **C** Left view with perpendicular cut-planes for flow quantification in collaterals (C1, C2), renal vein (RV) and portal vein (PV). Taken with permission from Lenz et al. (DOI:10.1055/a-0862-0778) [48].

▶ **Abb. 4** 4D-Fluss-MRT-basierte Darstellung der portalen Hämodynamik nach Lebertransplantation mit renoportaler Anastomose einer 49-jährigen Patientin. Geschwindigkeitskodierte 4D-Fluss-MRT-Bilder zeigen die Durchgängigkeit der renoportalen Anastomose (Pfeil) zwischen der linken Nierenvene (RV) und der Pfortader (PV), welche die Blutzufuhr der Transplantatleber sicherstellt. **A** Die schräg-anteriore Sicht zeigt die Geschwindigkeitsverteilung in der Vena cava inferior (IVC), Aorta (Ao), Truncus coeliacus (CT), Arteria mesenterica superior (SMA) und Arteria splenica (SA). **B** Isolierte Darstellung des orthograden helikalen Blutflusses in einer großen Ösophagusvarizen, welche über eine Kollaterale (C1) in die Nierenvene (RV) drainiert. **C** Ansicht von links mit orthogonalen, zum Gefäß liegenden Ebenen zur Quantifizierung des Blutflusses in den Kollateralen (C1, C2), der Nierenvene (RV) und der Pfortader (PV). Mit Genehmigung von Lenz et al. (doi:10.1055/a-0862-0778) [48].

be determined from anatomical imaging of the vessel diameter alone [2, 52]. In a porcine model, 4D flow MRI was successfully performed for the assessment of the hemodynamic significance of renal artery stenoses [53]. In humans, renal perfusion has been evaluated by this technique in a pediatric case of left renal artery stenosis with renovascular hypertension. Flow measurements before and after percutaneous transluminal renal angioplasty confirmed an increased blood flow after angiography [54].

A recent study assessed renal perfusion after kidney transplantation and compared intrarenal artery blood flow obtained by 4D flow MRI and Doppler ultrasound. The authors observed a significant correlation between ultrasound- and 4D flow MRI-derived flow velocities. They concluded that hemodynamic and morphological data obtained by 4D flow MRI for evaluation of transplant intrarenal arteries is useful in this setting [55].

OP-VIDEO

▶ **Video 4** Orthograde blood flow in varix and collaterals, indicating low risk for recurrence of variceal bleeding. Taken with permission from Lenz et al. (DOI:10.1055/a-0862-0778) [48].

▶ **Video 4** Orthograder Blutfluss in den Varizen und Kollateralen als Hinweis für ein geringes Risiko einer erneuten Varizenblutung. Mit Genehmigung von Lenz et al. (doi:10.1055/a-0862-0778) [48].

Abdominal aorta and mesenteric arteries

Progressive dilatation and aneurysm formation of the aorta is a risk factor for potentially life-threatening aortic dissection and rupture [56]. Although the formation of abdominal aneurysms is typically associated with atherosclerosis [57], the mechanism of the development of an aortic aneurysm is not yet clearly understood [58]. In order to identify predictors for aneurysm formation and dissection, recent research has investigated hemodynamic parameters such as 4D flow MRI-derived secondary flow patterns (e. g. vortices and helices) and WSS [13].

WSS represents mechanical stress on the vessel wall, which is a known stimulus for endothelial cell function [59], and may be associated with arterial remodeling and plaque formation [60, 61]. A standardized algorithm for 4D flow MRI-derived WSS evaluation has not been established. WSS estimates are influenced by the exact placement of the region of interest and by the chosen spatial resolution [62]. However, the relative intra- and interindividual distribution of WSS estimates might be reasonably accurate [5, 35]. In the abdominal aorta, elevated WSS was described adjacent to the ostia of the renal arteries in healthy volunteers [63]. Of note, this is the segment of the aorta where abdominal aneurysms commonly develop. However, future longitudinal studies need to investigate the predictive value of these altered 4D flow MRI-derived measurements in the abdominal aorta for formation of aneurysms and prediction of dissection.

4D flow MRI of the abdominal aorta may also be useful in patients after aortic dissection for determining blood flow changes. A recent study has shown that the assessment of flow alterations in the false and true lumen may be useful for the identification of patients with increased rates of aortic expansion [64]. Again, future longitudinal studies are needed to determine the significance of these 4D flow MRI-derived alterations and their potential for risk stratification of patients with aortic dissections.

After endovascular aneurysm repair, 4D flow MRI may help to detect and visualize endoleaks. The feasibility of this method to visualize flow into the aneurysm was recently demonstrated, thereby aiding in the differentiation of the specific types of endoleaks [65]. However, it should be kept in mind that the detection of small endoleaks may be difficult, particularly if susceptibility artifacts are present due to the metallic struts in the stent graft.

4D flow MRI has shown promising results addressing the assessment of smaller abdominal vessels such as the superior mesenteric artery and celiac trunk. In a recent feasibility study, 22 healthy volunteers were compared to ten patients with confirmed low-grade and mid-grade stenosis of the superior mesenteric artery or celiac trunk. Contrast-enhanced computed tomography served as standard of reference [66]. The peak and average velocities, the peak flow rate, stroke volume, and WSS were evaluated in both arteries using 4D flow MRI. Patients with a low-grade or mid-grade stenosis revealed significantly higher peak and average blood flow velocities in comparison to healthy individuals. Mid-grade stenoses were associated with a significantly higher WSS magnitude. Limitations of this study include the lack of a reference standard for 4D flow MRI-derived flow parameters and potential negative effects on image quality caused by high acceleration factors [66].

Fetal and uteroplacental hemodynamics

4D flow MRI might be used for prenatal cardiovascular angiography. In research, 4D flow MRI has already been used in animal studies to evaluate hemodynamics during pregnancy. While respiratory gating can be used to compensate for motion due to maternal breathing, compensation for fetal motion and cardiac triggering remains difficult [67]. In pregnant sheep, invasive triggering of the blood pressure enabled the visualization of arterial and venous blood flow patterns in the major fetal vessels [68]. In pregnant monkeys, 4D flow MRI allowed measurements in fetal and uteroplacental vessels [67]. Future studies with improved cardiac gating strategies such as recently developed MR-compatible Doppler ultrasound sensors [7] are needed for 4D flow MRI-based assessment of fetal hemodynamics.

Summary

4D flow MRI offers the possibility of functional evaluation of flow parameters in the complex abdominal vasculature beyond morphological assessment. A major advantage is the possibility to retrospectively evaluate arbitrary vessels of interest within the acquired three-dimensional volume off-line after acquisition. The ability of 4D flow MRI to perform qualitative and quantitative analyses offers the possibility of a comprehensive assessment of the abdominal blood flows in different vascular territories and organ systems. Results of recent studies indicate that 4D flow MRI improves understanding of altered hemodynamics in patients with abdominal disease and may be useful for monitoring therapeutic response. Future studies with larger cohorts aiming to integrate 4D flow MRI in the clinical routine setting are needed.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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