Introduction

Three-dimensional (3D) contrast-enhanced (CE) magnetic resonance (MR) portography is a quick and robust means of evaluating the portal venous system offering some advantages over currently used imaging modalities including catheter-based digital subtraction angiography (DSA), computed tomography, ultrasonography and non-enhanced MR angiography with time-of-flight (TOF) and phase contrast (PC) techniques [1]. With 3D CE MR portography a first-pass study of the mesenteric vasculature is performed (see VI.3) after rapid bolus injection of gadolinium-based contrast agent. Repeated sequences allow depiction of the intra- and extrahepatic portal venous anatomy. The images can then be reconstructed by means of maximum-intensity-projection (MIP) postprocessing, and a subtraction technique can be employed to eliminate arterial enhancement and demonstrate portosystemic shunts. The coronal source images simultaneously demonstrate parenchymal lesions of the liver, pancreas, biliary tract and spleen. Precise and reliable assessment of the portal venous system in patients with hepatic cirrhosis and portal hypertension is essential before liver transplantation, non-surgical transjugular shunting or surgical portosystemic shunting. Especially in patients with portal hypertension and a history of gastro-esophageal bleeding it is mandatory to determine whether the portal venous system is patent or the portal vein or its main branches are thrombosed [2].

Normal Anatomy

The mesenteric venous anatomy (Fig. 1) parallels the arterial distribution (see VI.3) [3-4]. The portal vein is formed by the splenic and superior mesenteric veins. The pancreatic, left gastroepiploic, short gastric, and inferior mesenteric veins and splenic vein branches drain into the main splenic vein. The inferior mesenteric vein receives its supply from the left colic, sigmoid and superior hemorrhoidal veins. It usually joins the splenic vein prior to the junction of the splenic vein with the superior mesenteric vein. The superior mesenteric vein receives its contribution from jejunal, ileal

Fig. 1. Normal anatomy of the portal venous system
A Portal vein
B Superior mesenteric vein
C Inferior mesenteric vein
D Lenal vein
I Right branch of the portal vein
II Left branch of the portal vein
a Coronary and pyloric veins
b Right and left gastroepiploic veins
c Superior hemorrhoidal vein
d Hemorrhoidal plexus
e Middle and inferior hemorrhoidal veins
Table 1. Overview of MR-contrast agents currently approved in Europe

<table>
<thead>
<tr>
<th>Commercial Name</th>
<th>Laboratory Name</th>
<th>Generic Name</th>
<th>Manufacturer</th>
<th>T1 relaxivity* mmol⁻¹ sec⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnevist®</td>
<td>Gd-DTPA</td>
<td>Gadopentetate dimeglumine</td>
<td>Schering</td>
<td>4.8</td>
</tr>
<tr>
<td>Gadovist®</td>
<td>Gd-BT-D03A</td>
<td>gadolinium-D03A-butiroli</td>
<td>Schering</td>
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<tr>
<td>Dotarem®</td>
<td>Gd-DOTA</td>
<td>Gadoterate meglumine</td>
<td>Guerbet</td>
<td>–</td>
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<tr>
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<td>Gd-BMA</td>
<td>Gadodiamide</td>
<td>Amersham Health</td>
<td>4.4</td>
</tr>
<tr>
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<td>Gadoteridol</td>
<td>Bracco</td>
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</tr>
<tr>
<td>MultiHance®</td>
<td>Gd-BOPTA</td>
<td>Gadobenate dimeglumine</td>
<td>Bracco</td>
<td>9.7</td>
</tr>
</tbody>
</table>

* in plasma at 0.47 T and 20 mHz

right colic, and middle colic veins. The coronary veins (right and left gastric veins) usually drain directly into the portal vein. The portal vein then divides into the right and left portal branches at the porta hepatic. Approximately one half of patients have the portal vein bifurcation outside the liver capsule. A common normal variant of the portal venous system is trifurcation of the main portal vein, which is present in about 8% of patients. In these patients, the main portal vein divides into the right posterior segmental branch, the right anterior segmental branch, and the left portal vein.

**MRA Techniques**

When performing 3D CE MR portography some important technical issues have to be considered. By the time a conventional extracellular MR-contrast agents reaches the portal vein, it is considerably diluted. This dilution is caused by the contrast extraction at the capillary level for redistribution into the extracellular compartment and Gd extraction in the liver [5]. Table 1 lists the MR contrast agents currently available in Europe and elsewhere for CE-MRA. Current commercially available gadolinium-based agents are extracellular in nature and most have similar T1 relaxation values of between approximately 4.4 and 5.6 mmol⁻¹ sec⁻¹. The one agent with truly unique physicochemical properties among the contrast agents listed in Table 1 is gadobenate dimeglumine (MultiHance®, Gd-BOPTA, Bracco Imaging SpA, Milan, Italy) which is currently approved in Europe and elsewhere for MR imaging of the CNS and liver and under investigation for applications in CE-MRA. Gadobenate dimeglumine differs from the other agents in two major respects. Firstly, unlike the other available gadolinium–based contrast agents which are excreted exclusively by glomerular filtration through the kidneys [6-9], Gd-BOPTA is eliminated from the body through both the renal (96-98% of the injected dose) and hepatobiliary (2-4% of the injected dose) pathways [10,11]. Secondly, due to a unique capacity among current agents for weak and transient interaction with serum albumin [12], Gd-BOPTA possesses a T1 relaxivity in plasma (9.7 mmol⁻¹ sec⁻¹) which is approximately twice that of most of the conventional gadolinium chelates [13].

These facts have to be taken into account when determining the contrast dosage. Thus, when using conventional extracellular MR-contrast agents (i.e. agents with no albumin binding) a dosage of 0.2 mmol/kg body weight is recommended for dedicated portal vein imaging. This dosage can be lowered when employing Gd-BOPTA [14].

A rather lower flip angle of 20°–30° is advantageous as it improves visualization of the diluted gadolinium in the portal vein. The images can be acquired in a coronal or axial slice orientation. Coronal imaging has the advantage of including the mesenteric arteries including the inferior mesenteric artery on the arterial phase (see chapter VI.3) and also including the superior and inferior mesenteric veins and retroperitoneal collaterals. The axial plane has the advantage of imaging the main portal vein and its branches “in-plane”, which usually results in higher resolution compared to reformations. Another advantage of the axial acquisition is the fact that the entire liver is depicted allowing the detection and characterization of hepatic tumors. Finally, axial imaging has a smaller field-of-view without wraparound artifacts if frequency encoding is right-to-left. However, one limitation of the axial plane is wrap-around in the slice direction (superior to inferior). Bright fat adjacent to the imaging volume hampers image quality. This problem can be eliminated by utilizing a fat suppression technique and by using an imaging volume that matches the entire volume of the coil sensitivity. In this way, tissue above and below the coil will have limited signal to wrap into the image volume [5].

3D axial imaging volumes can easily be prescribed from coronal localizers. The axial 3D volume should extend from just above where hepatic veins enter the inferior vena cava down to well below the spleno-portal confluence. On slower MR scanners it may be necessary to use a slice thickness of 5-6 mm to obtain adequate coverage.

When imaging in the coronal plane, it is crucial
to extend sufficiently anteriorly to include the entire portal and mesenteric venous system in the imaging volume. For planning of the 3D acquisition the portal vein should be readily identified on the localizer. Usually the main portal vein is depicted well on axial T1, T2 or gradient echo images.

High-performance gradient MR-scanners in combination with partial Fourier imaging can provide up to 50 imaging sections in a convenient 20 second breath-hold. MR scanners with inferior gradient performance may require thicker sections of up to 4 or 5 mm in order to extend far enough anteriorly (for coronal volumes) to include the portal vein and still be fast enough to be acquired during a breath-hold.

For portal venous phase imaging the breathhold interval needs to be kept rather short. A patient who can suspend breathing for 40 seconds during the arterial phase may be too winded for another 40-second breath-hold during the portal venous phase. Therefore, it is best to keep the acquisition time under 30 seconds per phase to enable patients to suspend breathing twice in a row with only a few seconds rest in between [5].

Analysis of the portal venous and equilibrium phase images can be accomplished rapidly by performing a series of overlapping thick maximum-intensity-projections (MIP). Volume rendering may not work as well because of hepatic parenchymal enhancement.

**Complementary Sequences**

A PC-MR scan can be employed to determine the direction of portal venous blood flow. A single 5-10 mm thick 2D phase contrast image is acquired in an axial or oblique plan, perpendicular to the portal vein. Typical imaging parameters are: 28 ms/6 ms TR/TE/Flip = 28/6/45° and VENC = 40 cm/s. On 2D phase contrast velocity map images, background tissues are gray, while blood flow is shown as either bright vixels or black pixels, depending on their direction of flow. By convention, flow in the superior-to-inferior (S/I), right-to-left (R/L), and anterior-to-posterior (A/P) directions is bright, whereas flow in the opposite direction is displayed as dark on velocity-encoded 2D phase contrast images. Through plane flow can similarly be mapped on oblique acquisitions. In order to interpret flow data correctly, the orthogonal plane coming closest to the scan obliquity needs to be determined. Alternatively, if the portal vein is more vertical than horizontal, a straight axial 2D phase contrast image can be acquired and the flow direction compared to the aorta and inferior vena.

For patients with limited breath-holding capabilities who could not suspend breathing during the portal venous phase, axial 2D gradient echo images can be acquired post-gadolinium during either short periods of apnea (5s) or quiet respiration. Paramagnetic contrast within the vascular system enhances time-of-flight image quality allowing use of relatively thick, 5-8 mm slices. For non-breath-held scans a sufficient number of averages, in conjunction with respiratory ordered phase encoding, will usually result in diagnostic image quality [5].

Patients with suspected parenchymal pathology benefit from T1- and T2-weighted spin echo imaging prior to contrast injection. These images can be used as a guide to ensure inclusion of all pathology in 3D contrast MRA data sets. For patients with suspected biliary obstruction or pancreatitis, a HASTE or single shot fast spin echo MRCP-type sequence in coronal or coronal oblique planes is also useful and can generally be performed in a single breath-hold or during quiet respiration.

**Clinical Examples for Various Clinical Indications and Pathologies**

3D CE MR portography can demonstrate the intrahepatic and extrahepatic portal venous system as well as hepatic veins. Its advantages over DSA include its large field of view, its short imaging time, and its noninvasive nature and low risk of complications, which permit repeated studies. Clinical applications of 3D CE MR portography include portal hypertension (portosystemic shunt, portal vein obstruction, hepatic vein obstruction), hepatic encephalopathy, ascending portal thrombophlebitis, hepatocellular carcinoma and pancreatobiliary tumors, gastrointestinal hemorrhage, and differentiation of splanchnic arterial disease from portal venous disease [1,15]. In patients with portal hypertension, 3D MR portography can be used to evaluate portosystemic shunt, hepatopetal collateral pathways, and obstruction of the portal or hepatic veins. In planning treatment for hepatic encephalopathy, it is important to identify the causative portosystemic shunt. In suspected cases of ascending portal thrombophlebitis, it is important to assess the severity of portal vein obstruction as well as portal collateral vessels. In patients with hepatocellular carcinoma or pancreatobiliary tumors, one must determine the presence or absence of portal vein invasion when planning treatment.

**Portal Hypertension**

DSA in patients with portal hypertension is often performed to measure portal venous pressures and the portal-systemic pressure gradient. These measurements can not be made directly using
MRI. However, for patients who require a portal-systemic shunt, 3D contrast MRA can be a useful guide for shunt planning (Fig. 2). MRA accurately assesses the patency of both spontaneous (Fig. 3) and surgical shunts (Figs. 4, 5) as long as metallic clips do not obscure portal venous anatomy. In conjunction with PC-MRA-techniques, shunt volumes can be determined non-invasively. TIPS shunts are more difficult to assess due to metallic stents. Most often, a stainless steel Wall stent is used to bridge the portal and systemic venous system. Even with echo times of less than 1 ms, the lumen of this metal stent cannot be evaluated by MRA.

**Liver Transplantation**

Imaging proof of a patent portal vein is required for a patient to be placed on the liver transplant waiting list. Ultrasound can image the portal vein but is not 100% reliable. When ultrasound fails to adequately visualize the portal vein, 3D CE MRA offers a safe, accurate, and comprehensive assessment of portal venous anatomy without requiring iodinated contrast [16, 17]. 3D CE MRA also evaluates the splenic vein, superior mesenteric vein (SMV), inferior mesenteric vein, IVC and potential varices (Fig. 6). Following liver transplantation, rising liver function tests may raise a suspicion of al-
**Fig. 4a, b.** 13-year old female patient with surgical splenorenal shunt due to portal venous hypertension caused by hereditary liver fibrosis in multicystic kidney disease. The arterial phase image (a) already shows an early enhancement of some venous structures (arrows) which in the portal venous phase (b) can be identified as the splenic vein (arrow) connected to the left renal vein (arrowhead). The study confirms patency of the surgical splenorenal shunt without stenosis at the site of anastomosis. Note the enlarged kidneys on both sides due to polycystic kidney disease [Images courtesy of Dr. G. Schneider]

**Fig. 5.** Different forms of surgical shunts in portal venous hypertension.
lograft ischemia. Since blood supply to the liver is primarily via the portal vein, this is the most important vessel to evaluate. The most common site of obstruction is at the anastomosis. Usually, anastomoses are easy to identify because of the caliber change between donor and recipient portal veins [18]. Stenosis of the transplant arterial anastomosis may be seen on the arterial phase of a portal venous study, but its smaller size and often folded, tortuous course can make it difficult to assess. Occlusion of the transplant artery is important to detect because it results in ischemia to the donor common bile duct and can lead to biliary strictures and leaks. It is also important to assess the IVC since supra- and infrahepatic IVC anastomoses may also become narrowed and flow limiting.

**Portal Vein Thrombosis and Cavernous Transformation**

Portal vein thrombosis often occurs in liver cirrhosis, ascending portal thrombophlebitis, pancreatitis, and other conditions and after sclerotherapy of a gastroesophageal varix [19]. It is important to assess portal venous patency in these diseases. Contrast-enhanced 3D MR portography provides detailed information not only about the location and length of portal vein obstruction but also about portal collateral pathways. Over time, a network of small collateral vessels develops to bypass the portal venous occlusion. This network of collaterals, known as cavernous transformation, is identified by its characteristic enhancement pattern in the hepatic hilum during portal venous and equilibrium phases of 3D CE MRA.

Table 2 gives an overview of the accuracy of 3D MR portography. In potential candidates for liver transplantation, it is necessary to evaluate portal venous patency [20]. Color Doppler US may not allow portal venous patency to be established [21], but contrast-enhanced 3D MR portography provides accurate information.

**Tumor Encasement**

In patients with pancreatobiliary tumors, it is important to evaluate portal vein invasion before surgery. CT and DSA have been used for this purpose. 3D CE MR portography is also an accurate way to diagnose portal vein invasion [22, 23].
Invasion of the portal vein makes tumor resection with clear margins nearly impossible, thus, removing the patient as a surgical candidate. Tumors in the pancreatic head may encase the SMV, portal vein, and medial splenic vein. These tumors are usually detected early because they cause biliary obstruction, and thereby may be more likely to be resectable. Tumors in the body and tail of the pancreas may become larger before being detected and more commonly occlude the splenic vein. Splenic vein occlusion has a tendency to produce short gastric varices serving as venous collaterals and can be seen on delayed images.

Budd Chiari

Budd-Chiari syndrome is a rare disorder characterized by hepatic outflow occlusion and caused by various conditions including congenital or idiopathic obstruction, hepatic vein thrombosis due to hypercoagulative state, hepatic veno-occlusive disease after liver transplantation, and hepatic tumors [24]. The major symptoms include ascites, hepatomegaly, and abdominal pain. It has been classified into three types according to the location of the occlusion [25, 26]. Type 1 is defined as occlusion of the inferior vena cava with or without hepatic vein occlusion; type 2, occlusion of major hepatic veins; and type 3, obstruction of the small centrilobular venules (hepatic veno-occlusive disease). From the clinical point of view, Budd-Chiari syndrome should be classified according to whether it can be treated with anticoagulants, surgery, or interventional procedures. In planning treatment, it is important to determine the location and length of hepatic outflow obstruction [24], and contrast-enhanced 3D MR portography is an accurate means of doing this. No hepatic veins can be visualized in hepatic veno-occlusive disease, whereas narrowing of the intrahepatic portal vein may be seen with a delayed circulation time.

### Pitfalls and Limitations

General contraindications to MR imaging also apply to 3D CE MR portography, which has several other limitations. First, there is a risk of allergic reactions to contrast media, although the incidence is low. Second, this technique is unable to demonstrate the flow direction of the portal venous system, unlike phase-contrast or time-of-flight MR angiography [27, 28]. Third, important portosystemic collateral vessels may be overlooked when they are too anterior or posterior to the imaging slab or when the slab is positioned inappropriately. Fourth, if the interval between injection of Gd-based contrast agent and the start of imaging is too prolonged, the arteries and portal vein may not be differentiated. Fifth, artifacts from respiratory motion and peristaltic bowel movement degrade image quality, especially in debilitated patients who are unable to hold their breath for 12–24 seconds. Sixth, when subtraction techniques are used, respiratory misregistration also degrades image quality.

### Clip and Stent Artifacts

Metal clips used for cholecystectomy as well as wallstents (used in TIPS) can cause susceptibility artifacts which may hamper visualization of the portal vein and IVC. These artifacts can be minimized by using the shortest possible echo time. Newer stents made of non-magnetic material such as nitinol or platinum cause less artifacts.

### Blurring

Many patients have limited breath-holding capabilities; therefore it might be difficult for those patients to suspend breathing twice in a row to image both the arterial and portal venous phase. Thus, it
is crucial to minimize the examination time and to stress the importance of breath-holding to the patient. Oxygen, 2 liters by nasal connulae, can help.

**Accuracy of MR Portography in the Literature**

The value of MRA as a non-invasive imaging modality has been increasingly recognized for the assessment of the portal venous system. Time-of-flight (TOF) and phase contrast (PC) MR methods have been shown to be promising for the assessment of the portal venous system. Disadvantages include motion artifacts due to breathing, long acquisition times and incomplete coverage of the entire portal venous system [29].

3D CE MR portography accurately detects portal vein thrombosis (Table 2). Kreft et al. [30] reported that relevant thromboses of the portal venous system were identified in correlation to catheter arteriographic correlation in 32 of 36 patients with portal hypertension. In 4 patients there were discordant findings between 3D CE MR portography and DSA [30]. Further studies have confirmed the role of 3D CE MR portography in detection of thrombosis in the portal venous system and imaging collateral pathways [31].

The analysis of the portal venous system can be complemented by analyzing the flow characteristics with PC-MRA-techniques. The measurement accuracy of PC flow mapping with regard to quantification of portal venous flow is well documented [32]. MR portography in combination with ultrasound examination is a very useful tool in the diagnosis of Budd Chiari syndrome [33]. In addition 3D CE MRA accurately depicts vascular anastomoses after liver transplantation [34].

Okumura et al [1] used contrast-enhanced 3D MR portography and DSA to assess the portal venous system and determine surgical resectability in 20 patients with pancreatobiliary tumors (pancreatic cancer in 13, bile duct cancer in two, carcinoma of the papilla of Vater in two, gallbladder cancer in two, and duodenal tumor in one). These patients were being considered as candidates for surgical resection. Of the 20 patients, 16 underwent surgical exploration, whereas four did not because their tumors were deemed unresectable at CT, DSA, and 3D CE MR portography. Twelve tumors were surgically resected. Results of 3D CE MR portography and DSA agreed in 14 of 16 patients (88%). 3D CE MR portography allowed identification of 11 of 12 resectable tumors and three of four unresectable tumors with one false-negative and one false-positive reading. DSA allowed identification of all 12 resectable tumors and two of four unresectable tumors with two false-negative readings. The accuracy of 3D CE MR portography was therefore the same as that of DSA.

**Conclusion**

MR angiography of the portal venous system has evolved from a research tool to a quick and robust clinical diagnostic modality and is in many centers the technique of choice for evaluating the anatomy of the portal venous system and its pathologic conditions, such as portosystemic shunt, portal vein thrombosis, portal vein invasion by hepatic and pancreatobiliary tumors, portal vein aneurysm, and hepatic vein obstruction. Evolving indications include the assessment of liver transplant patients before and after transplantation and of living related liver transplant donors.

**References**