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ABDOMINAL IMAGING

TECHNICAL NOTE

Post-contrast abdominal magnetic resonance imaging of critically ill patients using compressed sensing free-breathing golden radial angle imaging

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ABSTRACT

Obtaining diagnostic-quality magnetic resonance imaging (MRI) of the abdomen in critically ill patients can be difficult due to challenges with breath-holding and the inability to follow technologist instructions. Protocols that harness advances in commercially available MRI techniques provide a potential solution, particularly using the golden radial angle sparse parallel (GRASP) technique for dynamic post-contrast T1-weighted imaging. The GRASP technique uses a combination of free-breathing, a stack-of-stars radial acquisition, and compressed sensing reconstruction acquired over several minutes to produce motion-free images at time points defined by the user; these include the non-contrast, arterial, venous, and delayed images, which are typical of abdominal MRI protocols. The three cases discussed herein illustrate the use of this technique in providing both exquisite image quality and diagnostic value in the care of critically ill patients with hepatopancreaticobiliary diseases. Our work aims to raise awareness of this technique and its utility in imaging patients who cannot hold their breath for dynamic T1-weighted post-contrast imaging.

KEYWORDS

Aneurysm, biliary tract, free-breathing, intensive care unit, MRI, pancreatitis

Abdominal magnetic resonance imaging (MRI) of critically ill patients is often challenging. Altered mental status and respiratory failure requiring mechanical ventilation strongly increase the likelihood of motion artifacts and non-diagnostic imaging, often related to the inability to follow commands for adequate breath-holding.

Technical advances in commercially available MRI techniques offer a potential solution for obtaining diagnostic dynamic contrast-enhanced T1-weighted images in critically ill patients. The golden radial angle sparse parallel (GRASP) technique is ideally suited for imaging these patients.[1-3] In a study of non-cooperative patients undergoing liver MRI, 65.6%–80.5% of studies using GRASP for free-breathing imaging produced acceptable image quality, compared with 31.1% of patients using breath-holding imaging.[2]

The GRASP technique combines a 3D radial stack-of-stars *k*-space trajectory and compressed sensing for the free-breath acquisition of contrast-enhanced T1-weighted 3D MRI. Imaging takes place over several minutes, during which time data are continuously acquired in a semi-random, undersampled fashion. A sparsity transformation alters the *k*-space data such that most of the information is contained within only a few data points. A non-linear iterative reconstruction method is then used to reconstruct denoised images. The retrospectively self-gated reconstruction of radially acquired *k*-space data reduces motion artifact, and the use of the compressed sensing technique allows for high-quality reconstructions despite data undersampling. The golden angle offset of radially acquired spokes gives the user flexibility in defining the temporal resolution of reconstructed time points. In patients with renal failure and suspected bleeding, avoiding the additional iodinated contrast load from computed

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tomography (CT) angiography makes MRI an attractive alternative. Combining this technique with other motion-resistant sequences to create an MRI protocol tailored to the breathing patient provides a comprehensive abdominal evaluation.

This paper describes this technique as part of a moving patient protocol used in critically ill patients to obtain diagnostic-quality MRI free of respiratory motion artifact.

Technique

We employed the GRASP dynamic MRI sequence as part of a "moving patient" protocol, either selected by the radiologist prospectively at the time of protocolling a case when motion is anticipated or used by the technologist when motion or inability to actively participate in the exam is discovered at the time of performing the MRI. In addition to GRASP, this protocol also used respiratory-navigated free-breathing single-shot T2-weighted fast-spin echo, free-breathing radial stack-of-stars 3D gradient echo chemical shift, respiratory-navigated free-breathing radial T2 fat-suppressed fast-spin echo, free-breathing diffusion-weighted imaging (*B* values of 50, 400, and 800 s/mm^2), and free-breathing compressed-sensing 3D heavily T2-weighted magnetic resonance cholangiopancreatography (MRCP) sequences (Table 1).

The implementation of the GRASP sequence acquired data over 3 minutes of free-breathing, with the reconstruction of a non-contrast phase, three arterial phases, a portal venous phase (approximately 60–70 seconds post-injection), and a 3-minute delay. Automated subtraction images using the non-contrast phase as a mask were generated for each post-contrast time point.

Main points

- Critically ill patients are frequently unable to hold their breath for abdominal magnetic resonance imaging (MRI), potentially limiting the diagnostic value of breath-hold post-contrast dynamic imaging.
- Compressed sensing golden radial angle sparse parallel MRI offers the ability to obtain diagnostic-quality dynamic post-contrast imaging in such patients.
- This technique ideally supplements comprehensive abdominal MRI protocols but requires awareness on the part of the radiologist/technologist for appropriate incorporation, and specialized MRI scanner hardware to perform computationally intensive reconstructions for image acquisition.

The sequence output also included a "static" sequence, which used every spoke from the minutes-long radial acquisition to reconstruct higher signal-to-noise non-dynamic images.

No informed consent was required for the use of this commercially available MRI technique.

Case 1

Patient 1 was a 76-year-old man with stage 4 chronic kidney disease who underwent orthotopic liver transplantation 14 years prior for alcoholic cirrhosis. He initially presented for excision of his squamous cell skin cancer but was found with elevations in liver chemistries [aspartate aminotransferase 137 U/L (normal 10–50 U/L), alanine aminotransferase 340 U/L (normal 7–55 U/L), alkaline phosphatase 335 U/L (normal 40–130 U/L), total bilirubin 1.2 mg/dL (normal 0.1–1.2 mg/dL)]. Staging positron emission tomography with 2-deoxy-2-[fluorine-18] fluoro-D-glucose integrated with CT (not shown) identified incidental biliary dilation and choledocholithiasis associated with the transplanted liver. MRI/MRCP confirmed extensive common bile duct and common hepatic duct stones of up to 5.8 cm diameter, involving the confluence of the right and left ducts and extending 2.6 cm into the right posterior duct (Figure 1a, b). Endoscopic retrograde cholangiopancreatography was performed (Figure 1c); however, due to the extensive nature of the stone and intrahepatic extension, clearance could not be achieved, and a plastic biliary pigtail stent was placed into the right hepatic duct.

The patient returned 14 weeks later with hematemesis, endoscopic findings of hemobilia, and hemorrhagic shock requiring mechanical ventilation, vasopressor support, and blood transfusion. Imaging was required to guide clinical management but was limited by the patient's poor renal function [estimated glomerular filtration rate (eGFR) of 17 mL/min/1.73 m^2] and a desire to avoid iodinated contrast. Imaging was also limited by an inability to follow instructions for the exam due to shock and intubation. Hemobilia was thought to be related to a potential pseudoaneurysm, which can be associated with endoscopic procedural manipulation and biliary stone disease, although rare.[4-6]

Given the patient's clinical status and inability to hold his breath for conventional liver MRI, contrast-enhanced MRI was performed with gadoterate meglumine (Dotarem, Guerbet, Princeton, NJ) using the GRASP technique. Dynamic enhancement showed a 4 mm right hepatic artery pseudoaneurysm (Figure 1d, Video 1), caused by a combination of extensive choledocholithiasis and chronic biliary stenting, as the source of hemobilia. This was subsequently identified with cone-beam CT at catheter angiography and treated with coil embolization, resulting in the cessation of bleeding. The patient's hospital course was complicated by bacteremia and cholangitis. He ultimately expired 6 months later.

Case 2

Patient 2 was a 35-year-old man who sustained a gunshot wound to the abdomen requiring emergent operative intervention for a bleeding liver laceration and subsequent management in the intensive care unit (ICU) with mechanical ventilation. The bullet fragment was retained within the T12 spinal canal, resulting in paraplegia. A bile leak protocol MRCP with the hepatobiliary contrast agent gadoxetate disodium (Eovist, Bayer, Whippany, NJ) was requested to assess for bile leak and vascular injury. A thorough safety review determined that the bullet was likely ferromagnetic,[7] but given the suspected injury, the patient's documented paraplegia, and the potential need for hemihepatectomy, the benefits were deemed to outweigh the risks, and the decision was made to proceed with MRI. Gadoxetate was administered in the ICU before the patient was transported to the MRI department to minimize his duration outside of the ICU. Dynamic contrast-enhanced MRI was performed after administration of gadoterate meglumine using the GRASP technique, revealing a ballistic injury causing a bile leak from the right posterior duct and thrombosis of the posterior division of the right portal vein (Figure 2). The patient was ultimately managed with biliary stenting and did not require further operative intervention. The patient was discharged 2 weeks later.

Case 3

Patient 3 was a 21-year-old female university student hospitalized with severe acute pancreatitis. She developed new hypoxia requiring supplemental oxygen, fever, and hyponatremia, necessitating transfer to the ICU. The patient underwent MRI at 2 a.m. for evaluation of potential pancreatitis-related complications. The patient could not comply with breath-hold instructions during the exam, which prompted the MRI technologist to use the "moving patient" protocol.

Table 1. "Moving patient" abdominal magnetic resonance imaging protocol						
Sequence name	Slice thickness (mm)	Matrix (pixels)	TR (ms)	TE (ms)	NSA	Notes
T2W single-shot FSE coronal	6	320 × 320	1,000	100	1	Free-breathing respiratory-navigated
T1W 3D spoiled GRE Dixon axial	3	260 × 320	6.68	2.39, 4.77	1	Free-breathing radial acquisition; acquire in-phase and opposed-phase, reconstruct fat-only and water-only Dixon
T2W single-shot FSE axial	4	320 × 320	1,000	100	1	Free-breathing respiratory-navigated
T2W FSE fat-suppressed axial	6	260 × 320	3,000	93	1	Free-breathing respiratory-navigated radial acquisition
DWI single-shot axial	6	256 × 268	9,500	56	2, 4, 10	Free-breathing; obtain *B* values of 50, 400, 800; reconstruct ADC map
T1W 3D spoiled GRE axial GRASP	3	260 × 320	4.3	2.35	1	Compressed sensing free-breathing 3-minute radial acquisition; reconstruct non-contrast, 3 arterial phases, portal venous phase, 3-minute delay, and subtractions for each post-contrast phase
Coronal 3D MRCP	1	288 × 384	5,520	701	2	Compressed sensing free-breathing respiratory-navigated

TR, repetition time; TE, echo time; NSA, number of signal averages; T1W, T1-weighted; T2W, T2-weighted; 3D, three-dimensional; GRE, gradient-recalled echo; FSE, fast spin echo; DWI, diffusion-weighted imaging; GRASP, golden radial angle sparse parallel; MRCP, magnetic resonance cholangiopancreatography; ADC, apparent diffusion coefficient.

Figure 1. Seventy six-year-old man with right hepatic artery pseudoaneurysm related to choledocholithiasis and biliary stent placement. **(a)** Axial T2 single-shot fast-spin echo magnetic resonance imaging (MRI) shows a large volume of choledocholithiasis (arrow) filling the right hepatic duct. **(b)** Axial T1-weighted fat-suppressed 3D spoiled gradient echo MRI shows the extent of T1 hyperintense stone burden within the right hepatic ductal system (arrow). **(c)** Endoscopic retrograde cholangiopancreatography performed after the MRI shows a large volume of stone disease (arrows), which could not be adequately cleared and was managed with the placement of a plastic stent into the right hepatic duct. **(d)** T1-weighted fat-suppressed 3D gradient echo arterial phase MRI obtained during free-breathing using a compressed-sensing golden radial angle sparse parallel technique shows a right hepatic artery pseudoaneurysm (arrow) adjacent to a large T1 hyperintense right hepatic duct stone (arrowhead). Despite the patient freely breathing, there is no motion artifact, enabling detection of the subtle abnormality.

GRASP MRI revealed non-enhancement of the distal body and proximal tail of the pancreas, indicating acute necrosis (Figure 3). The patient subsequently developed walled-off necrosis secondary to a disconnected duct in the pancreatic tail that was managed with cystogastrostomy drainage.

Discussion

The aforementioned cases illustrate the value of the GRASP technique for problem-solving in complex clinical situations that can arise in hospitalized patients.[2]

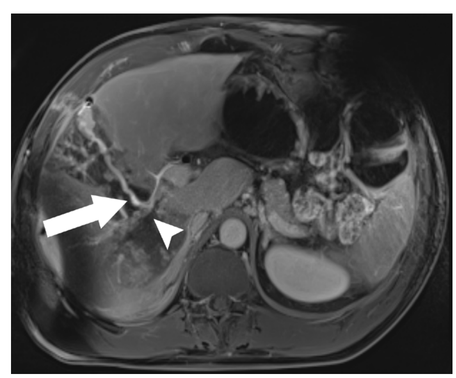

Figure 2. Thirty five-year-old man with ballistic liver injuries from a gunshot wound. Axial T1-weighted fat-suppressed 3D gradient echo arterial phase magnetic resonance imaging obtained during free-breathing using a compressed-sensing golden radial angle sparse parallel technique shows a large bile leak from the right hepatic duct (arrow) and traumatic occlusion of the posterior division of the right portal vein (arrowhead) in close proximity. Despite the patient freely breathing, there is no motion artifact, enabling clear delineation of these abnormalities.

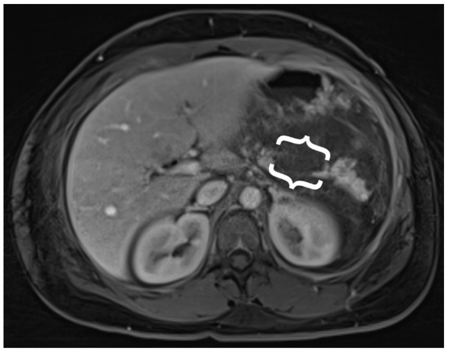

Figure 3. Twenty one-year-old woman with severe pancreatitis. Axial T1-weighted fat-suppressed 3D gradient echo arterial phase magnetic resonance imaging obtained during free-breathing using a compressed-sensing golden radial angle sparse parallel technique shows non-enhancement of the distal pancreatic body and proximal tail, consistent with necrotizing pancreatitis (brackets). Despite the patient freely breathing, there is no motion artifact, enabling clear delineation of the margin of necrosis.

For patient 1, a CT angiography would normally be the first-line diagnostic imaging test for a patient with this clinical scenario; however, the patient's chronic kidney disease and the expected need for additional iodinated contrast for catheter angiography led to MRI, which secured the diagnosis. Although patients with chronic kidney disease are at increased risk of nephrogenic systemic fibrosis (NSF), this patient had an eGFR >15 mL/min/1.73 m^2, meeting institutional criteria for administration of a macrocyclic ionic extracellular gadolinium contrast agent (gadoterate meglumine in this example), with benefits outweighing the low risk of NSF.[8] Breath-holding and timing normally pose a challenge in the MRI of critically ill ventilated patients. Arterial phase-timing and lack of respiratory motion are critical for distinguishing a dynamic contrast-enhanced hepatic pseudoaneurysm from adjacent tissues with similar enhancement. If a longer, non-dynamic, free-breathing radial acquisition had been performed without the compressed sensing technique, the high temporal resolution would not have been achievable. The potential streak artifact on CT from the adjoining, indwelling biliary stent was also avoided with MRI.

Patient 2 presented a complex challenge as he required mechanical ventilation and carried the additional risk of a ferromagnetic bullet near the spine. A moving patient protocol using GRASP MRI is ideally suited for imaging such a patient and maximizing the likelihood of obtaining diagnostic-quality imaging, a key factor to consider when weighing the risk of MRI causing further injury, as GRASP may prevent the need for re-imaging.

Patient 3 proved the value of GRASP MRI in imaging critically ill patients when the technologist is faced with a dyspneic patient. The rate of non-diagnostic abdominal MRI performed overnight can be reduced by the judicious application of moving patient protocols utilizing the GRASP technique, as in this case.

Although GRASP has been available for several years, the radiologist and/or technologist must know that this technique exists and can be used either routinely or for problem-solving, as we did in the provided cases. The GRASP technique also requires a high-end computing platform to perform complex imaging reconstruction. GRASP packages are available as an additional expense at the time of scanner purchase or as an upgrade. Limitations of the GRASP technique include radial "streak" artifacts and the inability to currently match the overall image quality of a good breath-hold standard acquisition, which is why we do not use this technique on every examination. In our anecdotal experience as a high-volume center for quaternary hepatopancreaticobiliary clinical referrals, we observe that this technique is underutilized in patients who present for second-opinion MRI consultation with outside imaging.

In conclusion, a moving-patient abdominal MRI protocol utilizing the GRASP technique for dynamic post-contrast imaging can provide value in the imaging and management of critically ill patients.

Conflict of interest disclosure

The authors declared no conflicts of interest.

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Video 1 link: https://youtu.be/1pW7nzD11U8

Video 1. Seventy six-year-old man with right hepatic artery pseudoaneurysm related to choledocholithiasis and biliary stent placement. T1-weighted fat-suppressed 3D gradient echo arterial phase magnetic resonance imaging obtained during free-breathing using a compressed-sensing golden radial angle sparse parallel technique shows a pseudoaneurysm (arrowhead) arising from the right hepatic artery (arrow) adjacent to a large T1 hyperintense right hepatic duct stone. Despite the patient freely breathing, there is no motion artifact, enabling detection of the subtle abnormality.