RadioGraphics

Dual Gradient-Echo In-Phase and Opposed-Phase Hepatic MR Imaging: A Useful Tool for Evaluating More Than Fatty Infiltration or Fatty Sparing[1]

Elmar M. Merkle, MD • Rendon C. Nelson, MD

TEACHING POINTS
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A T1-weighted gradient-echo in-phase and opposed-phase sequence has become a routine part of every hepatic magnetic resonance (MR) imaging protocol. Although this sequence is primarily used to identify common pathologic conditions, such as diffuse or focal steatosis and focal fatty sparing, it is also helpful in detection of pathologic entities associated with T2* effects owing to the double-echo approach. Thus, pathologic conditions such as hemochromatosis or hemosiderosis can be identified and characterized with a high level of confidence. In cases of iron storage disease, the hepatic parenchymal signal intensity decreases on the image with the longer echo time due to the continued decay of the transverse magnetization. In addition, susceptibility artifacts can be easily detected and characterized with in-phase and opposed-phase MR imaging. Metallic objects demonstrate a larger susceptibility artifact on the image with the second or longer echo time, which is usually the in-phase image. Finally, intrahepatic pneumobilia can be identified with the T1-weighted gradient-echo in-phase and opposed-phase sequence because gas also causes a susceptibility artifact, which is more pronounced on the image with the longer echo time. A complete understanding of both the chemical shift cancellation artifact and the T2* effects of the in-phase and opposed-phase sequence is important for correct interpretation of hepatic MR images.

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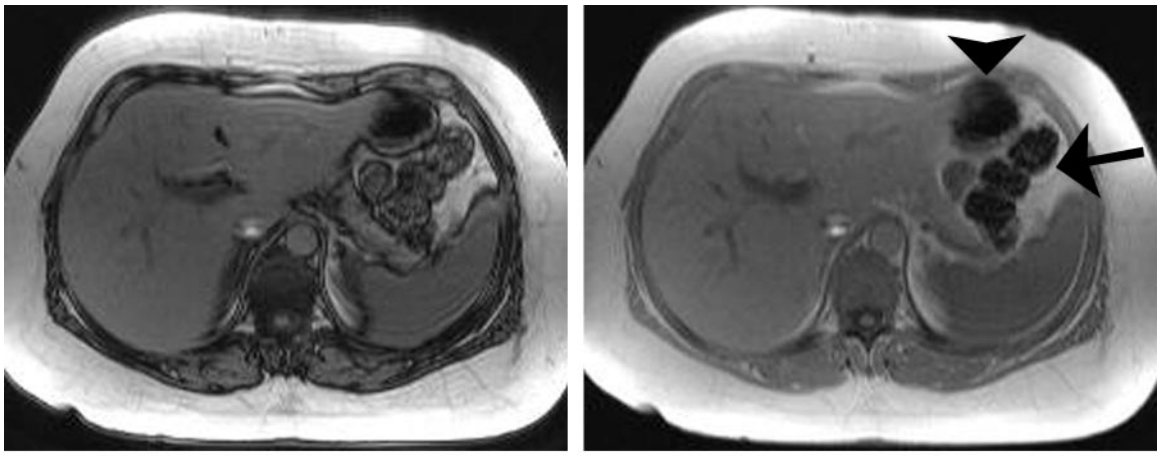
[1]From the Department of Radiology, Duke University Medical Center, Duke North, Room 1417, Erwin Rd, Durham, NC 27710. Received May 6, 2005; revision requested July 25 and received August 15; accepted August 15. All authors have no financial relationships to disclose. **Address correspondence to** E.M.M. (e-mail: *elmar.merkle@duke.edu*).



a. b.

Figure 1. Normal appearance of the liver at opposed-phase and in-phase hepatic MR imaging in a healthy volunteer. **(a)** Axial opposed-phase MR image shows a sharply defined black rim around organs with a fat-water interface. Note the drop in signal intensity in the vertebra (compared with that on the in-phase image) due to fatty bone marrow. However, there is no drop in signal intensity in the liver or subcutaneous tissue. **(b)** Axial in-phase MR image shows increased susceptibility artifacts (compared with those on the opposed-phase image) in the gas-filled splenic flexure (arrow) and stomach (arrowhead) due to the longer echo time.

Introduction

Soon after its introduction to clinical magnetic resonance (MR) imaging in the late 1980s, a gradient-echo in- and opposed-phase sequence has become a routine part of every liver MR imaging protocol (1–4). This sequence is primarily used to detect and characterize focal as well as diffuse steatosis of the liver by using the chemical shift cancellation artifact (also known as fat-water cancellation artifact, black lining artifact, or India ink artifact). Opposed-phase images demonstrate a sharply defined black rim around organs with a fat-water interface. Since this is a phase-cancellation effect, it is not limited to the frequency-encoding direction such as the classic chemical shift artifact, but may be seen in all pixels along the fat-water interface (Fig 1). In the past, the in-phase and the opposed-phase images were acquired within separate breath holds, which caused suboptimal registration between the corresponding in-phase and opposed-phase images. This problem has been solved, and nowadays both the in-phase and opposed-phase images are acquired within the same breath hold, allowing perfect registration between corresponding images (5–7).

Teaching Point

Besides the detection and characterization of focal steatosis and sparing, a gradient-echo in- and opposed-phase sequence is also very helpful in the visualization of T2* effects and susceptibility artifacts owing to the double-echo approach. In 3-T imaging, the echo time for in-phase and opposed-phase images needs to be adjusted because the frequency difference is twice as large as in standard 1.5-T imaging.

Hepatic Steatosis: Detection and Characterization by Using the Chemical Shift Cancellation Artifact

Owing to the symmetric 180° refocusing pulse in conventional spin-echo or fast spin-echo imaging, water and fat protons are always in phase at the

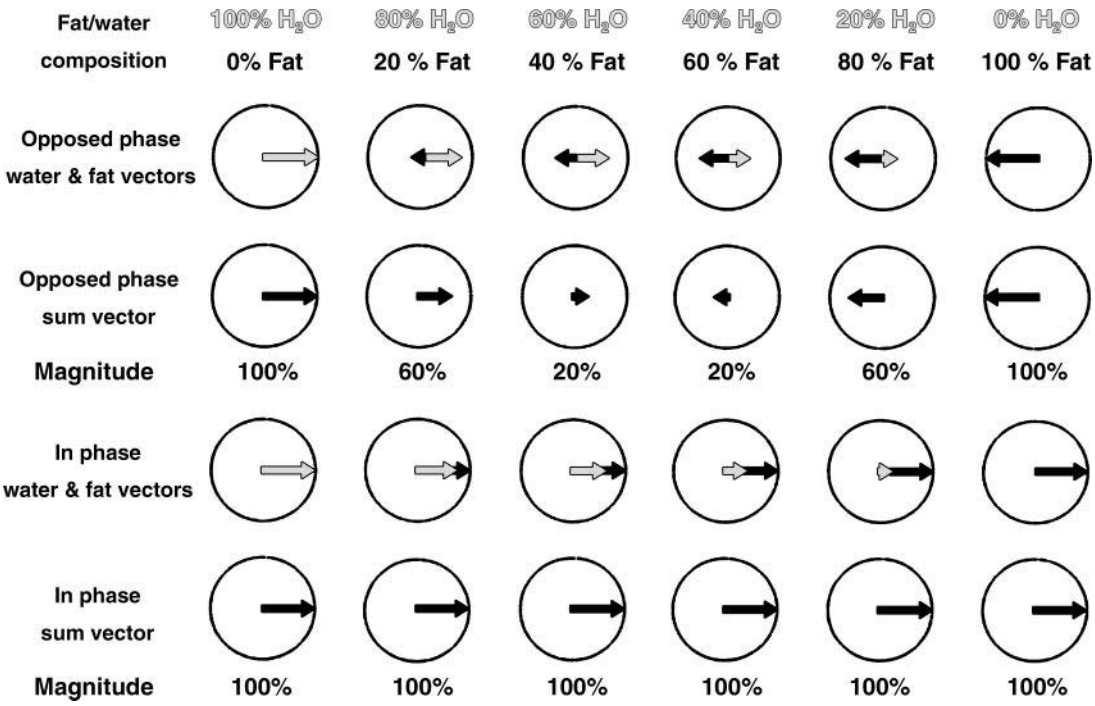


Figure 2. Underlying physics of in-phase and opposed-phase imaging. The signal intensity seen on opposed-phase images reflects the magnitude of the magnetic vector but not its phase (ie, direction). For this reason, tissue that consists of mostly fat protons (eg, subcutaneous fat) shows only little or no obvious drop in signal intensity. Furthermore, voxels with 50% fat signal and 50% water signal have a signal intensity of zero on opposed-phase images.

time the echo is collected. In a gradient-echo sequence, however, water and fat protons resonate in phase and out of phase with one another as a function of echo time and magnetic field strength. With a 1.5-T MR system, both fat and water protons are in phase at approximately 4.5 msec, 9.0 msec, 13.4 msec, and so on and out of phase (also referred to as opposed phase) at approximately 2.2 msec, 6.7 msec, 11.2 msec, and so on. While this sequence is frequently used to detect and characterize focal or diffuse steatosis of the liver, it should not be mistaken for a fat-suppressed sequence, as subcutaneous fat remains hyperintense on opposed-phase images.

Teaching Point

The signal intensity seen on opposed-phase images simply reflects the magnitude of the magnetic vector, but not its phase (ie, direction) (Fig 2). Thus, the displayed intensity is the absolute value of the difference between fat and water signals. This is why tissue that consists of mostly fat protons (eg, subcutaneous fat) shows only little or no obvious drop in signal intensity (<10% drop compared with the signal intensity on in-phase images). This also explains why voxels with 50% fat signal and 50% water signal will have a signal intensity of zero on opposed-phase images.

Hepatic steatosis is a common occurrence caused by accumulation of triglycerides within the cytoplasm of hepatocytes. While steatosis is most commonly diffuse, with occasional areas of spared parenchyma, focal and lobar or regional areas of steatosis are also encountered. Typical locations

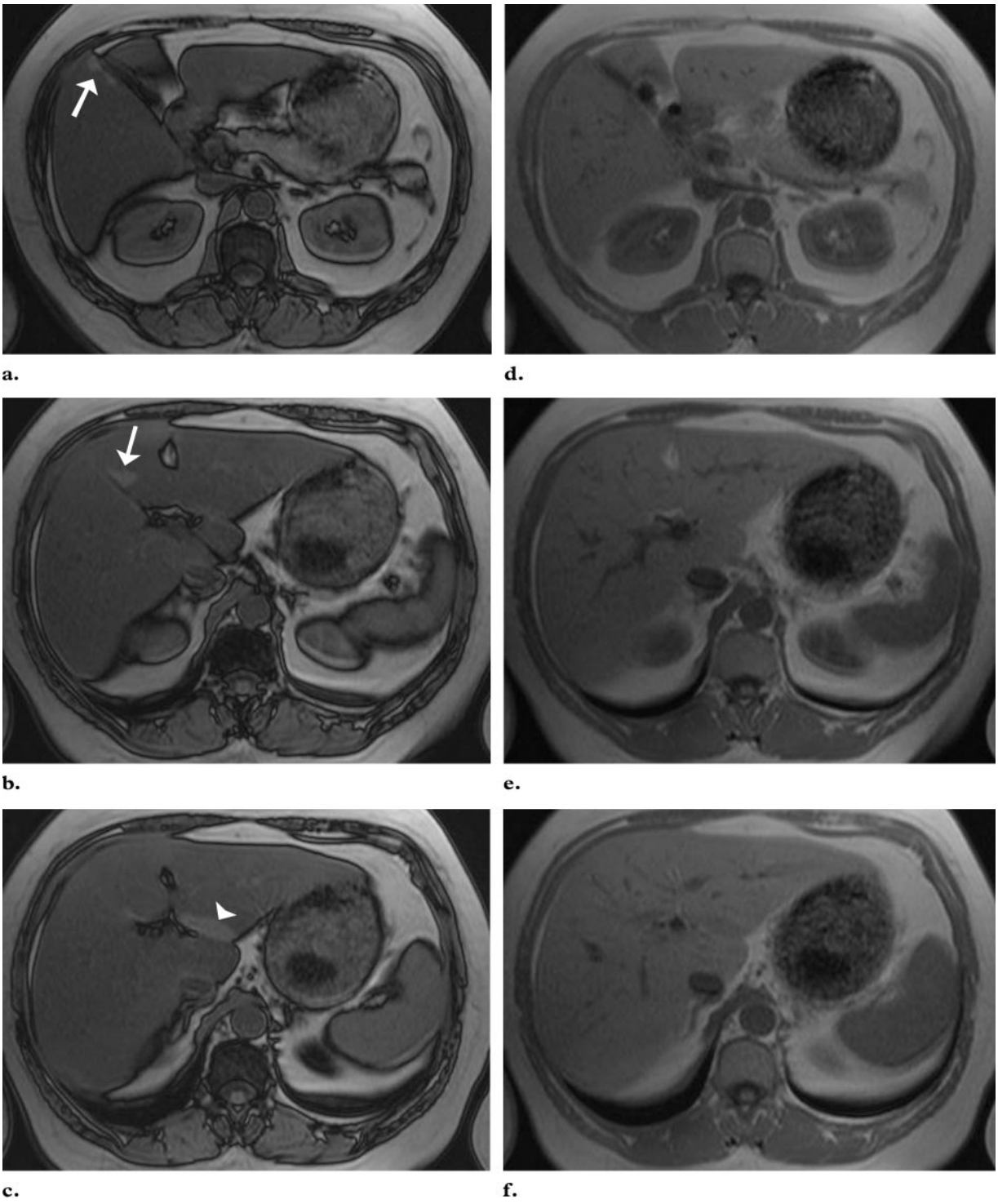
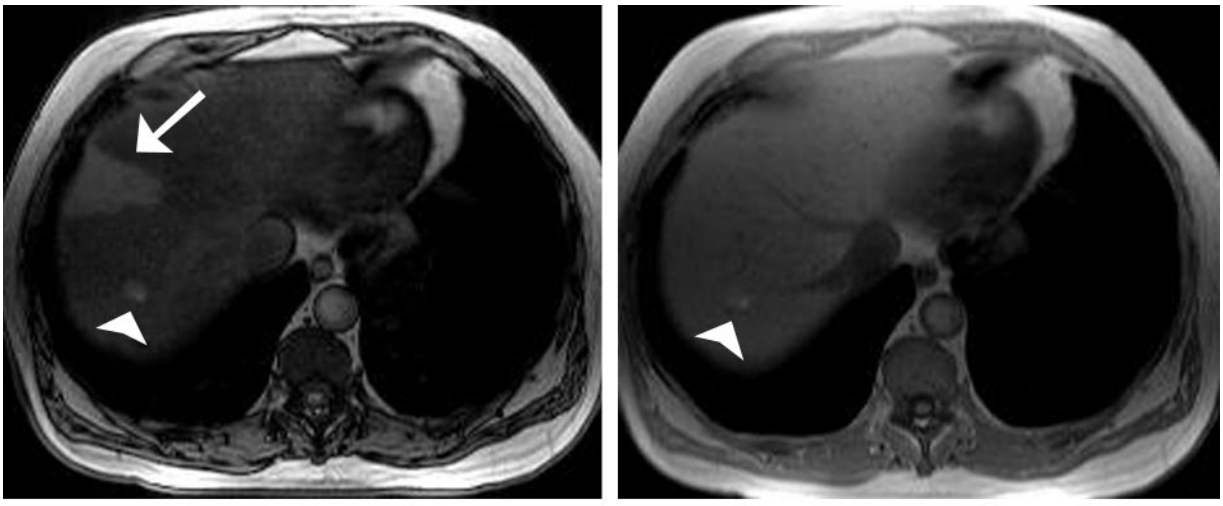


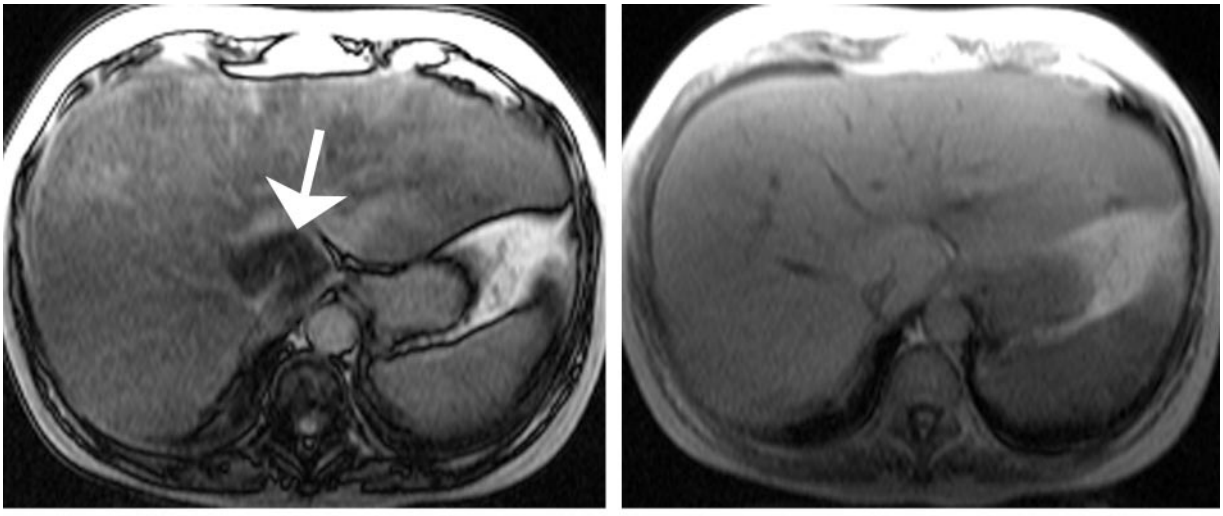
Figure 3. Focal fatty sparing. Opposed-phase **(a–c)** and corresponding in-phase **(d–f)** images show focal fatty sparing next to the gallbladder fossa (arrow in **a** and **b**) and the fissure of the ligamentum venosum (arrowhead in **c**).

for focal steatosis or sparing include anterior to the right portal vein, the gallbladder fossa, adjacent to the fissure of the teres ligament or venous ligament, or in a subcapsular region (Figs 3–6). If the area of focal sparing is wedge shaped, the presence of an underlying tumor near the apex of the focal sparing needs to be ruled out (Fig 4) (8). With focal steatosis or sparing, there should also



a. b.

Figure 4. Focal fatty sparing. Opposed-phase **(a)** and in-phase **(b)** images show wedge-shaped focal fatty sparing in the subcapsular region of segment VIII (arrow in **a**). It is important to rule out an underlying tumor near the apex of the focal sparing. Note the hemorrhagic cyst in segment VII (arrowhead).



a. b.

Figure 5. Diffuse steatosis hepatis with focal intensification. Opposed-phase **(a)** and in-phase **(b)** images show diffuse steatosis hepatis, which is markedly pronounced in the caudate lobe (arrow in **a**).

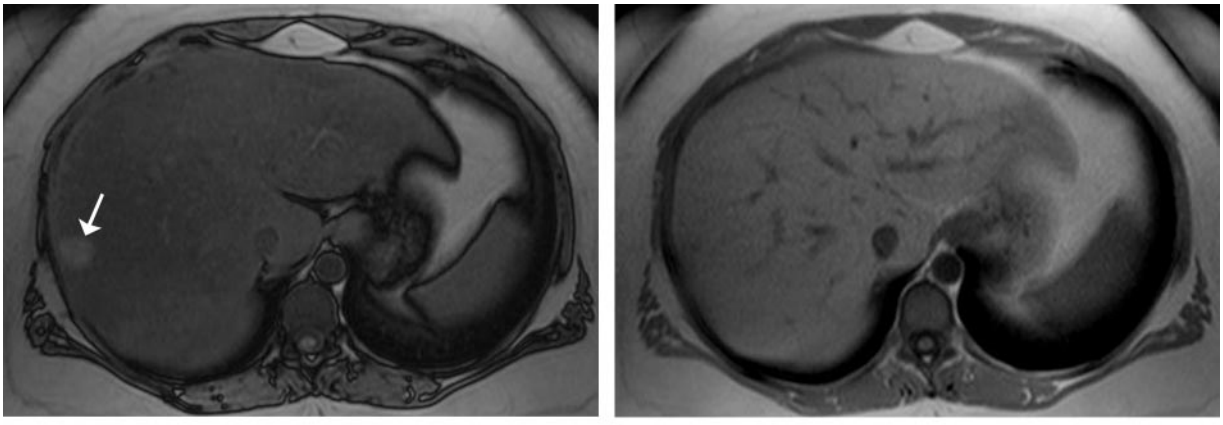


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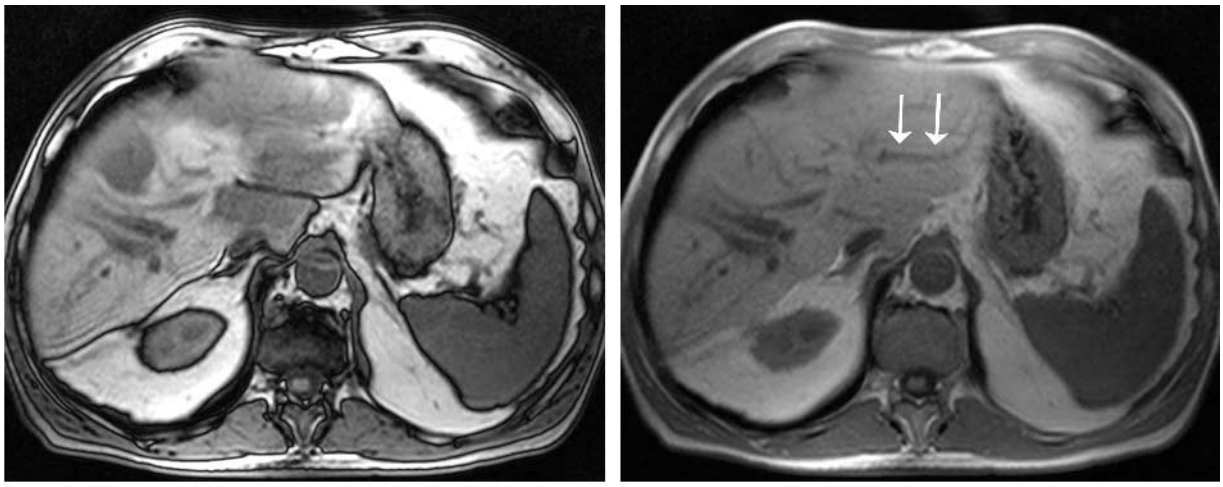
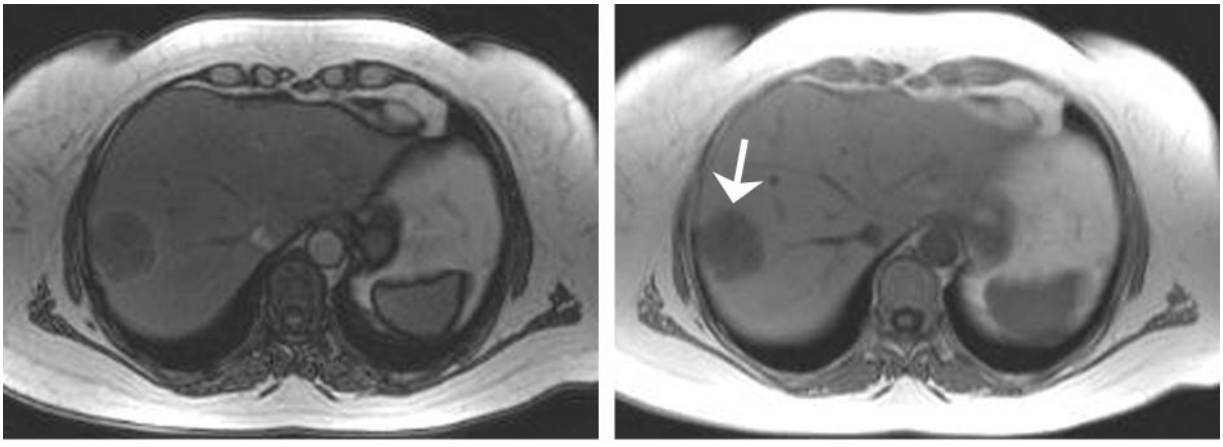
Figure 6. Focal fatty sparing. Opposed-phase **(a)** and in-phase **(b)** images show subcapsular focal fatty sparing, which produces a hepatic pseudotumor (arrow in **a**).



a. b.

Figure 7. Geographic steatosis hepatis. Opposed-phase **(a)** and in-phase **(b)** images show geographic steatosis hepatis. Note that the course of the vessel (arrows in **b**) is unaltered by the steatosis.



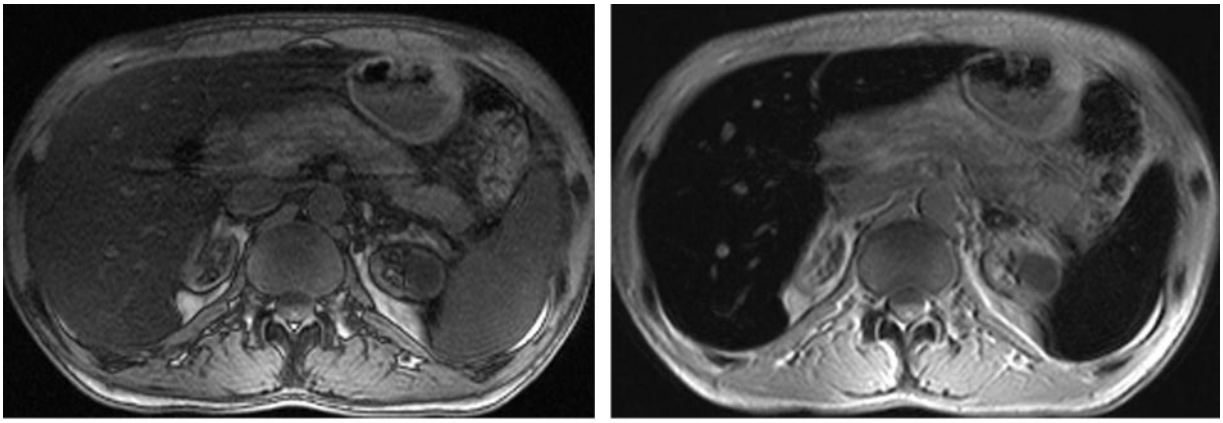
a. b.

Figure 8. Liver metastasis with peritumoral fatty sparing in a patient with breast cancer. Opposed-phase **(a)** and in-phase **(b)** images show a large right-sided subcapsular liver metastasis (arrow in **b**). The opposed-phase image shows a bright peritumoral rim, which represents peritumoral fatty sparing in an otherwise steatotic liver. Note that the peritumoral fatty sparing is not specific for malignant lesions but can also be seen in conjunction with benign masses such as hemangiomas.

be no mass effect on the adjacent parenchyma or displacement of vascular structures (Fig 7).

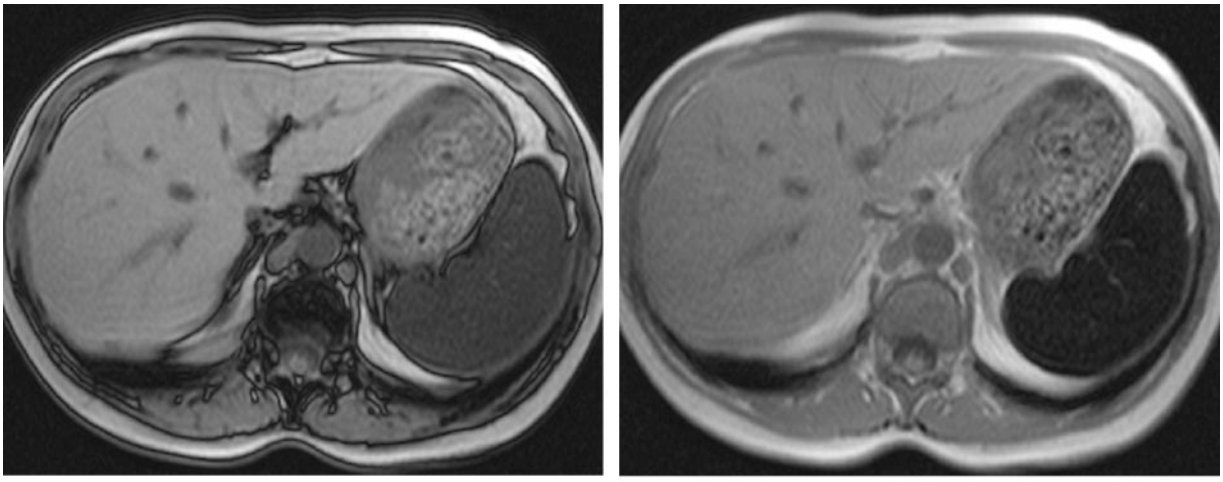
Gradient-echo in- and opposed-phase MR imaging allows reliable detection and characterization of these pseudolesions, which often spares the patient from additional imaging or even a percutaneous biopsy. In addition, gradient-echo in- and opposed-phase MR imaging is also very helpful in the detection of peritumoral fat sparing in patients with steatosis hepatis. This rim can be seen around benign hepatic masses such as hemangiomas as well as primary and secondary hepatic malignancies (Fig 8) (9,10).

Finally, the characterization of primary focal liver lesions such as hepatocellular carcinoma and adenoma can be improved by using the chemical shift cancellation artifact (11–14). These lesions may contain fat and water within the same voxel, which can be detected reliably with gradient-echo in- and opposed-phase MR imaging. Analysis of



a. b.

Figure 9. Transfusional hemosiderosis. Opposed-phase (echo time of 1.5 msec) **(a)** and in-phase (echo time of 4.9 msec) **(b)** images, obtained with an ultrahigh-field-strength 3-T MR system, show a marked drop in signal intensity in the liver (from 65 to 8 [arbitrary units]) and spleen (from 126 to 13) on the image with the longer echo time **(b)**. Iron storage causes significant local distortion of the nearby magnetic field, resulting in significant shortening of T2*.



a. b.

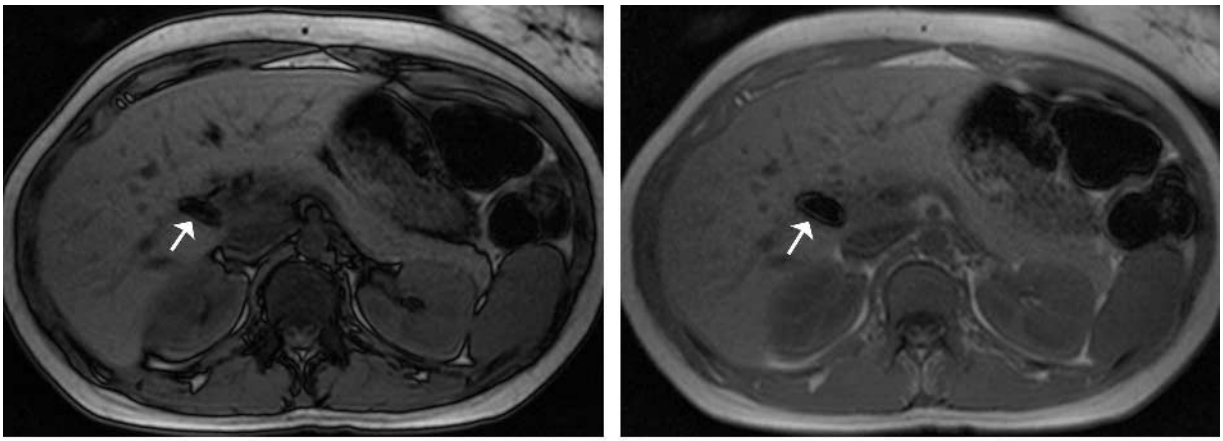
Figure 10. Transfusional hemosiderosis. Opposed-phase **(a)** and in-phase **(b)** images obtained with a high-field-strength 1.5-T MR system show iron deposition in the spleen and liver. The iron deposition is much more severe in the spleen; as a result, the drop in signal intensity on the image with the longer echo time **(b)** is much more pronounced in the spleen than in the liver.

the enhancement pattern following intravenous administration of gadolinium-containing contrast agents allows reliable differentiation of these hypervascular lesions from focal steatosis hepatis, which shows an enhancement pattern equivalent to that of normal liver.

Pronounced T2* Effects on Images with Longer Echo Times

Besides the visualization of focal steatosis hepatis or sparing, a dual gradient-echo technique is also very helpful in the visualization of T2* effects and susceptibility artifacts. This sequence allows pathologic conditions, such as hemochromatosis or hemosiderosis, to be easily detected and characterized with a high level of confidence (Figs 9, 10). In cases of iron storage disease, the hepatic parenchymal signal intensity decreases on the image with the longer echo time due to the continued decay of the transverse magnetization. It needs to be mentioned here that the drop in signal intensity due to T2* effects is opposite to the

Teaching Point



a. b.

Figure 11. Susceptibility artifact from a cholecystectomy surgical clip. Opposed-phase **(a)** and in-phase **(b)** images show a susceptibility artifact caused by a surgical clip (arrow). The artifact is larger on the image with the longer echo time (14 × 27 mm on the in-phase image vs 10 × 22 mm on the opposed-phase image).

drop in signal intensity due to steatosis if the opposed-phase image is acquired at a shorter echo time than the corresponding in-phase image. Thus, the hepatic signal intensity on opposed-phase and in-phase images can theoretically be identical in a patient with simultaneous hepatic steatosis and iron storage disease.

Pronounced Susceptibility Artifacts on Images with Longer Echo Times

Magnetic susceptibility is the extent to which a material becomes magnetized when placed within a magnetic field. Susceptibility artifacts occur as the result of microscopic gradients or variations in the magnetic field strength that occur near the interfaces of materials of different magnetic susceptibility. These artifacts are usually caused by metallic objects from previous surgical or interventional procedures near or in the imaging field of view, since the susceptibility of metal is much higher than that of soft tissue. However, susceptibility artifacts also occur next to gas-filled structures, such as the gas-filled bowel, since the susceptibility of gas is much smaller than that of soft tissue (Fig 1).

Susceptibility artifacts have the following characteristics (15,16): *(a)* They are more pronounced on gradient-echo images than on fast spin-echo images due to lack of the 180° refocusing pulse. *(b)* They increase with echo time on gradient-echo images due to the continued decay of the transverse magnetization. *(c)* They increase with voxel size due to a greater net change in local magnetic field strength across each voxel.

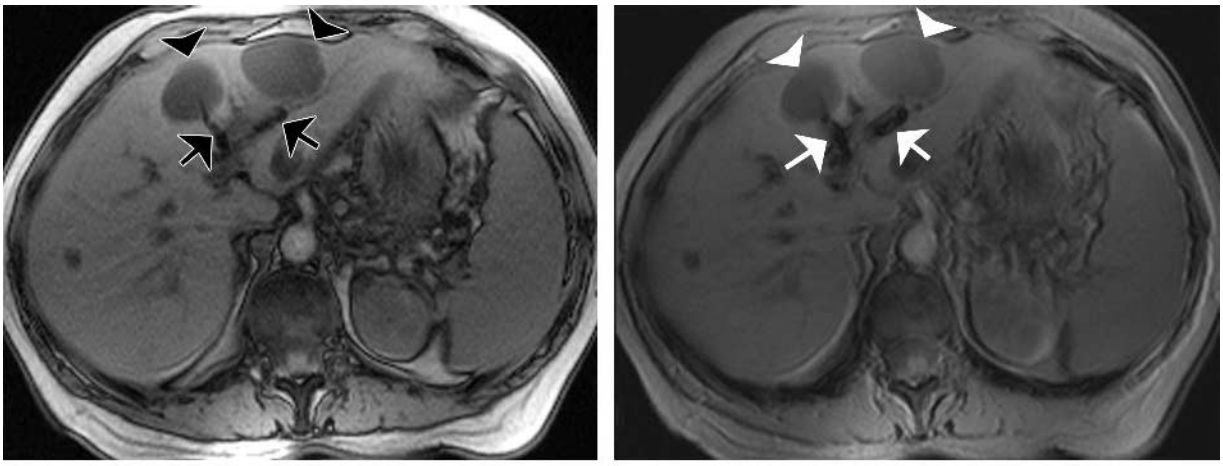
Susceptibility artifacts can be easily detected and characterized with a high level of confidence by using in- and opposed-phase MR imaging. Metallic objects demonstrate a larger susceptibility artifact on the image with the second or longer echo time, which is usually the in-phase image (Fig 11). In addition, this effect may also be helpful in detecting intrahepatic pneumobilia (Fig 12).

Teaching Point

Dual Gradient-Echo Imaging at 3 T

Chemical shift cancellation artifacts are due to a difference in the resonant frequency between water and fat. This difference in resonant frequency is directly proportional to the main magnetic field strength and has been measured to be approximately 3.5 ppm, resulting in a difference of about 225 Hz at 1.5 T or a difference of about 450 Hz at 3.0 T. Thus, the echo time for obtaining in-phase and opposed-phase images needs to be adjusted at 3 T, as the frequency difference is twice as large compared to standard 1.5-T MR systems. At 3 T, fat and water protons are in phase at echo times of 2.2 msec, 4.5 msec, 6.7 msec, and so on and opposed phase at 1.1 msec, 3.4 msec, 5.6 msec, and so on.

While most vendors agree that both echoes (in-phase as well as opposed-phase) should be



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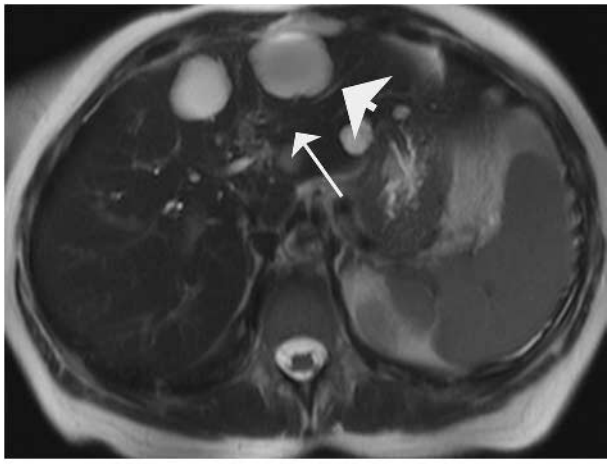

c.

Figure 12. Pneumobilia in a patient who underwent hepaticojejunostomy. **(a, b)** Opposed-phase (echo time of 1.5 msec) **(a)** and in-phase (echo time of 4.9 msec) **(b)** images, obtained with an ultrahigh-field-strength 3-T MR system, show susceptibility artifact caused by pneumobilia in the left hepatic lobe (arrows). The artifact is larger on the image with the longer echo time (7 mm perpendicular to the bile duct on the in-phase image vs 5 mm on the opposed-phase image). Arrowheads = simple hepatic cysts. **(c)** Axial turbo spin-echo T2-weighted image shows a normal peripheral intrahepatic duct (thick arrow). Note that the pneumobilia cannot be seen (thin arrow).

acquired during the same breath hold to avoid misregistration, there is no consensus on which pair of echoes to acquire. Currently, to acquire the first opposed-phase echo at an ultrashort echo time of 1.1 msec and the first in-phase echo only 1.1 msec later at 2.2 msec within the same breath hold (analogous to echo collection on a 1.5-T MR system with echo times of 2.2 msec for opposed-phase and 4.5 msec for in-phase imaging) would require unacceptably high receiver bandwidths. Thus, the second or third in-phase or opposed-phase echo needs to be collected.

Teaching Point

Currently, the in-phase MR signal is collected at an echo time of 2.5 msec (first in-phase signal) on ultrahigh-field-strength MR systems manufactured by GE Healthcare (Waukesha, Wis) and the opposed-phase signal at 5.8 msec (third opposed-phase signal). On the other hand, on 3.0-T MR systems manufactured by Siemens Medical Solutions (Erlangen, Germany), the opposed-phase MR signal is typically collected at an echo time of 1.5 msec (first opposed-phase signal) and the in-phase signal at 4.9 msec (second in-phase signal). While this discrepancy in echo collection schemes between the vendors does not cause significant problems in the detection of hepatic steatosis, it does affect the visualization of T2* effects and susceptibility artifacts. Since the hepatic parenchymal signal intensity will decrease on the image with the longer echo time in cases of hepatic iron storage disease, the liver parenchyma will appear darker on the opposed-phase image obtained with ultrahigh-field-strength MR systems manufactured by GE Healthcare and on the in-phase image obtained with MR systems manufactured by Siemens Medical Solutions.

Overall, susceptibility artifacts as well as T2* effects are more pronounced on 3-T MR images (Figs 9, 12) (17).

Conclusions

In-phase and opposed-phase MR imaging allows reliable detection of focal steatosis hepatis owing to the chemical shift cancellation artifact. Areas of steatosis demonstrate signal loss on opposed-phase images. In addition, T2* effects allow reliable detection of iron storage diseases as well as metal- or gas-related susceptibility artifacts. Areas of iron storage, metallic objects, or gas-filled structures demonstrate pronounced signal loss on the image with the longer echo time.

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Double Gradient-Echo Techniques for Hepatic MR Imaging: Beyond In-Phase and Opposed-Phase Imaging

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