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Breath-held MR Cholangiopancreatography (MRCP) using a 3D Dixon fat–water separated balanced steady state free precession sequence

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Abstract

A novel 3D breath-held Dixon fat–water separated balanced steady state free precession (b-SSFP) sequence for MR cholangiopancreatography (MRCP) is described and its potential clinical utility assessed in a series of patients. The main motivation is to develop a robust breath-held alternative to the respiratory gated 3D Fast Spin Echo (FSE) sequence, the current clinical sequence of choice for MRCP. Respiratory gated acquisitions are susceptible to motion artifacts and blurring in patients with significant diaphragmatic drift, erratic respiratory rhythms or sleep apnea. A two point Dixon fat–water separation scheme was developed which eliminates signal loss arising from B_0 inhomogeneity effects and minimizes artifacts from perturbation of the b-SSFP steady state. Preliminary results from qualitative analysis of 49 patients demonstrate robust performance of the 3D Dixon b-SSFP sequence with diagnostic image quality acquired in a 20–24 s breath-hold.

Keywords

MRCP; Biliary; steady state free precession

1. Introduction

Magnetic resonance cholangiopancreatography (MRCP) involves imaging fluid in the biliary tree while suppressing the background signal from non-fluid structures, and is most commonly performed using respiratory-triggered or navigator-gated three-dimensional (3D) fast spin echo (FSE)-based sequences, supplemented by thin and thick section single-shot fast spin echo acquisitions [1–6]. 3D FSE pulse sequences provide high spatial resolution volumetric images with excellent background suppression which can then be used to generate 3D reconstructions.

Respiratory or navigator gating performs well in subjects who have a steady respiratory rhythm. However, in patients with irregular or shallow respiratory rhythms, respiratory-

gated acquisitions may fail to trigger correctly, prolonging scan times, or may result in images with substantial motion artifact. Several modifications of the standard respiratory-gated 3D FSE MRCP pulse sequence have been proposed, including parallel imaging [7], navigator triggering in place of respiratory triggering [8], navigator gating with prospective acquisition correction (PACE) [9,10], sampling perfection with application optimized contrasts using different flip angle evolutions (SPACE) [11–14], and respiratory compensation using a reference respiration model [15]. These techniques have all resulted in improved image quality and reduced artifact in small series; however, they are not all widely available, and have not succeeded in eliminating motion artifact in all patients. Taylor et al. [16] have demonstrated that longer scan times result in a greater prevalence of diaphragmatic drift, further worsening image quality. In our experience a small but significant percentage of 3D FSE MRCPs are compromised by motion artifacts — we surveyed our last 100 clinically indicated 3D FSE MRCPs and found that approximately 5% were significantly limited by artifact to the extent of possibly compromising the diagnostic ability of the exam, while an additional 20% had mild-moderate artifact which reduced image quality without obviously affecting the diagnosis. While 2D single shot fast spin echo images generally provide diagnostic information in these cases, spatial resolution is compromised and 3D reconstructions of 2D data are of limited value.

Balanced steady state free precession (b-SSFP) pulse sequences have a number of features suggesting their potential utility for MRCP imaging, including short TRs and consequent short acquisition times, high signal-to-noise ratios (SNR), and T_2/T_1 contrast weighting, rendering fluid-containing structures bright. B-SSFP sequences are increasingly employed in standard hepatic MRI protocols, and have seen limited use as accessory techniques for MRCP [2,17,18]. The feasibility of 3D b-SSFP for MRCP has been demonstrated [19] where high spatial resolution images depicting the biliary tree with good SNR and contrast-to-noise ratio (CNR) were obtained in a single breath-hold. Fat suppression could be applied to improve the image quality further, increasing conspicuity of the biliary tree by reducing the background signal and consequently improving the quality of the 3D reconstructions. However, fat suppression in b-SSFP pulse sequences is non-trivial. The use of fat saturation pulses inevitably results in saturation of water signal due to B_0 heterogeneity. Furthermore, the use of intermittent fat suppression pulses to improve scan efficiency causes a perturbation of the SSFP steady state, resulting in ghosting artifacts and necessitating the use of steady-state catalyzing preparation schemes which can further prolong scan times. In areas with poor B_0 and B_1 homogeneity, the quality and degree of fat saturation are compromised.

In this study, we investigated the use of a two-point Dixon fat–water separated 3D b-SSFP sequence for robust fat-suppression as an adjunct to the standard respiratory-gated 3D MRCP acquisition. The elimination of explicit fat saturation pulses makes the technique robust to B_0 and B_1 heterogeneity and also eliminates artifacts resulting from any perturbation of the SSFP steady state. The use of high receiver bandwidths enabled the incorporation of both echoes in a single TR, minimizing the total scan time and permitting coverage of the entire biliary tree in a single breath-hold. Breath-held Dixon 3D b-SSFP acquisitions were obtained in 49 patients scheduled for clinically indicated hepatic or

pancreatic MRI/MRCP and compared with conventional clinical respiratory-triggered 3D FSE acquisitions.

2. Materials and methods

2.1. 3D Dixon b-SSFP Pulse sequence

A dual echo 3D balanced steady-state free precession pulse sequence with a bipolar readout was developed (Fig. 1). The bipolar implementation allowed minimization of TR by optimal placement of opposed-phase and in-phase echoes (1.2/2.4 ms at 3.0 T and 2.4/4.8 ms at 1.5 T). This not only minimizes banding artifacts in b-SSFP but also allows breath-held scans despite the dual echo acquisition. The dual echo acquisition was followed by a robust region-growing based 2-point Dixon fat–water separation technique [20]. The resulting fat suppression was relatively immune to B_0 field inhomogeneities. The elimination of explicit fat saturation pulses minimized any perturbations of the steady state magnetization that often cause banding artifacts in b-SSFP sequences. In order to further reduce the total scan time to a reasonable breath hold (<25 s), Auto-calibrating Reconstruction for Cartesian imaging (ARC), a hybrid-space parallel imaging scheme capable of two-dimensional acceleration was employed. For axial scans, a 1-D acceleration factor of 2–3 was used, while for coronal scans a 2D acceleration of 2.5×2 was used.

2.2. MRI

Patients were scanned on a 1.5 T GE Signa (n = 35) or 3.0 T GE Excite system (n = 14) (GE Healthcare, Waukesha, WI) using an 8-channel torso phased array coil.

Following localizer scans, a respiratory-gated 3D FSE sequence was acquired in the coronal oblique plane with the following parameters: 320×224 in-plane matrix with 60–70 1.2–1.6 mm sections acquired, 30–36 cm FOV, TR 3750 ms, effective TE ~650–900 ms, ETL 80–120, ± 42 kHz receiver bandwidth. Parallel imaging (ARC) was employed with an acceleration factor of 2. The acquisition time depended on the patients' respiratory rate as well as the imaging volume, but generally ranged from 4 to 6 min.

The breath-held 3D Dixon b-SSFP sequence was acquired in an axial oblique plane (n = 33), coronal oblique plane (n = 4), or both (n = 12) with the imaging parameters listed in Table 1.

2.3. Patients

For this HIPAA-compliant and IRB-approved retrospective study, clinical MRI records were searched for MRCP examinations in which both breath-held 3D Dixon b-SSFP and respiratory-triggered FSE acquisitions were obtained. 49 patients had clinically indicated MRCPs performed between 1/16/2010 and 8/17/2010 at 1.5 T or 3.0 T in which both the standard respiratory-triggered 3D FSE sequence and 3D Dixon b-SSFP were acquired.

There were 21 female and 28 male patients ranging in age from 5 to 82 years, with an average age of 52 years. Clinical indications for MRCP included cholangiocarcinoma (13 patients), primary sclerosing cholangitis [11], elevated liver function tests and/or suspected biliary obstruction [9], acute or chronic pancreatitis [6], pancreatic cyst or intraductal papillary mucinous neoplasm (IPMN) [5], and additional indications including choledochal

cyst, gallbladder polyp, metastatic disease, hepatic mass, and abdominal pain in single patients.

2.4. Data analysis

Images were evaluated by a fellowship-trained abdominal radiologist blinded to clinical or surgical results. 3D FSE and 3D Dixon b-SSFP images were assessed separately for each patient in reading sessions separated by 4 weeks to minimize recall bias. Within each reading session, 3D FSE and 3D Dixon b-SSFP images were alternated from patient to patient. In a final session, both sequences for each patient were compared side by side and a preferred sequence was selected.

Images were assessed for overall image quality on a scale of 1 to 5 (1 = uninterpretable; 2 = poor; 3 = fair; 4 = good; 5 = excellent) and the presence of artifacts also on a scale of 1 to 5 (1 = severe artifacts with nondiagnostic images; 2 = major artifacts with significant effect on diagnostic quality; 3 = moderate artifact with mild–moderate limitation of diagnostic interpretation; 4 = minimal artifact not significantly affecting diagnostic interpretation; 5 = no artifacts). Visualization of the common bile duct, intrahepatic biliary ducts, pancreatic duct, and gallbladder was rated on a scale of 1 to 5 (1 = not visualized and uninterpretable; 2 = poor visualization with limited diagnostic value; 3 = partial visualization; 4 = near complete visualization; 5 = complete visualization), with no score provided when these structures were anatomically absent. Visualization of intrahepatic biliary duct branching was also assessed on a scale of 1–4 (1 = visualization of only first order branches (right and left main ducts); 2 = visualization of 2nd order branching; 3 = visualization of 3rd order branching; 4 = visualization of 4th order or higher branches).

Images were assessed on a GE Advantage Windows workstation (GE Healthcare, Waukesha, WI) using 3D Volume Viewer software, which allowed reformatted images of arbitrary thickness to be viewed in any plane as well as maximum intensity projection (MIP) and volume rendered images.

2.5. Statistical analysis

A non-parametric Wilcoxon paired signed rank test was used to compare qualitative 3D Dixon b-SSFP and 3D FSE ordinal image scores, with a p -value < 0.05 denoting a significant difference. A non-parametric Mann–Whitney U test was used to compare qualitative 3D Dixon b-SSFP ordinal image scores from 1.5 T and 3.0 T examinations, with a p -value < 0.05 denoting a significant difference.

3. Results

Both standard respiratory-triggered 3D FSE and breath-held 3D Dixon SSFP images were successfully acquired in all patients, and in all cases were of diagnostic image quality. Diagnosis based on imaging results as well as clinical and pathological information included cholangiocarcinoma (11 patients), primary sclerosing cholangitis [9], acute or chronic pancreatitis [8], pancreatic cyst or IPMN [5], mildly dilated biliary ducts [4], biliary stricture [2], and additional results including choledocholithiasis, choledochal cyst, pancreas divisum, gallbladder polyp in one patient each, with 6 negative exams. No differences in the

diagnosis were noted between reading sessions for the 3D FSE and 3D Dixon b-SSFP sequences.

Results of the qualitative assessment of 3D FSE and 3D Dixon b-SSFP images are shown in Table 2. The standard 3D FSE images provided slightly superior image quality, with small but significant differences in scores for overall image quality, artifacts, visualization of the common duct and intrahepatic ducts, and intrahepatic branching, and no significant difference in the scores for visualization of the pancreatic duct and gallbladder. 3D FSE images were preferred over 3D Dixon b-SSFP images in 29/49 cases.

Examples of typical images from 3D Dixon b-SSFP and 3D FSE acquisitions along with the most frequently encountered artifacts are shown in Figs. 2–6. Fig. 2 shows sub-volume MIP images from both acquisitions in a patient with chronic pancreatitis and a mildly dilated and irregular pancreatic duct. The MIP image from the 3D FSE acquisition was preferred due to its greater detail as well as its superior depiction of the focal narrowing of the duct in the pancreatic neck. Notice also that higher order branching of intrahepatic biliary ducts is appreciated on the 3D FSE image, while faint background signal from intrahepatic portal vein branches can be seen on the 3D Dixon b-SSFP image. Fig. 3 shows sub-volume MIP images from a patient with central cholangiocarcinoma and significant dilatation of peripheral intrahepatic biliary ducts. In this case, the 3D FSE image is degraded by motion artifact resulting from mildly irregular respirations, while the 3D Dixon b-SSFP acquisition shows excellent image quality. Fig. 4 shows volume-rendered reconstructions and single source images from 3D FSE and 3D Dixon b-SSFP acquisitions in a patient with primary sclerosing cholangitis and a dominant central stricture. The image quality of both acquisitions was good, with a slight preference for the 3D FSE acquisition due to its superior volumetric coverage. The small filling defects within the gallbladder and a central right intrahepatic duct are well seen on the 3D Dixon b-SSFP source image. Fig. 5 shows a clear distinction between layering debris or small stones in the gallbladder neck and proximal cystic duct and pneumobilia in the common bile duct on an axial source image from a 3D Dixon b-SSFP acquisition, with relatively poor visualization of the common duct on a corresponding axial reformatted image from the 3D FSE acquisition, likely due to 3.0 T central shading artifact. Prominent banding artifact crossing the gallbladder is also illustrated on a more inferior b-SSFP source image. Fig. 6 shows similar MIP images from 3D Dixon b-SSFP and FSE acquisitions in a patient with primary sclerosing cholangitis. An axial source image from the b-SSFP acquisition illustrates the excellent uniform fat suppression, while a thicker axial MIP image illustrates the relatively high signal frequently encountered in mesenteric, portal, and hepatic veins as well as the inferior vena cava.

The most frequently encountered artifacts in the 3D Dixon b-SSFP images were banding artifacts, usually occurring in the hepatic dome adjacent to the diaphragm as well as adjacent to gas-filled bowel loops, or at the margins of the imaging volume. Signal loss related to susceptibility artifact from adjacent bowel gas or surgical clips was also occasionally problematic. Partial or complete fat–water swaps were seen in individual 3D Dixon b-SSFP images of 11 patients, typically near the lung–liver interface, although these artifacts only rarely affected the diagnostic utility of the acquisition.

Motion blurring was the most frequent artifact seen in the 3D FSE images, and a significant reduction in motion artifact with the breath-held 3D Dixon b-SSFP acquisition was the primary reason this pulse sequence was preferred over the standard acquisition in 16 cases. In two cases performed at 3.0 T prominent shading artifact resulted in significant signal loss on the 3D FSE acquisitions which was less problematic on b-SSFP images, and in two cases superior visualization of the pancreatic duct was noted on SSFP images.

3D reconstructions were more easily performed using the standard 3D FSE images, which had superior background suppression. High signal intensity from vascular structures including the portal veins, splenic veins, hepatic veins, and hepatic arteries was occasionally problematic in generating MIP and volume rendered images from b-SSFP source data. Fat suppression (disregarding fat-water swap errors) was excellent, and therefore high signal intensity from mesenteric or subcutaneous fat was not problematic in generating 3D reconstructions from b-SSFP data.

Scores of overall image quality for 3D Dixon b-SSFP acquisitions performed at 1.5 T and 3.0 T were not significantly different: the average scores were 3.4 and 3.2 respectively, with a p -value of 0.28. There was a small but significant difference in artifact scores: average scores were 3.3 and 2.9 at 1.5 T and 3.0 T, with a p -value of 0.03.

4. Discussion

In this preliminary qualitative study, we have demonstrated the feasibility of a 3D Dixon b-SSFP technique capable of depicting the biliary tree with adequate spatial resolution in a single short (20–24 s) breath-hold. The spatial resolution was slightly lower in comparison to the standard respiratory-triggered 3D FSE acquisition; however, it was adequate to generate useful 3D reconstructions in nearly all patients.

Most clinical MRCP protocols rely primarily on heavily T_2 -weighted 3D FSE pulse sequences acquired with respiratory triggering or navigator gating. Respiratory gating allows high spatial resolution acquisitions, and the long TEs typically employed provide excellent background suppression, which in turn enables relatively straightforward generation of 3D reconstructions. The major limitation of the 3D FSE-based pulse sequences is image blurring related to motion-induced artifact. This can occur in the setting of shallow or irregular respirations, sleep apnea, or prominent diaphragmatic drift. Motion artifact sufficient to degrade the overall image quality is seen in a small but significant percentage of patients in our practice. In these cases, 2D thin and thick section single shot fast spin echo images generally provide diagnostic information; however, high quality 3D reconstructions are not possible.

A breath-held 3D MRCP acquisition could therefore be useful as a supplemental technique in patients whose respiratory-gated images are limited, or as an alternative fast acquisition in patients for whom a full MRCP might not be necessary. The breath-held 3D Dixon b-SSFP acquisition is much faster than the standard respiratory-triggered 3D FSE technique (by a factor of at least 25), and therefore the 3D Dixon b-SSFP sequence could be added to a standard MRCP protocol with little added cost to the total examination time, or if substituted

for the 3D FSE technique would represent a substantial time savings. The utility of the breath-held 3D MRCP technique is suggested by the observation that the average image quality score obtained from the highest score of either the 3D Dixon b-SSFP acquisition or the standard 3D FSE acquisition was slightly but significantly higher when compared to the score from 3D FSE acquisitions alone (3.9 versus 3.6, with $p = 0.005$). Our results suggest that the 3D Dixon b-SSFP pulse sequence may be useful as such an alternative technique; however, the image quality of the standard 3D FSE acquisitions was generally preferred, indicating that it should probably not be considered as a replacement for the standard technique.

Limitations of the 3D Dixon b-SSFP technique include banding artifacts, most commonly encountered near the diaphragm and at the edges of the acquired volume. These artifacts can be minimized by careful shimming; however, they did occasionally interfere with visualization of important structures (Fig. 5). Susceptibility artifacts adjacent to surgical clips or bowel gas were occasionally encountered, and were more problematic in comparison to the standard 3D FSE acquisitions. Fat–water swaps were seen on individual images in 11 patients, typically near the lung–diaphragm interface, and represent an additional artifact likely related to inhomogeneities in the magnetic field. While the two point Dixon reconstruction algorithm [20] corrects for first and second order phase errors and is relatively robust to B_0 and B_1 heterogeneity, these errors do emphasize limitations of the reconstruction technique. Background suppression, particularly with regard to adjacent veins and arteries, was relatively poor in comparison to 3D FSE images — this generally resulted in slightly reduced quality of the 3D reconstructions. The limitation of a breath-held acquisition constrained the obtainable spatial resolution and total acquisition volume, both of which were generally reduced in comparison to the standard 3D FSE acquisitions, and occasionally resulted in motion artifact in patients with limited breath hold capacity.

On the other hand, fat suppression was excellent in nearly all cases — central fat suppression was successful in all patients, while the isolated fat–water swaps described previously involved predominantly subcutaneous fat in the superior-most slices and did not significantly affect the quality of the 3D reconstructions. The higher background signal of the b-SSFP acquisitions was occasionally useful for visualizing tumor surrounding bile ducts (Fig. 3) or encasing vessels. The 3D Dixon b-SSFP sequence was more resistant to central shading artifact encountered on 3.0 T systems (Fig. 5), and was the preferred sequence in two cases where this artifact was prominent on the standard 3D FSE images.

While most of the examinations were acquired on 1.5 T systems, the performance of the b-SSFP sequence at 3.0 T was fairly robust — scores of overall image quality were not significantly different when comparing 1.5 T and 3.0 T examinations; however artifacts were slightly increased, reflected in a small but significant difference in the average artifact scores.

The acquired in-plane frequency encoding matrix at 3.0 T was slightly lower than the corresponding 1.5 T matrix, a reflection of the shorter TEs used for the 3.0 T acquisition. This does place some limits on the in-plane spatial resolution; however the theoretical doubling of SNR at 3.0 T should allow higher parallel imaging acceleration factors, which in

turn could be used to reduce section thickness and improve overall spatial resolution or to simply reduce the total acquisition time. These variables were not explored in this initial feasibility study.

Sodickson et al. [21] have reported a breath-held 3D FSE sequence for MRCP with reasonable success. However, our spatial resolution and coverage are superior to those of their sequence (1.8×1.5×1.6 mm acquired resolution versus 1.6×2.5×4 mm) with comparable breath-holding times. The spatial resolution in the frequency-encoding dimension was restricted due to the stringent requirement of positioning the opposed-phase and in-phase echoes at 1.2/2.4 ms for 3.0 T and 2.4/4.8 ms for 1.5 T. The use of partially truncated echoes followed by homodyne [22] or Projections Onto Convex Sets (POCS) [23] processing could improve the resolution significantly while maintaining the fidelity of the fat–water separation.

Limitations of this study include its retrospective nature and the relatively small number of patients included. The 3D Dixon b-SSFP acquisition was performed at the discretion of the staff radiologists — while this was generally done to assess the utility of the new technique, it is possible that in some cases the decision to perform the b-SSFP sequence was made following acquisition of a suboptimal standard MRCP, thereby introducing bias into the image analysis.

In summary, the 3D Dixon b-SSFP pulse sequence provided robust, high quality MRCP images, and warrants further investigation as an accessory technique for assessment of the biliary and pancreatic ducts.

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Fig. 1.

Dual-echo bipolar readout 3D b-SSFP pulse sequence used for breath-held 3D MRCP. Due to the high receiver bandwidths used, it was possible to position the echoes at 1.2 ms and 2.4 ms (3.0 T) or 2.2 ms and 4.4 ms (1.5 T) in a single TR, resulting in short scan times.

Fig. 2. Sub-volume maximum intensity projection (MIP) images from 3D Dixon b-SSFP MRCP (axial acquisition) (A) and conventional 3D FSE MRCP (B) in a 57 year old male patient with previous episodes of pancreatitis. Both images reveal findings consistent with chronic pancreatitis, with mild diffuse dilatation of the pancreatic duct and small side branch ducts. The conventional 3D FSE MRCP sequence was preferred for its superior depiction of the mild pancreatic ductal stenosis in the pancreatic neck as well as superior visualization of intrahepatic biliary ducts.

Fig. 3. Sub-volume MIP images from 3D Dixon b-SSFP MRCP (coronal acquisition) (A) and conventional respiratory-triggered FSE MRCP (B) in a 60 year old female patient with suspected cholangiocarcinoma reveal a central obstructing lesion consistent with cholangiocarcinoma with diffuse dilatation of peripheral intrahepatic biliary ducts. Coronal oblique (C) and sagittal oblique (D) reformatted images (1.6 mm thickness) from the 3D Dixon b-SSFP acquisition demonstrate the mildly hypointense central tumor surrounding the common bile duct and bifurcation. Note overall uniform fat suppression as well as mild banding artifact at the superior margin of the images. The 3D Dixon b-SSFP sequence was preferred due to the moderate motion artifact seen in the conventional acquisition.

Fig. 4. Volume-rendered anterior and posterior reconstructions from 3D Dixon b-SSFP MRCP (coronal acquisition) (A, B) in a 65 year old male patient with primary sclerosing cholangitis demonstrate central obstruction and moderate intrahepatic biliary dilatation, greatest in the left lobe. Note also peripheral strictures in right sided ducts. Coronal source image from 3D Dixon b-SSFP acquisition (C) reveals a filling defect in a central left duct (arrowhead) as well as stones or debris within the gallbladder. Corresponding volume-rendered reconstructions (D and E) from the 3D FSE acquisition and corresponding coronal source image (F) reveal similar findings. The 3D FSE acquisition was preferred due to its greater anterior-posterior volumetric coverage.

Fig. 5. Axial source images from 3D Dixon b-SSFP MRCP in a 65 year old male patient with history of cholangiocarcinoma demonstrate (A) layering small stones or debris in the gallbladder neck and cystic duct (arrow), as well as a small focus of gas within the common bile duct (arrowhead). Prominent banding artifact is seen crossing the gallbladder fundus (B). Pneumobilia is more difficult to visualize on a corresponding axial reformatted image from coronal oblique 3D FRFSE MRCP (C). The Dixon b-SSFP acquisition was preferred due to its superior depiction of the common bile duct.

Fig. 6. Sub-volume MIP images from 3D Dixon (A) and 3D FSE (B) MRCP acquisitions in a 45 year-old female patient with primary sclerosing cholangitis demonstrate multifocal strictures throughout intrahepatic and extrahepatic biliary ducts. A thin common bile duct stent is faintly visualized on both images. Axial source image from 3D Dixon acquisition (C) demonstrates uniform fat suppression, with slight banding artifact along the anterior right margin of the liver. Axial sub-volume MIP image from 3D Dixon b-SSFP acquisition (D) shows moderate background signal within the main and right portal veins, left renal vein, splenic vein, and inferior vena cava. The 3D Dixon b-SSFP acquisition was preferred due to slight motion blurring of the conventional 3D FRFSE images.

Table 1

Imaging parameters for 3D Dixon b-SSFP acquisitions at 1.5 T and 3.0 T.

	1.5 T	3.0 T
TR (ms)	6.0–6.4	4.0
TE ₁ (ms)	2.4	1.2
TE ₂ (ms)	4.8	2.4
Receiver bandwidth (kHz)	125	142
Flip angle	50	45
Matrix	224 × 256	192 × 224–256
Section thickness (mm)	1.6–2.4	1.6–2.0
# sections	40–54	46–60
Field of view (cm)	32–40	32–40
Acquisition time (s)	20–24	20–24

Table 2

Qualitative ratings of standard 3D FSE MRCP images and 3D Dixon b-SSFP images.

	3D FSE	3D Dixon SSFP	<i>p</i> -value
Overall image quality	3.6	3.3*	0.030
Artifacts	3.6	3.2*	0.002
Pancreatic duct	3.0	2.9	0.303
Common bile duct	3.8	3.4*	0.016
Intrahepatic ducts	3.4	3.1*	0.036
Intrahepatic branching	3.2	2.8*	0.003
Gallbladder	3.2	3.0	0.46

Quality scores ranged from 1 (uninterpretable) to 5 (excellent); artifact scores ranged from 1 (severe) to 5 (none); intrahepatic branching ranged from 1 (1st order) to 4 (4th order or higher); and the remainder of the scores ranged from 1 (not visualized) to 5 (completely visualized). Ratings were compared using a non-parametric Wilcoxon paired signed rank test.

* denotes scores significantly different from 3D FSE scores ($p < 0.05$).