Objective: The aim of this study was to evaluate the clinical feasibility of fast 3-dimensional (3D) magnetic resonance cholangiopancreatography (MRCP) using compressed sensing (CS) in comparison with conventional navigator-triggered 3D-MRCP.

Materials and Methods: This retrospective study was approved by our institutional review board, and the requirement of informed consent was waived. A total of 84 patients (male-to-female ratio, 41:43; mean age, 47.3 ± 18.8 years) who underwent conventional 3D navigator-triggered T2-weighted MRCP using sampling perfection with application optimized contrasts (SPACE) and fast 3D MRCP using SPACE with high undersampling combined with CS reconstruction (CS SPACE; CS-MRCP) on a 3 T scanner were included. Among them, 28 patients additionally underwent 3D breath-hold CS-MRCP (BH-CS-MRCP) with 5.7% k-space sampling. Three board-certified radiologists then independently reviewed the examinations for bile duct and pancreatic duct visualization and overall image quality on a 5-point scale, and image sharpness and background suppression on a 4-point scale, with the higher score indicating better image quality. In addition, diagnostic performance for the detection of anatomic variation and diseases of the bile duct, and pancreatic disease were assessed on a per-patient basis in the subgroup of 28 patients who underwent conventional MRCP, CS-MRCP, and BH-CS-MRCP in the same manner.

Results: Mean acquisition times of conventional MRCP CS-MRCP, and BH-CS-MRCP were 7 minutes (419.7 seconds), 3 minutes 47 seconds (227.0 seconds), and 16 seconds, respectively (P < 0.0001, in all comparisons). In all patients, CS-MRCP showed better image sharpness (3.54 ± 0.60 vs 3.37 ± 0.75, P = 0.04) and visualization of the common bile duct (4.55 ± 0.60 vs 4.29 ± 0.78, P = 0.034) and pancreatic duct (3.47 ± 1.22 vs 3.26 ± 1.32, P = 0.025), but lower background suppression (3.00 ± 0.54 vs 3.37 ± 0.58, P = 0.001) than conventional MRCP. Overall image quality was not significantly different between the 2 examinations (3.51 ± 0.95 vs 3.47 ± 1.09, P = 0.75). The number of indeterminate MRCP examinations for the anatomic variation and disease of the bile duct significantly decreased on CS-MRCP, from 16.7% to 9.5%–11.9% and 8.4%–15.6% to 3.6%–8.4% in all readers (P = 0.003–0.03). In the 28 patients who underwent BH-CS-MRCP, better image quality was demonstrated than with conventional MRCP and CS-MRCP (4.10 ± 0.84 vs 3.44 ± 1.21 vs 3.50 ± 1.11, respectively, P = 0.002, 0.001). Sensitivities for detecting bile duct disease was 88.9% to 100% on both BH-CS-MRCP and conventional MRCP (P > 0.05), and for detecting pancreatic disease was 66.7% to 83.3% on BH-CS-MRCP and 50.0% to 72.2% on conventional MRCP (P = 0.002 in reader 1, 0.06–0.47 in readers 2–3).

Conclusions: Compressed sensing MRCP using incoherent undersampling combined with CS reconstruction provided comparable image quality to conventional MRCP while reducing the acquisition time to within a single breath-hold (16 seconds).

Key Words: compressed sensing, 3D-MRCP, breath-hold, cholangiography

Received for publication January 31, 2017; and accepted for publication, after revision, March 18, 2017.

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Clinical Feasibility of 3-Dimensional Magnetic Resonance Cholangiopancreatography Using Compressed Sensing: Comparison of Image Quality and Diagnostic Performance

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Three-dimensional (3D) magnetic resonance cholangiopancreatography (MRCP) has been well-established as a useful noninvasive test for the evaluation of the bile duct and pancreatic duct anatomy and its pathology, without the potential risks of endoscopic retrograde cholangiopancreatography such as pancreatitis, perforation, or bleeding.1–2 However, as most 3D-MRCP examinations are performed using a heavily T2-weighted fast or turbo spin echo sequence in a respiratory-triggered manner,3–5 the acquisition time of 3D-MRCP accounts for a substantial portion of the entire examination time.6–8 Particularly in patients with irregular breathing patterns, acquisition times can often be prolonged up to 10 minutes or even longer, with the resultant respiratory-triggered 3D-MRCP measurements tending to be prone to image blurring and motion artifacts, which in turn frequently results in suboptimal image quality.7–8

Thus, there have been several attempts to reduce the scan time using respiratory gating, parallel imaging, or via other rapid sequences.8–12 One such recent attempt is the application of compressed sensing (CS), which can improve the speed of MR imaging by exploiting image redundancies in sampling and reconstruction.8,13–15 Compressed sensing inherently requires 3 conditions including sparsity or transform sparsity of the target image, incoherent sampling, and a reconstruction algorithm that enforces sparsity constrained by data consistency.16,17,13–17 As conventional 3D-MRCP often acquires little data according to respiratory-gating and suppresses most background signals, it is consistent with one of the prerequisites of CS, data sparsity.13,17 Therefore, if an appropriate reconstruction algorithm enforcing sparsity for MRCP with high spatial resolution could be obtained using CS reconstruction with a high undersampling of k-space data, it may ultimately be able to reduce the scan acquisition time.18 Until now, there has been 1 previous study that demonstrated the feasibility of fast MRCP using the CS technique by comparing its imaging quality with conventional MRCP.18 However, to our knowledge, there has been no study demonstrating the clinical applicability of CS-MRCP with a comparison of its imaging quality and diagnostic performance in revealing biliary or pancreatic diseases with conventional respiratory-triggered MRCP with high spatial resolution.

Therefore, the purpose of this study was to evaluate the clinical feasibility of 3D-MRCP using CS reconstruction and high undersampling of k-space data in comparison with conventional 3D-MRCP.
MR Imaging Acquisition

For all patients, 3D-MRCP was performed at a 3 T system (MAGNETOM Skyra; Siemens Healthcare, Erlangen, Germany) including a conventional navigator-triggered MRCP protocol based on the SPACE sequence and CS-MRCP based on a prototypical SPACE sequence that allows incoherent undersampling combined with CS reconstruction. All examinations used either a 48- or a 60-channel body-array coil. Conventional 3D-MRCP was performed first, followed by CS-MRCP. Thereafter, BH-CS-MRCP was performed at the end, if included. All 3 sequences were performed before contrast media administration.

Conventional MRCP

Magnetic resonance cholangiopancreatography was performed using 3D SPACE in combination with reduced volume excitation (ZOOMit) and the navigator-triggered prospective acquisition correction technique. Detailed acquisition parameters are as follows: field of view (FOV), 256 × 256 mm²; repetition time (TR), variable depending on the respiratory rate; echo time (TE), 661.0 milliseconds; flip angle (FA), 100 degrees; acceleration factor, 3; number of excitations (NEX), 1; spectral selective fat saturation to suppress signal intensity from fat; matrix, 256 × 256; section thickness, 1 mm; resolution (interpolated), 1 × 1 × 1 mm (0.5 × 0.5 × 1 mm); number of coronal sections, 80–96; and acquisition time varying with the breathing pattern of the patient.

Compressed Sensing MRCP

Compressed sensing MRCP was performed using a prototypical 3D SPACE sequence with an incoherent undersampling scheme and CS reconstruction technique (CS SPACE, Siemens). In this prototype sequence, incoherent undersampling is obtained using a Poisson-Blisk pattern in 2 phase encoding dimensions. In addition, the fluctuation of echo train trajectories due to irregular sampling of k-space was mitigated by increasing the smoothness of train trajectories. For CS-MRCP, an acceleration factor of 22 (4.5% k-space data sampling) was achieved during the acquisition. Detailed acceleration parameters are as follows: FOV, 380 × 380 mm²; TR, variable depending on the respiratory rate; TE, 983.0 milliseconds; FA, 100 degrees; NEX, 2; spectrally selective fat saturation to suppress signal intensity from fat; matrix, 384 × 384; section thickness, 1 mm; resolution (interpolated), 1 × 1 × 1 mm (0.5 × 0.5 × 1 mm); number of coronal sections, 80–96; and acquisition time, variable.

Breath-Hold Compressed Sensing MRCP

The aforementioned prototype 3D turbo spin echo sequence (CS SPACE) was applied. To achieve a single breath-hold scan time, the following modifications were made in comparison with CS-MRCP: an acceleration factor of 17 (5.7% k-space data sampling) was achieved during acquisition; FOV, 380 × 380 mm²; TR/TE, 1700/674 milliseconds; FA, 95 degrees; spectrally selective fat saturation to saturate fat signal intensity; NEX, 1; matrix 384 × 307; section thickness, 1.1 mm; resolution (interpolated), 1 × 1 × 1.1 mm(0.5 × 0.5 × 1.1 mm); and number of coronal sections, 96. Acquisition time was 16 seconds.

Compressed sensing reconstruction was implemented in C++ and integrated in the scanner reconstruction environment. A SENSE-based optimization problem with additional sparsity enforcing regularization was resolved using a fast iterative soft-thresholding algorithm. Regularization of the redundant Haar wavelet transform was chosen, and sparsity was enforced by the L1-norm of the redundant Haar wavelet coefficients. Iteration was performed 20 times for image reconstruction. Total reconstruction times were approximately 5 minutes for each of the CS-MRCP and BH-CS-MRCP data sets.

Image Analysis

Three board-certified radiologists (J.H.Y., S.M.L., and H.J.K., with 11, 6, and 5 years of clinical experience in abdominal MR imaging, respectively) independently reviewed the conventional MRCP, CS-MRCP, and BH-CS-MRCP examinations. Reconstructed maximal intensity projection images were anonymized and distributed to the reviewers in random order, without information of the data acquisition methods.

Image Quality Assessment

Reviewers graded images for the bile duct including the common bile duct (CBD), cystic duct, bilateral first, and second intrahepatic ducts (IHDS), and pancreatic duct visualization (1, no visualization; 2, poorly visualized with limited diagnostic value; 3, partial [less than one half] or blurry with decreased image quality; 4, clear but partial [more than one half] or not clear [mild blur]; and 5, complete and clear duct) and overall image quality (1, undiagnostic; 2, poor image quality [below average]; 3, fair [average]; 4, good; and 5, excellent) on a 5-point scale. In addition, image sharpness (1, nondiagnostic; 2, substantial blur; 3, mild blur with mild image quality degradation; 4, no or minimal blur) and background suppression (1, significant background signal that hampers diagnostic capability of readers; 2, substantial background signal with significant image quality degradation; 3, noticeable background signal with mild image quality decrease; and 4, sufficient background suppression without decreasing image quality) were assessed on a 4-point scale, with higher scores indicating better image quality.

Evaluation of Diagnostic Performance

The presence of bile duct anatomic variation was determined based on MRCP images and recorded as likely presence, unlikely presence, and indeterminate presence on MRCP. The presence of disease in the bile duct and pancreas was also evaluated in the same manner, and the abnormality was described in detail when the disease was likely present in a patient. Image analysis was performed for the subgroup of 28 patients with conventional MRCP, CS-MRCP, and BH-CS-MRCP in the same manner.

Standard of Reference for Anatomic Variation and Diseases of the Bile Duct and Pancreas

The standard of reference for bile duct anatomic variations was determined based on surgery (n = 39) and imaging-based diagnosis (n = 45) including all imaging sequences of contrast-enhanced pancreaticobiliary MR imaging in our institution (n = 21), contrast-enhanced pancreaticobiliary MR imaging with T1-weighted cholangiography using a hepatocyte-specific.
contrast agent (n = 17), and endoscopic or percutaneous cholangiography (n = 7). Images were interpreted by a board-certified radiologist (J.M.L. with 21 years of clinical experience in abdominal MR imaging) who did not attend the MRCP review session. Among the 84 patients, 57 patients did not show bile duct anatomic variation, and the remaining 27 patients showed anatomic variations as follows: right posterior duct drains to the left intrahepatic duct (n = 10), right posterior duct drains to the common hepatic duct (n = 4), trifurcation of the right anterior, posterior and left duct (n = 11), accessory B5 drains to the common hepatic duct (n = 1), and cystic duct to the right main intrahepatic duct (n = 1).

With regard to the presence of bile duct disease, diseases were confirmed by surgery (n = 3), biopsy (n = 7), choledochoscopy (n = 1), or clinical diagnosis (n = 73). Among 84 patients, 69 patients did not show bile duct abnormality, and 15 patients were diagnosed with a distal CBD stricture (n = 1), choledochal cyst type I (n = 1), recurrent pyogenic cholangitis (n = 3), right intrahepatic duct stricture (n = 1), left intrahepatic duct stricture (n = 4), Klatskin tumor type IV (n = 4), and choledochal cyst type V (n = 1).

For pancreatic disease, diagnosis was made via clinical features (n = 80) based on imaging including cholangiography, endoscopic ultrasonography, and follow-up cross sectional imaging, followed by surgery (n = 2) and biopsy (n = 2). Sixty patients did not show any signs of pancreatic lesions, and the remaining 24 patients were diagnosed with branch-duct type intramural papillary neoplasms (n = 16), pancreatic cysts (n = 3), a pancreatic adenocarcinoma (n = 1), pancreatic neuroendocrine tumors (n = 3), and a pancreatic lipoma (n = 1).

Statistical Analysis
A paired-sample t test or Wilcoxon signed-rank test was used to compare the acquisition time, image sharpness, background suppression, visualization of the bile duct and pancreatic duct, and overall image quality between conventional MRCP and CS-MRCP as appropriate. In addition, the Friedman test was performed for comparison of the aforementioned items among conventional MRCP, CS-MRCP, and BH-CS-MRCP groups followed by post hoc analysis in 28 patients with 3 sequences. Intraclass correlation coefficients with a 2-way model were obtained to assess reader agreement on each qualitative analysis item. Intraclass correlation coefficient values were interpreted as poor (<0.40), fair to good (0.40–0.75), or excellent (>0.75). Sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) of each sequence in the detection of bile duct anatomic variation, bile duct disease, and pancreatic disease were calculated on a per-patient basis. If anatomic variation and diseases of the bile duct or pancreas were correctly assessed by a reader, we classified the result as a true-positive result for per-patient sensitivity in the detection of bile duct anatomic variation or the presence of disease. All statistical analyses were conducted using commercial software (MedCalc, version 12; Medcalc Software, Mariakerke, Belgium; IBM SPSS Statistics, version 23.0; SPSS Inc, IBM, Armonk, NY). P < 0.05 was considered to indicate a statistical significance. To check whether the nonsignificant results of image quality between conventional MRCP and CS-MRCP were due to a lack of statistical power, a 95% confidence interval of the difference was suggested using a noninferiority margin28,29 of 0.35 as suggested in a previous study, which demonstrated a significant difference between the 2 different MRCP protocols in 52 patients.10

RESULTS

Comparison of Acquisition Time, Image Quality, and Duct Visualization Between Conventional MRCP and CS-MRCP

The average acquisition time was significantly shorter on CS-MRCP than on conventional MRCP (227.0 ± 66.3 vs 419.7 ± 115.1, P < 0.0001). There were no significant differences in overall image quality between conventional MRCP and CS-MRCP (3.47 ± 1.09 vs 3.51 ± 0.95, respectively, P = 0.75) (Fig. 1). The difference in overall image quality was 0.04 (95% CI, −0.18 to 0.26), which did not exceed the lower non-inferiority margin (−0.35). Imaging sharpness was slightly higher in CS-MRCP than on conventional MRCP (3.54 ± 0.60 vs 3.37 ± 0.75, P = 0.04), and the CBD and pancreatic duct were better visualized on CS-MRCP than on conventional MRCP (Table 1, P = 0.034, 0.025, respectively) (Fig. 2). However, background signal was better suppressed on conventional MRCP than CS-MRCP (3.37 ± 0.58 vs 3.00 ± 0.54, P < 0.001).

Comparison Among Conventional MRCP, CS-MRCP, and BH-CS-MRCP

In the 28 patients who underwent all 3 examinations, overall image quality was significantly higher on BH-CS-MRCP (4.10 ± 0.84) than on conventional MRCP and CS-MRCP (3.44 ± 1.21, 3.50 ± 1.11, respectively, P = 0.002, 0.001). Breath-hold CS-MRCP showed better imaging sharpness than conventional MRCP and CS-MRCP (Table 2, P < 0.0001, 0.005, respectively), as well as better visualization of the CBD (Table 2, P = 0.004, 0.012, respectively) (Figs. 2, 3). The bilateral first intrahepatic duct tended to be more clearly visualized on BH-CS-MRCP than on conventional MRCP or CS-MRCP (Table 2).

Interreader Agreement

Intraclass correlation coefficients of each item are summarized in Table E1, Supplemental Digital Content 1, http://links.lww.com/RLI/A318. Intraclass correlation coefficients were fair to excellent for all items on conventional MRCP (0.43–0.82), on CS-MRCP (0.53–0.79), and BH-CS-MRCP (0.48–0.92) except image sharpness on conventional MRCP (0.38).

FIGURE 1. Three-dimensional MRCP in a 55-year-old woman who is a living liver donor candidate. Conventional MRCP (A) showed suboptimal quality to evaluate bile duct anatomic variation due to image blurriness owing to motion artifacts, whereas CS-MRCP (B) showed acceptable image quality by demonstrating the CBD, both first, second HHDs (arrowheads), and the pancreatic duct (arrows).
Diagnostic Performance for Bile Duct Anatomic Variation

The incidence of indeterminate images for the evaluation of bile duct anatomic variation was significantly reduced on CS-MRCP from 16.7%–22.6% to 11.9%–9.5% in readers 1 to 3 (Table 3, P = 0.02, 0.003, respectively) (Fig. 2). On conventional MRCP, readers showed 74.1% to 85.2% sensitivity and 84.0% to 87.0% PPV. On CS-MRCP, 74.1% to 81.5% sensitivity and 87.0% to 90.9% PPV were observed (Table E2, Supplemental Digital Content 1, http://links.lww.com/RLI/A318).

In the 28 patients who underwent the conventional MRCP, CS-MRCP, and BH-CS-MRCP examinations, the incidence of indeterminate imaging features was 17.9% to 28.6% on conventional MRCP, 14.3% on CS-MRCP, and 10.7% on BH-CS-MRCP (Table 3). A statistical difference was observed between conventional MRCP and BH-CS-MRCP in reader 3 (P = 0.002). Sensitivity, specificity, PPV, and NPV of each reader in each examination are summarized in Table E3, Supplemental Digital Content 1, http://links.lww.com/RLI/A318.

Diagnostic Performance for the Bile Duct and Pancreatic Disease

In all patients, the incidence of indeterminate imaging findings for bile duct disease decreased from 8.4% to 15.6% on conventional MRCP to 3.6% to 8.3% on CS-MRCP (Table 4, P < 0.05). The incidence of indeterminate imaging findings for pancreatic disease also decreased on CS-MRCP from 23.8%–29.8% to 14.3%–15.5% in readers 2 to 3 (Table 4), except in reader 1 (P = 0.06). Sensitivity for detecting bile duct disease was significantly increased on CS-MRCP in reader 2 (Table 4, P = 0.006), but no statistical significance was observed in readers 1 and 3 (P = 0.12, 0.12). However, all readers showed significantly higher sensitivity for detecting pancreatic disease on CS-MRCP (Table 4, P < 0.05).

In the 28 patients who underwent BH-CS-MRCP, sensitivities were 88.9%–100% for detecting bile duct disease, but there was no significant difference between conventional MRCP and BH-CS-MRCP in all readers (Table E4, Supplemental Digital Content 1, http://links.lww.com/RLI/A318, P > 0.05). Sensitivities for detecting pancreatic disease were 76.9% to 83.3% on BH-CS-MRCP and 50.0% to 72.2% on conventional MRCP (Table E4 Supplemental Digital Content 1, http://links.lww.com/RLI/A318). There were no statistical significances of sensitivity between conventional MRCP and BH-CS-MRCP in readers 1 to 3 (Table E4, Supplemental Digital Content 1, http://links.lww.com/RLI/A318, P > 0.05), but it was significantly higher on BH-CS-MRCP in reader 1 (61.1% vs 83.3%, P = 0.002).

DISCUSSION

Our study demonstrated that CS-MRCP, using the prototype CS-SPACE sequence with 4.5% to 5.7% k-space sampling and a
TABLE 2. Comparison of Image Quality and Duct Visualization Among 3D Conventional MRCP, CS-MRCP, and BH-CS-MRCP

<table>
<thead>
<tr>
<th></th>
<th>Conventional MRCP</th>
<th>CS-MRCP</th>
<th>BH-CS-MRCP</th>
<th>Conventional vs CS</th>
<th>Conventional vs BH-CS</th>
<th>CS vs BH-CS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acquisition time, s</td>
<td>440.2 ± 113.6 (297, 745)</td>
<td>234.6 ± 73.2 (64, 382)</td>
<td>16</td>
<td>&lt;0.0001*</td>
<td>&lt;0.0001*</td>
<td>&lt;0.0001*</td>
</tr>
<tr>
<td>Imaging sharpness</td>
<td>3.18 ± 0.80 (1.33, 4.00)</td>
<td>3.42 ± 0.63 (1.67, 4.33)</td>
<td>3.80 ± 0.04 (2.33, 4.33)</td>
<td>0.40</td>
<td>&lt;0.0001*</td>
<td>0.005*</td>
</tr>
<tr>
<td>Background suppression</td>
<td>3.43 ± 0.59 (1.00, 4.00)</td>
<td>3.20 ± 0.53 (1.33, 4.00)</td>
<td>3.55 ± 0.44 (2.33, 4.00)</td>
<td>0.14</td>
<td>0.29</td>
<td>&lt;0.0001*</td>
</tr>
<tr>
<td>Duct visualization</td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>CBD</td>
<td>4.39 ± 0.73 (2.33, 5.00)</td>
<td>4.55 ± 0.65 (2.67, 5.00)</td>
<td>4.79 ± 0.50 (3.00, 5.00)</td>
<td>0.12</td>
<td>0.004*</td>
<td>0.012*</td>
</tr>
<tr>
<td>Cystic duct</td>
<td>2.90 ± 1.29 (1.00, 5.00)</td>
<td>3.24 ± 1.24 (1.00, 5.00)</td>
<td>3.51 ± 1.37 (1.00, 5.00)</td>
<td>0.065</td>
<td>0.13</td>
<td>0.18</td>
</tr>
<tr>
<td>Right first IHD</td>
<td>4.08 ± 1.05 (1.67, 5.00)</td>
<td>4.21 ± 0.74 (2.67, 5.00)</td>
<td>4.51 ± 0.64 (2.67, 5.00)</td>
<td>0.39</td>
<td>0.014*</td>
<td>0.013*</td>
</tr>
<tr>
<td>Left first IHD</td>
<td>4.00 ± 1.15 (1.33, 5.00)</td>
<td>4.18 ± 0.92 (1.00, 5.00)</td>
<td>4.43 ± 0.87 (2.00, 5.00)</td>
<td>0.12</td>
<td>0.006*</td>
<td>0.038</td>
</tr>
<tr>
<td>Right second IHD</td>
<td>3.53 ± 1.26 (1.00, 5.00)</td>
<td>3.44 ± 1.19 (1.67, 5.00)</td>
<td>3.91 ± 1.04 (1.67, 5.00)</td>
<td>0.79</td>
<td>0.076</td>
<td>0.006*</td>
</tr>
<tr>
<td>Left second IHD</td>
<td>3.38 ± 1.19 (1.00, 5.00)</td>
<td>3.44 ± 1.09 (1.00, 5.00)</td>
<td>3.67 ± 1.09 (1.67, 5.00)</td>
<td>0.53</td>
<td>0.11</td>
<td>0.104</td>
</tr>
<tr>
<td>Pancreatic duct</td>
<td>3.58 ± 1.24 (1.00, 5.00)</td>
<td>3.81 ± 1.12 (1.00, 5.00)</td>
<td>3.54 ± 1.32 (1.00, 5.00)</td>
<td>0.067</td>
<td>0.85</td>
<td>0.164</td>
</tr>
<tr>
<td>Overall image quality</td>
<td>3.44 ± 1.21 (1.33, 5.00)</td>
<td>3.50 ± 1.11 (1.67, 5.00)</td>
<td>4.10 ± 0.84 (1.33, 5.00)</td>
<td>0.64</td>
<td>0.002*</td>
<td>0.001*</td>
</tr>
</tbody>
</table>

Values are mean ± standard deviation (range). *P value < 0.017 indicates statistically significant difference between conventional MRCP, CS-MRCP, and BH-CS-MRCP examinations.

MRCP indicates magnetic resonance cholangiopancreatography; CS-MRCP, compressed sensing magnetic resonance cholangiopancreatography; BH-CS-MRCP, breath-hold compressed sensing magnetic resonance cholangiopancreatography; CBD, common bile duct; IHD, intrahepatic duct.

nonlinear iterative reconstruction algorithm integrating coil sensitivity encoding, was able to provide comparable image quality with conventional navigator-triggered MRCP but with a significantly shorter acquisition time. The mean acquisition time of CS-MRCP in our study was 227.0 seconds, whereas conventional 3D-MRCP took 419.7 seconds to be achieved. Furthermore, CS-MRCP showed better imaging sharpness than conventional MRCP, as well as a higher score of CBD and pancreatic duct visualization. In fact, none of the other ducts showed a lower score on CS-MRCP than on conventional MRCP. Moreover, with the CS SPACE pulse sequence, which uses a variable-density Poisson-disk random undersampling pattern of the 2 phase-encoding dimensions,24,30 we were able to push the scan acquisition time to a limit of 16-second breath-holds. In our study, 16-second BH-MRCP showed significantly higher image sharpness and better visualization of the CBD, IHDs, and overall image quality than navigator-triggered conventional MRCP and CS-MRCP. As mentioned earlier, the prolonged scan time of conventional MRCP of longer than 5 minutes can be responsible for hampering the workflow, lowering patients' tolerance of biliary or pancreas protocol MR examinations, and for creating motion artifacts at MRCP. In this regard, our study results may be clinically valuable not only for improving the image quality but also for improving the overall workflow of pancreatobiliary MR imaging.

The better imaging sharpness of CS-MRCP observed in our study can be attributed to the shorter acquisition time and less motion-related imaging blurring in comparison with conventional MRCP. Given that BH-CS-MRCP in 16 seconds provided significantly sharper images and better image quality than conventional MRCP and CS-MRCP in our study, we believe that motion artifacts may be the key element that determines overall image quality. Indeed, there have been several previous attempts to reduce the scan time of MRCP using partial k-space sampling, parallel imaging such as sensitivity encoding (SENSE) or generalized autocalibrating partially parallel acquisitions (GRAPPA), fast T2 gradient spin echo techniques, or balanced steady-state free precession techniques.9–12,31,32 In this study, we applied CS as this technique has been thought to be suitable for MRCP for several reasons. Most importantly, the sampled data sparsity of MRCP was a major reason for applying CS.14,16 Although different image textures and uncommon noise patterns would be produced by applying CS as different data

FIGURE 3. Three-dimensional MRCP examinations in a 58-year-old man with multiple BD-IPMNs. On conventional MRCP (A), the overall image quality is lower than average due to image blurriness, and BD-IPMNs is seen with blurred margins (arrows). On CS-MRCP (B), BD-IPMNs are observed with better conspicuity (arrows); however, anatomic structures and BD-IPMNs are still blurred due to motion artifacts. Image sharpness and overall image quality increased on BH-CS-MRCP (C), which clearly depicted 4 BD-IPMNs, in comparison with conventional MRCP and CS-MRCP. The acquisition times were 7 minutes 19 seconds for conventional MRCP, 4 minutes 13 seconds for CS-MRCP, and 16 seconds for BH-CS-MRCP.
### TABLE 3. Number of Indeterminate Cases for Detecting Bile Duct Anatomic Variation in Different MRCP Sequences

<table>
<thead>
<tr>
<th></th>
<th>Conventional (A)</th>
<th>CS-MRCP (B)</th>
<th>BH-CS-MRCP (C)</th>
<th>P</th>
</tr>
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<tbody>
<tr>
<td>Patients with CS-MRCP (n = 84)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reader 1</td>
<td>16.7% (14/84)</td>
<td>9.5% (8/84)</td>
<td>—</td>
<td>0.02*</td>
</tr>
<tr>
<td>Reader 2</td>
<td>16.7% (14/84)</td>
<td>9.5% (8/84)</td>
<td>—</td>
<td>0.02*</td>
</tr>
<tr>
<td>Reader 3</td>
<td>22.6% (19/84)</td>
<td>11.9% (10/84)</td>
<td>—</td>
<td>0.003*</td>
</tr>
<tr>
<td>Patients with BH-CS-MRCP (n = 28)</td>
<td></td>
<td></td>
<td></td>
<td>A vs B</td>
</tr>
<tr>
<td>Reader 1</td>
<td>17.9% (5/28)</td>
<td>14.3% (4/28)</td>
<td>10.7% (3/28)</td>
<td>0.62</td>
</tr>
<tr>
<td>Reader 2</td>
<td>21.4% (6/28)</td>
<td>14.3% (4/28)</td>
<td>10.7% (3/28)</td>
<td>0.28</td>
</tr>
<tr>
<td>Reader 3</td>
<td>28.6% (8/28)</td>
<td>14.3% (4/28)</td>
<td>10.7% (3/28)</td>
<td>0.03</td>
</tr>
</tbody>
</table>

*P value < 0.05 and 0.017 indicate significant difference of incidence of indeterminate cases between 2 and 3 sequences in each reviewer.

CS-MRCP indicates compressed sensing magnetic resonance cholangiopancreatography; BH-CS-MRCP, breath-hold compressed sensing magnetic resonance cholangiopancreatography.

### TABLE 4. Per-Patient Sensitivity, Specificity, PPV, and NPV of Conventional MRCP and CS-MRCP for Detecting Bile Duct and Pancreatic Disease in 84 Patients

<table>
<thead>
<tr>
<th></th>
<th>Bile Duct Disease</th>
<th>Pancreatic Disease</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conventional MRCP</td>
<td>CS-MRCP</td>
</tr>
<tr>
<td>Reader 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indeterminate, %</td>
<td>8.3% (7/84)</td>
<td>3.6% (3/84)</td>
</tr>
<tr>
<td>Sensitivity, %</td>
<td>80.0% (12/15)</td>
<td>86.7% (13/15)</td>
</tr>
<tr>
<td>Specificity, %</td>
<td>100% (69/69)</td>
<td>100% (69/69)</td>
</tr>
<tr>
<td>PPV, %</td>
<td>100% (12/12)</td>
<td>100% (13/13)</td>
</tr>
<tr>
<td>NPV, %</td>
<td>95.8% (69/72)</td>
<td>95.8% (69/72)</td>
</tr>
</tbody>
</table>

| Reader 2       |                   |         |         |                   |         |         |
| Indeterminate, %| 15.5% (13/84)     | 8.3% (7/84)| 0.016   | 29.8% (25/84)     | 15.5% (13/84)| 0.003  |
| Sensitivity, %  | 60.0% (9/15)      | 73.3% (11/15)| 0.006  | 45.8% (11/24)     | 58.3% (14/24)| 0.02   |
| Specificity, % | 100% (69/69)      | 100% (69/69)| >0.05  | 98.3% (59/60)     | 100% (60/60)| >0.05  |
| PPV, %         | 100% (9/9)        | 100% (11/11)| >0.05  | 91.7% (11/12)     | 100% (14/14)| >0.05  |
| NPV, %         | 92.0% (69/75)     | 94.5% (69/73)| >0.05  | 81.9% (59/72)     | 85.7% (60/70)| >0.05  |

| Reader 3       |                   |         |         |                   |         |         |
| Indeterminate, %| 13.1% (11/84)     | 7.1% (6/84)| 0.03   | 23.8% (20/84)     | 14.3% (12/84)| 0.013  |
| Sensitivity, % | 86.7% (13/15)     | 80.0% (12/15)| >0.05  | 66.7% (16/24)     | 79.2% (19/24)| 0.004  |
| Specificity, % | 94.2% (65/67)     | 98.6% (68/69)| >0.05  | 98.3% (59/60)     | 96.7% (58/60)| >0.05  |
| PPV, %         | 76.5% (13/17)     | 92.3% (12/13)| >0.05  | 94.1% (16/17)     | 90.5% (19/21)| >0.05  |
| NPV, %         | 97.0% (65/67)     | 95.8% (68/71)| >0.05  | 88.1% (59/67)     | 92.1% (58/63)| >0.05  |

Values in the bracket are 95% confidence interval. P value < 0.05 indicates significant difference of incidence of indeterminate cases between 2 sequences in each reviewer. Indeterminate cases were considered as negative for bile duct anatomic variation for calculating sensitivity, specificity, PPV, and NPV in each reader and each sequence.

PPV indicates positive predictive value; NPV, negative predictive value; MRCP, magnetic resonance cholangiopancreatography; and CS-MRCP, compressed sensing magnetic resonance cholangiopancreatography.
sampling and reconstruction methods would be applied to enhance incoherent undersampling artifacts and the sparsity of its solution, because MRCP images are characterized by its inherently high T2 contrast of fluid signals in pancreaticobiliary structures, the potential alteration of image texture and artifact patterns would not affect the image quality of MRCP significantly. 

Also in our study, we successfully obtained BH-CS-MRCP in 28 patients using a 16-second breath-holding time, and the overall image quality of BH-CS-MRCP was demonstrated to be better than conventional navigator-triggered MRCP or CS-MRCP. The better image quality observed with this technique can be attributed to the improvement in image sharpness and duct visualization, which attributed to reducing motion artifacts by applying sparsity-based integrated sensitivity-encoding reconstruction and high undersampling of k-space data (5.7%). Similar results to our study were reported recently by Chandarana et al. showing that BH 3D-MRCP with diagnostic quality could be acquired with 5% k-space sampling and sparsity-based reconstruction at 3 T and that the image quality of BH 3D-MRCP showed similar or superior image quality for pancreatic and CBD compared with respiratory-triggered 3D-MRCP. However, compared with the previous study, which used a similar prototypical CS SPACE sequence, we made a few improvements in terms of image quality and workflow. First, we used body coils with larger numbers of coil elements, which allowed for a higher signal-to-noise ratio and higher acceleration rates by exploiting joint sparsity, and may have contributed to the better image quality of BH-CS-MRCP over conventional MRCP, despite of the shorter acquisition time. 

Second, we used online reconstruction which improved the workflow, while the previous study used in house off-line reconstruction. We also found in our study that CS-MRCP provided better diagnostic performance for detecting pancreatic diseases, with a decreased incidence of indeterminate examinations for the evaluation of bile duct anatomic variation and bile duct disease than conventional navigator-triggered MRCP. Our study results also showed that the improved image quality can contribute to the detection of more diseases and anatomic variations by reducing the number of suboptimal quality examinations. The present study holds value in demonstrating the clinical applicability and usefulness of CS-MRCP in comparison with conventional navigator-triggered MRCP, because although the previous study on BH-CS-MRCP demonstrated that CS-MRCP may provide similar image quality in comparison with conventional MRCP, it did not evaluate its diagnostic performance in biliary or pancreatic diseases. In addition, in our study, there were no significant differences in diagnostic performance for revealing biliary or pancreatic diseases between BH-CS-MRCP and conventional MRCP, which may be related with the small number of patients undergoing BH-CS-MRCP. However, based on our study results showing the superior image quality of BH-CS-MRCP compared with the other methods, we believe that BH-CS-MRCP may provide comparable or better diagnostic performance for detecting pancreatic or bile duct disease than conventional MRCP. Further studies with a large population and variable diseases are warranted to better address this issue in the future.

It is important to note that the application of CS-MRCP using the CS SPACE sequence with a high undersampling of k-space data and integrated CS reconstruction would contribute to remarkably reducing the scan time of navigator-triggered MRCP. Indeed, several studies have demonstrated that conventional navigator-triggered MRCP can provide excellent isotropic spatial resolution (1 mm³) for revealing biliary or pancreatic disorders and demonstrated excellent diagnostic performance for evaluating biliary or pancreatic disorders compared with endoscopic retrograde pancreateocholangiography or direct cholangiography. However, despite of the excellent spatial resolution of 3D T2-weighted MRCP, it is one of the sequences requiring the longest acquisition time, showing vulnerability to motion artifacts in body MR imaging. With CS-MRCP, we were able to reduce the scan time by 50% in comparison with conventional MRCP with no significant difference in image quality, yet with a reduced incidence of indeterminate imaging features. Furthermore, comparable or better image quality MRCP was able to be obtained in a single breath-hold by being resistant to motion artifacts, which may help patients with irregular breathing patterns to obtain MRCP with acceptable image quality. Our study results suggest that conventional MRCP might be able to be replaced with CS-MRCP or even BH-CS-MRCP because it provides comparable image quality in a significantly shorter time. In addition, CS-MRCP and BH-CS-MRCP may be capable of solving the issue of unpredictable scan times and reducing the risk of failed examinations in those patients, which would ultimately result in improved workflow and lower costs of pancreaticobiliary MR imaging.

Our study has several limitations. First, this is a retrospective study, thus there may have been unavoidable bias. Second, the number of patients in our study, especially those who had all 3 MRCP examinations, was small and thus may have weakened our statistical power in demonstrating possible superiority of image quality using CS-MRCP in comparison with conventional MRCP. Further prospective studies with large population would be warranted. Third, the study cohort was a relatively heterogeneous patient population for determining the diagnostic performance of conventional MRCP and CS-MRCP methods. Fourth, the standard of reference was based on results of radiologic examinations in some patients. However, most patients had benign diseases, which were not indicative histologic confirm. Fifth, we could not test the diverse regularization parameters of CS reconstruction for CS-MRCP and therefore, each protocol of CS-MRCP and BH-CS-MRCP might have room for improving image quality. Last, we reviewed only maximal intensity projection images, and there is the possibility of improving the diagnostic performance for all sequences if we reviewed the source images.

In conclusion, CS-MRCP using incoherent undersampling combined with CS reconstruction provided comparable image quality to conventional MRCP while reducing the acquisition time to within a single breath-hold (16 seconds).

ACKNOWLEDGMENT

We thank to Chris Woo (B.A., USA) for his editorial assistance.

REFERENCES

10. Iitani R, Namimoto T, Takaoka H, et al. Clinical impact of 3-dimensional balanced turbo-field-echo magnetic resonance cholangiopancreatography at 3 T: All rights reserved.


