Three-dimensional Fast-Recovery Fast Spin-Echo MRCP: Comparison with Two-dimensional Single-Shot Fast Spin-Echo Techniques

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Purpose:
To retrospectively evaluate the technical quality of and the visibility of the biliary tree and pancreatic duct on magnetic resonance (MR) cholangiopancreatographic (MRCP) images obtained with a single-breath-hold three-dimensional (3D) fast-recovery fast spin-echo (FRFSE) sequence in comparison with conventional two-dimensional (2D) single-shot fast spin-echo (SSFSE) thin-section and thick-slab sequences.

Materials and Methods:
Institutional review board approval was obtained; informed consent was not required for this HIPAA-compliant study. MRCP was performed at 1.5 T in 53 consecutive patients (25 men and 28 women, aged 23–84 years). A single-breath-hold volume acquisition was performed by using the 3D FRFSE sequence and the conventional 2D SSFSE sequences. Two radiologists graded studies obtained with each sequence in a blinded fashion, and the paired Student t test was used to assess differences in technical quality, visibility of eight individual ductal segments of the biliary tree and pancreatic duct, and number of ductal segments visualized per patient.

Results:
Studies obtained with 3D FRFSE were of significantly higher technical quality than those obtained with thin-section 2D SSFSE ($P < .02$ for both readers). The 3D FRFSE maximum intensity projection reconstruction and 2D SSFSE thick-slab sequence proved statistically equivalent with regard to the overall visibility of the biliary tree and pancreatic duct and the number of ductal segments visualized per patient. In comparison with 2D SSFSE thin-section imaging, however, 3D FRFSE imaging produced an improved overall duct segment visibility grade of 0.45 on a three-point visibility scale ($P < .001$), with a corresponding average per-patient improvement of 1.9 out of eight possible fully visualized duct segments ($P < .001$).

Conclusion:
The 3D FRFSE sequence shows promise for improved visibility of the pancreatic duct and biliary tree, compared with the conventional 2D SSFSE thin-section and thick-slab approach, while permitting the entire MRCP examination to be performed in a single breath hold.

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Magnetic resonance (MR) cholangiopancreatography (MRCP) typically employs heavily T2-weighted images of the biliary tree and pancreatic duct, in which bile, pancreatic juices, or other stationary or slowly moving fluids appear hyperintense relative to other abdominal tissues. Although a variety of imaging techniques have been used for MRCP, current protocols often use a two-dimensional (2D) single-shot fast spin-echo (SSFSE) sequence to obtain a combination of coronal thin-section images and rotating oblique-coronal thick-slab images. To obtain contiguous images with no gap, coronal thin-section MR imaging is generally performed in an interleaved fashion in one or multiple adjacent acquisitions. Respiratory or other patient motion produces misregistration between MR images, which may result in areas of missed anatomic features and limits the suitability of these thin-section data for maximum intensity projections (MIPs) or other multiplanar reformations. Thick-slab MR images provide an overview of biliary and pancreatic ductal anatomic characteristics and are obtained along rotating oblique-coronal planes, with the goal of capturing the entire biliary tree or pancreatic duct on one image. Thick-slab MR imaging, however, is operator-dependent, and a high-quality study necessitates identification of complex anatomic characteristics by a skilled technologist or a radiologist monitoring the examination. Even when examinations are well performed, inherent in-plane volume averaging effects may obscure small stones or anatomic variants.

The three-dimensional (3D) fast-recovery fast spin-echo (FRFSE) MR sequence is a new pulse sequence that may be performed in a single breath hold and produces images that are inherently contiguous and registered. These images are thus ideal for multiplanar reformations, and rotating oblique-coronal MIP reconstructions may provide an anatomic overview similar to that with conventional thick-slab MR images. Thus, the 3D FRFSE sequence offers the possibility of replacing the combined thin-section and thick-slab MRCP approach with a simplified single-volume acquisition. Toward furthering this goal, the purpose of our study was to retrospectively evaluate technical quality and visibility of the biliary tree and pancreatic duct by comparing MRCP image sets obtained with the single-breath-hold 3D FRFSE sequence and those obtained with conventional 2D SSFSE imaging including thin-section and thick-slab acquisitions.

**Materials and Methods**

GE Medical Systems (Waukesha, Wis) provided the use of the 3D FRFSE pulse sequence for this study and information about hidden sequence parameters. The authors had full control of both the data and the information submitted for publication.

**Patients**

We retrospectively evaluated MR studies from 53 consecutive patients referred for MR imaging of the liver or pancreas between September 18, 2002, and November 25, 2002. Our routine clinical protocol at that time included both 2D SSFSE and 3D FRFSE imaging to increase the yield from our MRCP examinations, which our abdominal imaging group had previously considered suboptimal with 2D SSFSE imaging alone. Institutional review board approval was obtained, informed consent was not required, and this study was compliant with the Health Insurance Portability and Accountability Act. Of the 53 patients, there were 25 men and 28 women aged 23–84 years (mean age, 51 years). Women ranged in age from 35 to 81 years (mean age, 53 years), and men ranged in age from 23 to 84 years (mean age, 49 years). Results of a two-tailed Student t test showed no statistically significant difference in age between men and women (P = .27). Patients were referred for a wide variety of indications, as follows: 24 patients (45%) were known to have or were suspected of having liver lesions, seven patients (13%) were known to have or were suspected of having pancreatic masses or pancreatitis, six patients (11%) had hepatitis or cirrhosis, seven patients (13%) had abnormal liver function test findings, 10 patients (19%) had abdominal pain, and one patient (2%) had a splenic mass. These numbers exceed 100% because of coexisting indications in some patients.

**MR Imaging Technique**

Technologists imaged all patients with a 1.5-T MR imaging unit (Signa LX, software version 8.4; GE Medical Systems). There were no dietary restrictions before imaging, and no oral contrast material or antiperistaltic agents were used. Each patient underwent imaging with conventional 2D SSFSE MRCP sequences, which included coronal thin-section imaging and rotating oblique-coronal thick-slab MR imaging, followed by a single-breath-hold 3D FRFSE MR sequence. Imaging parameters are summarized in the Table. Breath holds for thin-section 2D SSFSE and 3D FRFSE imaging were at end inspiration after two preceding full respiratory cycles. Typically, at least three previous similar breath-hold sessions had been performed as part of a preceding liver or pancreas MR imaging examination. A 10–15-second pause was used between thin-section 2D SSFSE interleaved acquisitions. Thick-slab MR images were...
obtained at end inspiration of sequential breath-holds, after expiration and repeat full inspiration.

The 2D SSFSE thin-section images were obtained by using an interleaved acquisition strategy with a section thickness of 3 mm and no gap. The number of coronal images obtained varied from 15 to 68 (median, 21) divided into one to four contiguous acquisitions, with a breath-hold duration of 20-30 seconds per acquisition. These values varied according to the patient’s anatomic characteristics and the technologist who obtained the images. On the basis of the field of view and matrix used, in-plane image resolution was 1.6 x 1.6 mm. The 2D SSFSE thick-slab images were obtained as four to six rotating oblique-coronal images with 40-mm-thick sections, a breath-hold duration of 3 seconds per image, and an in-plane image resolution of 0.8 x 1.0 mm. Technologists prescribed oblique thick-slab images from a previously performed transverse T2-weighted FRFSE sequence (repetition time msec/echo time msec, 2500/90) and had sample annotated images to aid in slab placement. The technologists were instructed at minimum to obtain slabs oriented parallel to the pancreatic head, in a straight coronal plane, parallel to the pancreatic tail, and centered obliquely on the middle portion of the common bile duct to cover the biliary tree. Additional slabs were obtained at the technologist’s discretion.

For the 3D FRFSE sequence, the imaging parameters were as follows: 1500/480, 4-mm-thick sections, and an in-plane image resolution of 1.6 x 2.5 mm. Phase encoding was in both the left-right and anteroposterior directions, with half-Fourier acquisition in the left-right direction. Each excitation filled a full coronal plane in k-space, with 18 excitations performed to phase encode the anteroposterior “section” direction. Zero-filled interpolation was used to reconstruct the 4-mm-thick coronal sections in 2-mm increments (ZIP2; GE Medical Systems) and to achieve an image matrix size of 512 along the left-right direction (ZIP512; GE Medical Systems) for better MIP reconstructions. Four coronal images (total extent, 8 mm) were then discarded from both the front and back of the image volume to remove distortions from imperfect section-selection profiles. The total breath-hold duration was 24 seconds per image. Imaging parameters are summarized in the Table. Rotating MIP reconstructions of the 3D FRFSE MR data were performed with a workstation (Voxar 3D version 4.1SR1; Voxar, Framingham, Mass) to produce oblique images rotating about the z-axis in 10° increments.

Image Analysis

Two abdominal radiologists (K.J.M. and M.A.B., with 6 and 8 years of abdominal MR imaging experience, respectively), independently graded the MRCP studies. Studies from each of the four sequence types (2D SSFSE thin-section, 2D SSFSE thick-slab, coronal 3D FRFSE, and 3D FRFSE rotating MIP reconstruction) were graded in separate viewing sessions that were separated by at least 1 week. Studies were read in different orders in each session, as follows: (a) alphabetically by name and sequentially by (b) medical record number, (c) department accession number, and (d) date of acquisition. Readers were blinded to all identifying patient information but could not be blinded to sequence type because each produces images with a characteristic appearance. The 2D thin-section and thick-slab MR images and the coronal 3D FRFSE MR images were viewed with a picture archiving and communications, or PACS, workstation (Impax R4, AGFA, Ridgefield Park, NJ; display resolution, 1024 x 1024) that allowed the adjustment of magnification, window, and level settings. Three-dimensional FRFSE MIP reconstructions were viewed with a workstation (Voxar; display resolution, 1600 x 1200).

Each reader evaluated the technical quality on the basis of a qualitative glance of overall contrast-to-noise ratio and artifact severity, as follows: grade of 1, excellent; grade of 2, slightly limited; grade of 3, marginal; grade of 4, poor; and grade of 5, unreadable. For example, a study with a grade of 3 might exhibit substantial visible noise or motion artifact while remaining of diagnostic quality, whereas a study with a grade of 5 would be considered nondiagnostic, with a contrast-to-noise ratio so poor that the ductal system is barely distinguishable. Both readers assessed the visibility of eight ductal segments: the right hepatic duct, left hepatic duct, common hepatic duct, cystic duct, common hepatic duct, cystic duct, common hepatic duct, cystic duct, and common hepatic duct. The results were compared with a qualitative grading of each sequence type. A grade of 1 demonstrated excellent diagnostic quality, whereas a grade of 5 was considered nondiagnostic, with a contrast-to-noise ratio so poor that the ductal system is barely distinguishable. Both readers assessed the visibility of eight ductal segments: the right hepatic duct, left hepatic duct, common hepatic duct, cystic duct, common hepatic duct, cystic duct, common hepatic duct, cystic duct, and common hepatic duct.

Summary of MRCP Imaging Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Thin Section</th>
<th>Thick Slab</th>
<th>3D FRFSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Echo time (msec)</td>
<td>800</td>
<td>900</td>
<td>480</td>
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<tr>
<td>Repetition time (msec)</td>
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<td>NA</td>
<td>1500</td>
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<tr>
<td>Bandwidth</td>
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<td>31.25</td>
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<tr>
<td>Acquisition plane</td>
<td>Coronal</td>
<td>Rotating oblique coronal</td>
<td>Coronal 3D</td>
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<td>Field of view (cm)</td>
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<td>26 x 26</td>
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</tr>
<tr>
<td>Section thickness (mm)</td>
<td>3*</td>
<td>40</td>
<td>4</td>
</tr>
<tr>
<td>No. of images</td>
<td>15–68 (median, 21)</td>
<td>4–6</td>
<td>14</td>
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<td>Matrix</td>
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<td>320 x 256</td>
<td>256 x 120</td>
</tr>
<tr>
<td>Resolution (mm)</td>
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<td>0.8 x 1.0 x 40</td>
<td>1.6 x 2.5 x 4</td>
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<tr>
<td>Other options</td>
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<td>Flow compensation</td>
<td>ZIP2, ZIP512</td>
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<td>Acquisition strategy</td>
<td>1–4 interleaved acquisitions</td>
<td>4–6 short breath holds</td>
<td>Single breath hold</td>
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<td>Breath-hold duration (sec)</td>
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<td>24 total</td>
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<tr>
<td>Half-Fourier direction</td>
<td>Left to right</td>
<td>Left to right</td>
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</tr>
</tbody>
</table>

Note.—NA = not applicable.

* No intersection gap.
mon bile duct, pancreatic duct head, pancreatic duct body, and pancreatic duct tail. Each segment was graded on a three-point scale, as follows: grade of 1, completely visualized; grade of 2, incompletely visualized; and grade of 3, not visualized. A grade of “NA” was given if the segment was not covered in the imaging volume or not seen because of a pathologic condition or previously performed surgery. Standardatomic definitions of duct segments were used. The left and right hepatic ducts were considered completely visualized if they could be seen from their confluence to their first-order intrahepatic branches. Readers assigned a grade of 1 to a cystic duct remnant if they believed that a cholecystectomy had been performed and that they could visualize the entire cystic duct remnant. The determination that segments were absent owing to a pathologic condition or previously performed surgery was made solely from the interpretation of the MRCP study under review.

Statistical Analysis
A variety of statistical comparisons were performed (by K.H.Z.) by using software (S-Plus; http://www.insightful.com) within each of the two arms of comparison, as follows: (a) thin-section 2D SSFSE versus coronal 3D FRFSE and (b) thick-slab 2D SSFSE versus 3D FRFSE MIP reconstruction. All results were analyzed independently for each reader, and consensus was not used in cases of disparate grading. Conventional interpretations of $P$ values were used for all statistical tests, with a $P$ value of less than .05 considered to be indicative of a statistically significant difference.

Technical quality.—For each of the two readers and for each of the two arms of the study, technical quality grades were compared by calculating a mean grade difference and $P$ value by using the paired Student $t$ test. Studies were then classified into a “diagnostic group,” which included studies with technical quality grades that ranged from excellent to marginal (grades 0–3), and a “nondiagnostic group,” which included studies with poor and unreadable technical quality grades (grades 4 and 5). The diagnostic group was used in a subsequent analysis in an attempt to better compare studies of similar technical quality.

Duct segment visibility.—For all segment visibility comparisons, we eliminated segments from calculations if they were not seen with either of the two sequences within that comparison arm owing to inadequate anatomic coverage from a prescription error or absence of the segment owing to a pathologic condition or previously performed surgery. For example, if the pancreatic duct body was cut off because the image prescription volume did not extend anterior enough, then that segment was eliminated—even if it was fully visualized with the other sequence.

For each of the eight anatomic duct segments, for each of the two readers, and in each of the two arms of the study, a mean visibility grade difference and $P$ value were calculated by using the paired Student $t$ test. The same calculation was performed by pooling all valid segments from all patients. This pooled-segment analysis of duct segment visibility was then repeated with the subset of studies considered to be of diagnostic quality.

Results
Of the 53 patients, 42 (79%) had normal-caliber biliary and pancreatic ducts. Conversely, 11 patients (21%) had abnormalities at MRCP, including biliary dilatation in seven patients (13%), strictures in two (4%), and postoperative changes (excluding cholecystectomy) in five (9%). Cholecystectomy had been performed in 13 patients (25%). Cholelithiasis was present in five patients (9%), pancreas divisum in eight (15%), and an aberrant biliary tree anatomy in 11 (21%). These data were obtained from surgical and dictated radiology reports—including those from the MRCP study under evaluation and from the associated liver or pancreatic MR examinations—solely to provide an approximate sense of how “normal” the structures of interest were in our study population. Figure 1 demonstrates sample images from the four MRCP image sets in a patient with a normal-caliber biliary tree. Figure 2 shows the four sequences in a patient with a Klatskin tumor.

Technical Quality
Results of the comparison of technical quality grades are displayed in Figure 3. For both readers and in both arms of the comparison, the technical quality of the 3D FRFSE studies was judged to be higher than that of the corresponding 2D SSFSE studies. The mean grade differences varied between 0.4 and 0.9 with the five-point grading scale. $P$ values obtained with the paired Student $t$ test demonstrated these differences to be statistically significant for both readers, although the values were more highly significant for reader B ($P = .02$ for reader A, $P \leq .002$ for reader B).

To place these technical quality differences into a more clinically relevant context, studies were divided into a di-
agnostic group, which included studies with technical quality grades ranging from excellent to marginal (grades 0–3), and a nondiagnostic group, which included studies considered to be of poor or unreadable technical quality (grades 4 and 5). With use of these criteria for the thin-section comparison arm, readers A and B considered 17 and 16 of the 53 thin-section studies, respectively, to be nondiagnostic. Readers A and B considered 15 and 12 studies, respectively, to be of inadequate quality with 2D SSFSE imaging alone, two and three studies to be of inadequate quality with both sequences, and no studies and one study to be of inadequate quality with 3D FRFSE imaging alone. Thus, the vast majority of nondiagnostic studies are due to the poor quality of the 2D SSFSE studies, with 32% and 28% of SSFSE thin-section studies considered to be technically inadequate by readers A and B, respectively. Conversely, readers A and B considered only 4% and 8% of 3D FRFSE studies to be technically inadequate, respectively.

In the thick-slab comparison arm, readers A and B considered 19 and 23 studies (of 53 thick-slab studies total), respectively, to be nondiagnostic, with 12 and 18 studies of inadequate quality with 2D SSFSE imaging alone, five and three studies of inadequate quality with both sequences, and two and two studies of inadequate quality with 3D FRFSE MIP reconstruction alone. Again, most nondiagnostic studies were excluded because of the poor quality of the 2D SSFSE studies, with 32% and 40% of 2D SSFSE thick-slab studies considered to be technically inadequate by readers A and B, respectively, compared with only 13% and 9% with 3D FRFSE MIP reconstructions.

Duct Segment Visibility

Comparison of duct visibility included only valid duct segment pairs—those segments not judged absent from either image set on the basis of poor anatomic coverage, previously performed surgery, or pathologic condition. Of the maximum possible 424 segments (eight anatomic segments in 53 patients), the comparison of the 2D thin-section images versus coronal 3D FRFSE source images included 379 valid segment pairs for reader A and 392 for reader B. The comparison arm of 2D SSFSE thick-slab imaging versus 3D FRFSE MIP reconstruction included 404 and 408 valid segment pairs, respectively.

Figures 4 and 5 display results of the duct visibility comparisons, both on a segment-by-segment basis and for all anatomic segments combined. Figure 4 shows the results of the comparison between 2D SSFSE thin-section and 3D FRFSE imaging. For both readers, a highly significant \( P < .001 \) improvement in duct visibility grade was achieved with 3D FRFSE imaging, with a mean visibility grade difference for all segments of 0.4–0.5 with the three-point grading scale. Reader A found each individual anatomic segment to be better visualized with 3D FRFSE imaging for each of the eight segments \( P \leq .003 \). Reader B found a highly significant \( P \leq .004 \) improvement in duct visibility for all segments in the biliary tree and the pancreatic body, a statistically significant \( P = .02 \) improvement in the pancreatic head, and a nonsignificant \( P = .08 \) trend toward improve-
Figure 2: MR images of a Klatskin tumor. (a) Sequential thin-section coronal 2D SSFSE images (800/800, 3-mm-thick sections) with horizontal line added for reference. Motion-related in-plane misregistration is evidenced by superior displacement of the biliary tree on the two right-hand images, whereas through-plane misregistration results in duplicate coverage of the same anatomic features (arrows) on the first and third images (although it is just as likely to fail to depict anatomic features). (b) Sequential source coronal 3D FRFSE images (1500/480, 4-mm-thick sections interpolated to 2 mm) demonstrate uniform image registration and spacing. (c) Example oblique coronal 2D SSFSE thick-slab images (900/900, 40-mm-thick slab) and (d) corresponding MIP reconstructions from the 3D FRFSE data. Note improved visibility of the thin-caliber pancreatic duct (arrowheads) with the 2D versus the 3D technique. In (d), ability to reconstruct images at any angle assists with evaluation of intrahepatic ductal invasion by cholangiocarcinoma because the right hepatic duct is clearly obstructed beyond its first-order intrahepatic confluence (arrow).
ment in the pancreatic tail. When we repeated the pooled segment analysis with the subset of diagnostic studies, the mean duct segment grade differences shown in Figure 4 decreased from 0.47 to 0.27 for reader A and from 0.43 to 0.20 for reader B, with both differences remaining statistically significant ($P < .005$).

Conversely, the pooled-segment comparison shown in Figure 5 demonstrates the overall statistical equivalence of 2D SSFSE thick-slab MR imaging and 3D FRFSE rotating MIP reconstruction, with a slight, nonsignificant trend toward improved visibility with 2D thick-slab MR imaging. The reason for this trend is revealed by the individual segment comparisons, which for both readers exhibit statistically significant ($P \leq .05$) improved visibility grades for the three segments of the pancreatic duct with thick-slab MR imaging. These results, however, are partially negated in the overall pooled segment analysis by the improved visibility of the common bile duct with 3D FRFSE (the improvement was statistically significant for...
reader A and nonsignificant for reader B) and by the slight, nonsignificant increase in the number of segments better seen with 3D FRFSE throughout most of the biliary tree. When we repeated the pooled segment analysis with the subset of diagnostic studies, the mean duct segment grade differences shown in Figure 5 increased from the statistically insignificant values of 0.06–0.09 to statistically significant values of 0.29 for both readers (P = .003).

**Number of Duct Segments Visualized per Patient**

To place duct visibility differences into clinical context on an individual patient basis, Figure 6 shows the difference in the number of segments visualized per patient with the two techniques. Two different threshold criteria were used to define segment visibility, as follows: segments that were completely visualized (grade 1) and those that were at least partially visualized (grades 1 or 2). In the thin-section comparison arm with the more stringent visibility criterion, 3D FRFSE imaging resulted in an average of 4.8 fully visualized segments per patient. The average number of fully visualized segments per patient with 2D SSFSE imaging was 2.9, for an average per-patient improvement of 1.9 segments. These results were statistically significant (P < .001) for both readers. With use of the less-stringent threshold, 3D FRFSE imaging resulted in an average of 6.2 segments that were at least partially visualized per patient, versus 4.8 with 2D SSFSE imaging, for an average per-patient improvement of 1.3 segments. Again, this finding was statistically significant (P < .001) for both readers. Similar calculations in the comparison of thick-slab 2D SSFSE imaging versus 3D FRFSE rotating MIP reconstruction show a slight trend toward better overall visibility with 2D SSFSE imaging, although these results are not statistically significant.

Figure 7 shows the results of the same calculation as in Figure 6, repeated with the subset of diagnostic studies. As noted earlier, most nondiagnostic studies were eliminated due to the poor technical quality of the 2D SSFSE study. Although this is seen to reduce the benefits of 3D FRFSE over 2D SSFSE, there remains a statistically significant improvement in the number of visualized ducts with 3D FRFSE imaging over thin-section 2D SSFSE imaging, with an excess of 0.8–1.3 fully visualized segments per patient (P < .001 and P = .01 for readers A and B, respectively) and 0.5–0.6 fully or partially visualized segments with the less stringent visibility criterion (P = .005 and P = .05 for readers A and B, respectively). In the thick-slab comparison arm after the exclusion of studies of low technical quality, most studies were again discarded due to the poor technical quality of the thick-slab 2D SSFSE study. Within this subset of higher-quality studies, Figure 7 demonstrates a statistically significant advantage of 2D SSFSE thick-slab imaging over 3D FRFSE MIP reconstruction, with a per-patient benefit of 1.3–1.4 fully visualized segments with thick-slab imaging (P < .001) and 0.7–1.0 fully or partially visualized segments with the less-stringent criterion (P < .001 and P = .03 for readers A and B, respectively).

**Interobserver Agreement**

Figure 8 shows the κ statistic and percentage agreement between the two readers for the four image sets on the basis of visibility grades from all anatomic segments pooled for all patients. Good interobserver agreement is demonstrated for all four image sets, without great variations between the different techniques.
Discussion

Since its introduction in 1991, imaging techniques used for MRCP have undergone a progressive evolution. Initial investigators used T2-weighted steady-state free-precession gradient-echo sequences (1,2). Subsequent investigators used rapid acquisition with relaxation enhancement, or RARE (3), and its counterparts fast spin echo and turbo spin echo in both 2D (4) and 3D (5) implementations. These sequences all consist of a long series of spin echoes with a different phase-encoding step performed during each echo. The long echo trains lend these sequences to heavy T2 weighting, making them well suited to the visualization of fluid in MRCP. Since the first application of a single-shot RARE technique to MRCP (6), most MRCP examinations have been performed with similar single-shot, long-echo-train acquisitions (7–9). These take a variety of different names, including single-shot RARE, half-Fourier acquisition single-shot turbo spin-echo (HASTE; Siemens, Iselin, NJ), and SSFSE and single-shot turbo spin-echo sequences. Both thin-section and thick-slab techniques have been used independently (10,11), although most current protocols include a combination of thick-slab imaging to provide an anatomic overview and thin-section imaging to provide fine detail.

The FRFSE sequence is similar to the conventional fast spin-echo pulse sequence in that a long train of spin echoes is used to acquire multiple phase-encoding steps. Immediately after the last echo used for signal acquisition, however, residual transverse magnetization is refocused into a final spin echo and then flipped back along the z-axis by a 90° fast-recovery pulse to increase longitudinal magnetization and create a driven equilibrium (12). This essentially jump-starts the T1 relaxation process before the next excitation, which increases the signal-to-noise ratio for tissues with long T2 relaxation times because these tissues have more transverse magnetization remaining at the end of the long echo train. MRCP is thus a natural application for the technique because the biliary and pancreatic fluids of interest have inherently slow T2 relaxation.

Three-dimensional acquisition is also appealing for MRCP because it provides intrinsically contiguous sections that may be used to reconstruct images in any projection, which yields the anatomic overview normally provided with thick-slab 2D images. Volumetric acquisition itself boosts the signal-to-noise ratio: As each excitation covers the entire volume, every phase-encoding step essentially adds an additional signal average, which results in an increase in signal-to-noise ratio by the square root of the number of sections. Conversely, the primary theoretical disadvantage of 3D

![Figure 7](image1.png)

**Figure 7:** Graph shows total number of visualized segments per patient after exclusion of nondiagnostic studies (poor or unreadable technical quality); only diagnostic studies of excellent, slightly limited, and marginal quality were included. Data are for thin-section 2D SSFSE versus coronal 3D FRFSE imaging (2D thin vs 3D coronal) and thick-slab 2D SSFSE imaging versus 3D FRFSE rotating MIP reconstruction (2D thick vs 3D MIP). Bar graph data are the excess number of segments visualized with the 3D technique over the corresponding 2D technique (negative numbers indicate greater number of segments visualized with 2D technique vs 3D technique). Two separate visibility threshold criteria were used for each reader and comparison arm: segments that were fully visualized and segments that were either fully or partially visualized. Corresponding P values (Student’s t test) are beneath each bar.

![Figure 8](image2.png)

**Figure 8:** Graph shows interobserver agreement (kappa and percentage agreement) between the two readers. Data were calculated from visibility grades of all pooled anatomic segments for each of the four pulse sequences. 2D thick = thick-slab 2D SSFSE, 2D thin = thin-section 2D SSFSE, 3D coronal = coronal 3D FRFSE, 3D MIP = 3D FRFSE MIP reconstruction.
acquisition is that artifacts from patient motion are distributed in a complex fashion throughout the full set of images; therefore, short breath-hold times are crucial for good image quality.

The 3D FRFSE pulse sequence capitalizes on the combined benefits of FRFSE imaging and volumetric acquisition. In fact, the benefits of driven equilibrium or fast recovery are only realized with sequences in which a given voxel undergoes repetitive excitation, as in 3D acquisition strategies. The flip-back pulse has no effect on single-shot acquisitions because signal is not subsequently collected from the same section. The added signal-to-noise ratio achieved with both the fast-recovery flip-back pulse and the 3D acquisition enables one to shorten the repetition time enough to achieve a realistic breath-hold time, and the volumetric acquisition enables the flexibility of multplanar reformation after one acquisition. A comparison of 3D FRFSE with 3D fast imaging employing steady-state acquisition (FIESTA; GE Medical Systems) and 2D SSFSE MRCP has recently been performed by other investigators in a small number of patients (14).

In our study, the technical quality of image sets obtained with the 3D FRFSE sequence was routinely higher than that with the corresponding 2D SSFSE thin-section and thick-slab sequences. In addition, 3D FRFSE imaging resulted in markedly fewer studies of nondiagnostic technical quality. Furthermore, for this sequence only a single coronal volume needs to be placed over the biliary tree and pancreatic ducts; there is no need to arrange the rotating oblique-coronal 2D SSFSE thick-slab planes.

In comparison with thin-section 2D SSFSE imaging, 3D FRFSE imaging provided increased visibility of all individual ductal segments across the patient population (although this improvement did not attain statistical significance in the sole case of the pancreatic tail for reader B), with a corresponding increase in the number of ductal segments seen per patient. Calculations were repeated in the smaller subset of diagnostic studies in an attempt to correct somewhat for the inconsistencies in technical quality of 2D SSFSE studies, which greatly biased the comparison toward the SSFSE technique. There nonetheless remained a statistically significant benefit in the number of ductal segments visualized per patient, which suggests that even with further optimization of the standard 2D SSFSE thin-section sequence, 3D FRFSE imaging would remain beneficial.

In our thick-slab MR imaging comparison arm, the overall results obtained on a per-patient basis with 3D FRFSE MIP reconstruction were comparable with those obtained with 2D SSFSE thick-slab imaging, although thick-slab images are statistically better for depicting the small-caliber pancreatic duct. This can be explained by the superior in-plane resolution of the thick-slab 2D SSFSE images. Exclusion of studies considered to be of nondiagnostic technical quality again greatly biased the comparison toward the SSFSE technique, and a statistically significant overall benefit emerged in the number of ductal segments visualized per patient with thick-slab SSFSE imaging. This highlights the inconsistent technical quality of the 2D SSFSE thick-slab studies. It does suggest, however, that if optimal thick-slab MR images could be routinely obtained in a real-world setting, they would be superior to 3D FRFSE MIP reconstructions and may thus remain a useful complementary technique until 3D FRFSE imaging can be performed with higher in-plane and through-plane resolution.

Our study has the following limitations: The scope of the study was not intended as a comparison of techniques for particular disease states, and differences in the ability to make specific clinical diagnoses can only be inferred. Most of our patients (80%) had a normal small-caliber biliary tree and pancreatic duct. Although this would seem beneficial for highlighting subtle differences in the discriminatory thresholds of the sequences being compared, one might expect these differences to be less crucial in cases of ductal disease that typically contain at least some dilated segments.

From a statistical standpoint, a potential limitation of our study is that there is an inherent assumption that individual segment grades are statistically independent. The eight ductal segments in a given sequence, however, might be expected to show partial correlation owing to the overall technical quality of the sequence being assessed. This might have an effect on our pooled segment results included in Figures 4 and 5 but would not be expected to influence the other results presented or the overall conclusions drawn from our study.

A further limitation of our study is that the 2D SSFSE thin-section and thick-slab MR techniques that served as the standard for comparison could certainly benefit from further optimization, including, for example, a decrease in the larger-than-necessary field of view used with thin-section imaging (although this would decrease the signal-to-noise ratio and might necessitate a compensatory increase in section thickness). Although the long echo time used with these sequences generally provides adequate background suppression, the addition of fat-saturation pulses to both SSFSE sequences might provide an additional benefit. Further technologist training to standardize image prescription of the 2D SSFSE sequences would likely also be beneficial.

Finally, optimization of the 3D FRFSE sequence parameters remains a work in progress. Further shortening of the breath-hold duration would be advantageous, and multplanar reformations could benefit from more isotropic voxel dimensions. The recent advent of parallel imaging techniques offers promise in this regard. Although parallel imaging has recently been applied in combination with respiratory-triggered 3D FRFSE imaging (15,16), to our knowledge it has not been reported in single-breath-hold MRCP techniques. The decreased imaging time it allows could be applied toward further reducing breath-hold duration and/or increasing spatial resolution, although the corresponding decrease in signal-to-noise ratio would need to be assessed. For example, the time savings of a typical clinical parallel imaging acceleration...
factor of two would enable a 3D FRFSE sequence to be performed with thinner 3-mm-thick coronal sections and a more uniformly achievable breath-hold duration of approximately 16 seconds.

In summary, the results of our study have demonstrated a significant benefit of 3D FRFSE imaging over conventional 2D SSFSE thin-section imaging. Although the increased in-plane resolution of optimally performed thick-slab 2D SSFSE imaging provides better visualization of small-caliber pancreatic ducts compared with 3D FRFSE MIP reconstruction, in a realistic setting there is overall statistical equivalence of the thick-slab and MIP techniques. In this setting, 3D FRFSE imaging enables a complete MRCP examination to be performed in a single breath hold, which decreases the examination time, simplifies image prescription, and provides images of routinely improved technical quality compared with 2D SSFSE imaging.

References


