A single-breath-hold magnetic resonance cholangiopancreatography using Compressed Sensing: A pilot study at 1.5T and 3T

Hélène Blaise[1]; Khalid Ambarki Ph.D.[2]; Elisabeth Weiland, Ph.D.[3]; Valérie Laurent, M.D., Ph.D.[1]

[1] Department of Radiology, Nancy University Hospital, Vandoeuvre-lès-Nancy, France
[2] Siemens Healthineers, Saint-Denis, France
[3] Siemens Healthineers, Erlangen, Germany

Abstract

Background and purpose
Rapid imaging is essential in clinical MR imaging of the abdomen. Currently available high-resolution 3D magnetic resonance cholangiopancreatography (MRCP) techniques are typically respiratory triggered and time demanding.

The aim of the present study is to compare the image quality of a single-breath-hold Compressed Sensing (CS) 3D SPACE MRCP and the conventional respiratory-triggered (RT) 3D SPACE[1] MRCP sequence at both magnetic field strengths (1.5T and 3T).

Materials and methods
40 patients were enrolled for this retrospective study; 20 patients were scanned at 1.5T and 20 patients at 3T. The mean age was 54 years ranging from 22 to 85 years. Of those, 16 were male and 24 were female.

Results
No difference was found in the overall image quality and blurring between the conventional RT MRCP sequence and the prototype single-breath-hold CS MRCP sequence at 1.5T. At 3T, significantly better overall quality and sharpness was observed in the single-breath-hold CS MRCP images compared to the conventional method.

Conclusions
The single-breath-hold CS MRCP prototype provides a similar or superior overall quality and sharpness compared to the respective conventional sequence at 1.5T and 3T.

[1] WIP, the product is currently under development and is not for sale in the US and in other countries. Its future availability cannot be ensured.

Introduction

Magnetic resonance cholangiopancreatography (MRCP) is a non-invasive imaging technique that allows evaluation of the bile and pancreatic duct anatomy and provides highly relevant information in cases of stenosis of the gall bladder duct or occlusion of the pancreatic duct indicating related diseases. Currently, MRCP is either performed with breath-hold thick-slab two-dimensional acquisition or with respiratory-triggering (RT) using three-dimensional acquisition. MRCP can be performed using heavily T2-weighted fast-spin echo sequences such as sampling perfection with application-optimized contrast using different flip angle evolutions (SPACE) [1].

This technique is a three-dimensional acquisition typically providing images of isotropic and high spatial resolution with good background suppression. In clinical routine, maximum-intensity-projection reconstructions can be done to provide a comprehensive overview of the biliary and the pancreatic systems. Due to breathing motion, the MRCP SPACE sequence uses a prospective RT technique to ensure that data is only acquired in a specific phase of the respiratory cycle. Thus, only a small amount of *k*-space data is acquired during each respiratory cycle. Consequently, the acquisition time is long, with an average of 6 minutes in our experience. Under unfavorable circumstances, it may even exceed 10 minutes when the patient has an irregularly respiratory rate. Furthermore, it is hard to breathe regularly over 6 minutes and patients with abdominal pain tend to have an irregular respiratory rate, significantly increasing blurring and motion artifacts. In MR imaging of the abdomen, MRCP is one of the longest sequences and often longer acquisition time is associated with sub-optimal image quality [2, 3]. There is a clinical need for better techniques that shorten the scan time without comprising on image quality.

It is well known that MR images are compressible and contain redundant information. If only the main components of an MR image can be assessed, this will allow the measurement of fewer data and thus will accelerate the acquisition process. This challenge can be achieved using Compressed Sensing (CS) MR technique. The CS MR technique is based on three notions [4]:

1. Image sparsity
2. Incoherent sampling
3. Use of appropriated reconstruction method to enforce sparsity for image recovery.

An example of image sparsity is MR angiography where only few pixels (vessels) are bright and the majority of pixels are dark due to background tissue suppression. The information content of the image can thus be represented by a small amount of measurements. The second aspect is the incoherent sampling which is a requirement for subsequent optimization of image quality with iterative reconstruction. A well-established method for incoherent sampling is the random or pseudo-random fashion method where phase-encoded lines are omitted causing incoherent, 'noise-like' artifacts instead of discrete artifacts. Images with incoherent artifacts can't be used for clinical diagnosis. These incoherent artifacts need to be eliminated using appropriate iterative reconstruction methods in order to reconstruct images with quality comparable when incoherent *k*-space sampling is not applied.

CS was successfully applied in cerebral MR angiography imaging in different diseases [5, 6]. It is obvious that similarities exist between MR angiography and MRCP, therefore it is reasonable to assume that CS can be applied for MRCP. Recently, these three basic requirement concepts for CS were applied for MRCP application using a new compressed sensing 3D SPACE MRI sequence. This technique is based on a pseudo-random under-sampling with a variable density Poisson disc pattern. Previous studies have shown promising findings using a single-breath-hold 3D CS-MRCP sequence with comparable findings as the RT conventional MRCP sequence [2, 7]. To our knowledge, the breath-hold CS MRCP sequence has not been evaluated at 3T and 1.5T field strength. In the present study, we used a similar single-breath-hold (17 seconds) protocol of a non-product CS-SPACE MRCP sequence[1] and described our experience at both 1.5T and 3T field strengths on a 1.5T MAGNETOM Avanto^{fit} system (using software version *syngo* MR E11C) and a 3T MAGNETOM Skyra system (using software version *syngo* MR E11C).

The purpose of the present study is to compare the image quality of a prototype single-breath-hold CS-SPACE MRCP sequence and the conventional RT SPACE MRCP.

Method

Patient group study
40 patients were recruited for this retrospective study, the MR examinations were performed during the period from January through April 2018. 20 patients were scanned at 1.5T and 20 at 3T. The mean age was 54 years ranging from 22 to 85 years. Of those, 16 patients were male and 24 were female.

Magnetic resonance imaging
The patients were scanned using a 1.5T MRI system (MAGNETOM Avanto^{fit}, Siemens Healthcare, Erlangen, Germany) or a 3T (MAGNETOM Skyra, Siemens Healthcare, Erlangen, Germany). Patients were scanned each time in supine position, feet-first. An 18-channel body-matrix coil and a 32-channel posterior spine coil were used. Only coil elements that covered the volume-of-interest were selected for all MRCP acquisitions.

All MRI investigations included the conventional RT SPACE MRCP sequence as well as the single-breath-hold CS-SPACE MRCP. The conventional MRCP sequence was always performed first. The main MRI parameters are described below:

Conventional RT SPACE MRCP: FOV = 400 x 400 mm^2; TR = variable depending on respiratory rate; TE = 711 ms / 705 ms (1.5T/3T); FA = 140°/120°; number of averages = 1.4/2.0; parallel imaging factor = 2; 64 coronal sections were acquired. The acquired voxel size was 1.1 x 1.0 x 1.5 mm^3 (reconstructed to 1 x 1 x 1.2 mm^3) at 1.5T and 1.2 x 1.0 x 1.5 mm^3 (reconstructed to 0.6 x 0.6 x 1.2 mm^3) at 3T. The acquisition time was between 4 and 10 minutes.

Single-breath-hold CS-SPACE MRCP: FOV = 400 x 400 mm^2; TR = 1700 ms; TE = 426 ms / 432 ms; FA = 120°/120°; number of excitation = 1.9/1.4; 64 coronal sections were acquired. The acquired size was 1.2 x 1.2 x 2.4 mm^3 (reconstructed to 0.6 x 0.6 x 1.2 mm^3) at 1.5T and 1 x 1 x 2.2 mm^3 (reconstructed to 0.5 x 0.5 x 1.1 mm^3) at 3T. The acquisition time was about 17 seconds for both magnetic field strengths. During the acquisition of this sequence an acceleration factor of 23 was achieved.

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CS reconstruction was done inline based on a SENSE optimization problem to enforce sparsity. Spatial regularization was performed using Haar wavelet transform [6]. 20 iterations were executed to reconstruct the images and the required time for reconstruction was about 6 minutes.

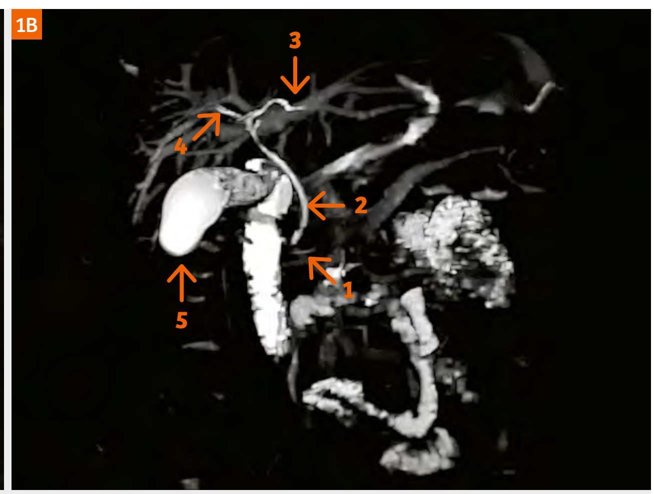
Image quality assessment

The native images of both MRCP sequences were independently analyzed by two raters. The image quality grading was based on the visualization of the main structures of the bile and pancreatic duct systems: Right and left intrahepatic ducts (IHs), pancreatic duct and cystic duct. These structures are shown in Figure 1 on a reconstructed MIP data from both MRCP sequences in the same patient. The grading of the visualization of these structures as well as the overall image quality were based on a 5-points scale. Background suppression and image blurring was evaluated using a 4-points scale as shown on Table 1. The average of both raters was used for statistical analysis to compare BH CS MRCP and RT MRCP sequences.

Statistical analysis

All measured variables (overall quality, blurring, background suppression and duct visualization) were expressed as mean ± standard deviation (SD). A two-tailed Wilcoxon signed-rank test was used to compare the mean values of the measured variables between the conventional RT-SPACE and the single-breath hold CS MRCP sequence. A non-parametric test (Wilcoxon test) was used because the small sample size (n = 20) of the present study. P-values < 0.05 were considered as statistically significant.

Conventional RT MRCP



Single-breath-hold CS MRCP

Figure 1:
MIP of the conventional respiratory-triggering (RT) and the single-breath-hold Compressed Sensing (CS) MRCP sequence in the same patient at 1.5T. Numbers represent the main pancreatic and bile ducts: (1) Pancreatic; (2) bile; (3) left intrahepatic; (4) right intrahepatic and (5) gallbladder.

Image quality variables	Overall image quality	Image blurring	Background suppression	Duct visualization
Score 1	Not diagnostic	Not diagnostic	Significant background signal	No visualization
Score 2	Poor	Substantial blur	Substantial background signal	Poor visualization
Score 3	Fair	Mild blur	Noticeable background signal	Partial visualization
Score 4	Good	No or minimal blur	Sufficient background suppression	Clear and not complete
Score 5	Excellent	Not applicable	Not applicable	Clear and complete

Table 1:
Measured variables and scores to compare the conventional respiratory-triggering and the single-breath-hold Compressed Sensing MRCP sequence.

Results

Table 2 shows the results of the evaluation of MRCP images at 1.5T.

At 1.5T, no difference was found in the overall image quality and image blurring between the conventional RT MRCP sequence and the prototype single-breath-hold CS MRCP sequence.

Furthermore, the main hepatic and bile ducts were equally visualized in the conventional MRCP and the single-breath-hold CS MRCP images. However, the background suppression was significantly better in the conventional sequence compared to the prototype sequence.

The evaluation of the MRCP images at 3T is shown in Table 3.

At 3T, the overall image quality was significantly improved and significantly less blurring was observed in the single-breath-hold CS MRCP images compared to the conventional RT MRCP images.

Interestingly, the cystic and the pancreatic ducts were better visualized in the prototype MRCP images. There was a tendency for a better visualization of the right and left intrahepatic ducts in the single-breath-hold CS MRCP images (Table 3). Background suppression was similar for both MRCP sequences.

Figures 2 and 3 show the comparison between the conventional respiratory-triggering MRCP and the respective single-breath-hold CS MRCP sequence at 1.5T and at 3T.

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Measured variables	Conventional RT MRCP	Single-breath-hold CS MRCP	P-value
Overall image quality	3.23 ± 1.51	3.58 ± 1.17	0.34
Blurring	3.05 ± 1.00	3.13 ± 1.10	0.93
Background suppression	**3.48 ± 0.73**	**2.00 ± 0.83**	**< 0.001**
Cystic duct	3.20 ± 1.72	3.23 ± 1.70	0.95
Pancreatic duct	2.65 ± 1.52	2.58 ± 1.54	0.95
Right intrahepatic duct	3.48 ± 1.46	3.55 ± 1.49	0.95
Left intrahepatic duct	3.55 ± 1.28	3.75 ± 1.38	0.72

Table 2:
Values of the measured variables (mean ± SD) of MRCP images at **1.5T** using the conventional respiratory triggering (RT) and the single-breath-hold compressed sensing (CS) sequence.

Measured variables	Conventional RT MRCP	Single-breath-hold CS MRCP	P-value
Overall image quality	**3.25 ± 0.99**	**4.17 ± 0.71**	**< 0.001**
Blurring	**2.92 ± 0.92**	**3.60 ± 0.45**	**< 0.001**
Background suppression	3.27 ± 0.82	3.57 ± 0.47	0.09
Cystic duct	**2.55 ± 1.40**	**3.40 ± 1.34**	**0.005**
Pancreatic duct	**3.52 ± 1.14**	**4.27 ± 0.68**	**0.02**
Right intrahepatic duct	3.55 ± 1.24	4.05 ± 0.97	0.06
Left intrahepatic duct	3.52 ± 1.16	3.95 ± 1.02	0.13

Table 3:
Values of the measured variables (mean ± SD) of MRCP images at **3T** using the conventional respiratory triggering (RT) and the single-breath-hold compressed sensing (CS) sequence.

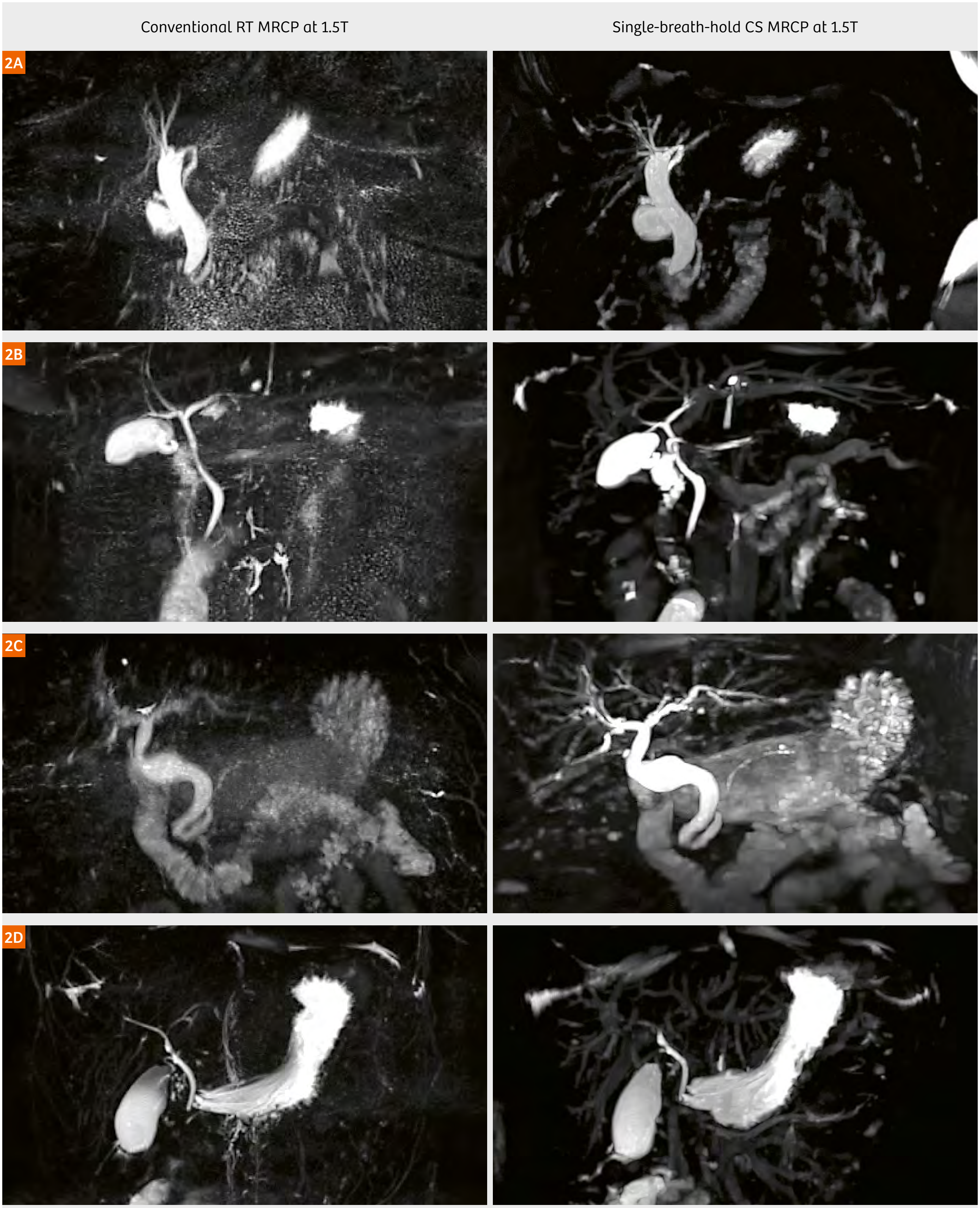

Figure 2:
MIP of the conventional respiratory-triggering (RT) and the single-breath-hold compressed sensing MRCP sequence in four different patients at **1.5T**.

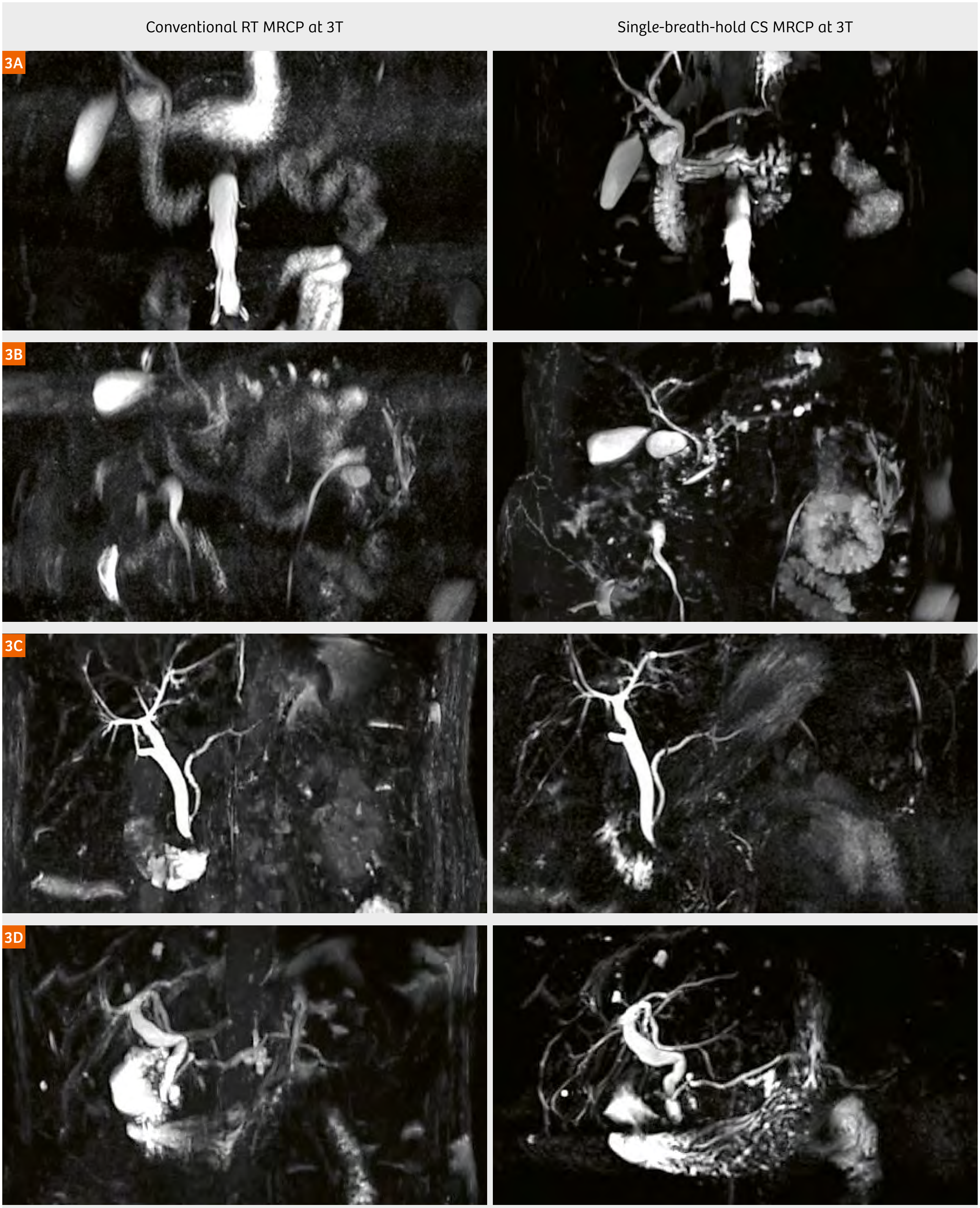

Figure 3:
MIP of the conventional respiratory-triggering (RT) and the single-breath-hold compressed sensing MRCP sequence in four different patients at **3T**.

Discussion and conclusion

Nowadays rapid MR imaging is of utmost importance for clinical decision making, whilst the comfort of the patient is crucial. Indeed, it is very important that the patient spends the shortest time in the magnet bore in order to get him/her back for a follow-up MR examination. To achieve this goal, development of rapid MR acquisition techniques is critical. One of the most promising techniques for rapid MR imaging is a highly undersampled acquisition in combination with compressed-sensing reconstruction method. The present study has demonstrated the clinical applicability of such a method for MRCP imaging.

At 3T, the quality of the breath-hold CS MRCP images was clearly superior and the main bile and pancreatic ducts were better visualized compared to the conventional MRCP images. Interestingly, at 1.5T the image quality and the visibility of the main ducts were comparable between the breath-hold CS MRCP and the conventional sequence. These findings are very promising since the acquisition time of the single-breath-hold was at least 17 times shorter than the conventional technique.

The main disadvantage of the conventional RT MRCP sequence is clearly the longer acquisition time. Indeed, for patients with irregular respiratory motion, the acquisition time can exceed 10 minutes and the resulting images suffer from motion artifacts and blurring as shown in Figure 2 (B and C) and in Figure 3 (A and B).

The overall quality and sharpness of the single-breath-hold CS MRCP images was good at 3T, this is in agreement with a study by Yoon et al. [2] where similar findings were reported: mean overall image quality: 4.17 vs. 4.10; mean image blurring: 3.60 vs. 3.80. It is interesting to note the better image quality and sharpness at 3T compared to 1.5T with the single-breath-hold CS MRCP sequence. However, this was not the case with the conventional MRCP sequence; there is a clear benefit to perform compressed-sensing reconstruction for MRCP imaging at higher magnetic field strength.

To our knowledge, this is the first 1.5T study showing similar image quality between the single-breath-hold CS and the conventional MRCP sequence. Furthermore, the visibility of the main ducts was also comparable between both sequences. However, in the single-breath-hold CS MRCP images the background suppression was near to poor with substantial background. This was not observed at 3T, where sufficient background suppression was achieved. Therefore it would be beneficial to improve the background suppression of the single-breath-hold CS MRCP sequence at 1.5T.

An important issue with the evaluated single-breath-hold CS MRCP prototype implementation is the reconstruction time of the images. In the present study, the reconstruction time was about 6 minutes. This has to be addressed for a future product implementation e.g. by a GPU implementation, the reconstruction time needs to be as short as possible in order to facilitate the workflow of the MR protocol and also in case where the images need to be interpreted rapidly by the radiologist.

In conclusion, the single-breath-hold CS MRCP prototype provides a similar (at 1.5) or superior (at 3T) overall quality and sharpness compared to the conventional sequence.

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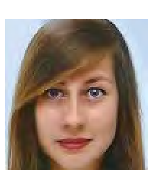
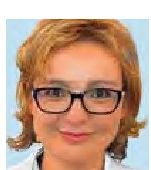
Contact

Hélène Blaise
Hôpital universitaire Nancy
Rue du Morvan
54511 Vandoeuvre-lès-Nancy
France





Hélène Blaise Valérie Laurent