Image Quality Improvement of Dynamic Contrast-Enhanced Gradient Echo Magnetic Resonance Imaging by Iterative Denoising and Edge Enhancement

Sebastian Gassenmaier, MD, Judith Herrmann, MD, Dominik Nickel, PhD, Stephan Kannengiesser, PhD, Saif Afat, MD, Ferdinand Seith, MD, Rüdiger Hoffmann, MD, and Ahmed E. Othman, MD

Objectives: The aim of this study was to investigate the impact of a novel edge enhancement and iterative denoising algorithm in 1.5-T T1-weighted dynamic contrast-enhanced (DCE) gradient echo (GRE) magnetic resonance imaging of the abdomen on image quality, noise levels, diagnostic confidence, and lesion detectability.

Materials and Methods: Fifty patients who underwent a clinically indicated magnetic resonance imaging with DCE imaging of the abdomen between June and August 2020 were included in this retrospective, monocentric, institutional review board–approved study. For DCE imaging, a series of 3 volume interpolated breath-hold examinations (VIBES) was performed. The raw data of all DCE imaging studies were processed twice, once using standard reconstruction (DCEs) and again using an edge enhancement and iterative denoising approach (DCEDE). All imaging studies were randomly reviewed by 2 radiologists independently regarding noise levels, arterial contrast, sharpness of vessels, overall image quality, and diagnostic confidence using a Likert scale ranging from 1 to 4, with 4 being the best. Furthermore, lesion detectability was evaluated using the same ranking system.

Results: All 50 imaging studies were successfully reconstructed with both methods. Interreader agreement ($\kappa$) was substantial to perfect for both readers. Arterial contrast and sharpness of vessels were rated superior by both readers with a median of 4 in DCEDE versus a median of 3 in DCEs ($P < 0.001$). Furthermore, noise levels as well as overall image quality were rated higher with a median of 4 in DCEDE compared with a median of 3 in DCEs ($P < 0.001$). Lesion detectability was evaluated to be superior in DCEDE with a median of 4 versus DCEs with a median of 3 ($P < 0.001$). Consequently, diagnostic confidence was also rated to be superior in DCEDE with a median of 4 versus DCEs with a median of 3 ($P < 0.001$).

Conclusions: Iterative denoising and edge enhancement are feasible in DCE imaging of the abdomen providing superior arterial contrast, noise levels, and overall image quality. Furthermore, lesion detectability and diagnostic confidence were significantly improved using this novel reconstruction method. Further reduction of acquisition time might be possible via reduction of increased noise levels using this presented method.

Key Words: magnetic resonance imaging, dynamic contrast-enhanced imaging, noise, signal-to-noise ratio, abdomen

Magnetic resonance imaging (MRI) of the abdomen has become state of the art for multiple pathologies over the last 20 years. Especially, requests for further clarification of pathologies in liver or pancreas can be often answered best using MRT. A multiparametric MRI approach for tissue characterization represents standard of care with dynamic contrast-enhanced (DCE) imaging being the key element. The up-to-date most commonly applied technique in this regard is given by spoiled gradient echo (GRE) imaging, which drastically reduces acquisition time (TA) and allows volumetric acquisitions in a breath-hold, for example, via using a T1-weighted volume-interpolated breath-hold examination (VIBE). The acquisitions are typically accelerated using parallel imaging with the main tradeoff being the reduction in the signal-to-noise ratio (SNR). Although free-breathing acquisitions have been introduced in recent years as alternatives, these techniques are still not applied on a regular basis in daily clinical routine. Regarding these issues, DCE imaging remains the most challenging task in abdominal MRI but is also most relevant for identification of vessels’ anatomy, tumor identification, or further diagnostics of focal liver lesions. Especially, the early arterial phase often lacks SNR due to the reduced contrast of organs, particularly using 1.5-T scanners. In recent studies, it could be shown that an iterative denoising approach is able to significantly improve image quality of hepatobiliary phase imaging as well as precontrast imaging.

Therefore, the aim of this study was to analyze this edge enhancement and iterative denoising algorithm in 1.5-T DCE imaging of the abdomen (DCEDE) and its impact on image quality, noise levels, lesions’ detectability, and readers’ confidence compared with standard-reconstructed DCE imaging (DCEs).

MATERIALS AND METHODS

Study Design

This retrospective, monocentric study was approved by the institution’s ethics committee with waiver of informed consent. All procedures are in line with the Declaration of Helsinki of 1964 and its later amendments.

Fifty patients who underwent a clinically indicated contrast-enhanced MRI of the abdomen including DCE imaging between June and August 2020 were included in this study. No additional sequences beyond standard-care were obtained.

Magnetic Resonance Imaging Acquisition Parameters

All examinations were performed using clinically approved 1.5-T MRI scanners (Siemens MAGNETOM Aera [n = 36] and Avanto [n = 14]; Siemens Healthcare, Erlangen, Germany). Patients were examined in a supine position using an 18-channel body coil and a 32-channel spine coil. All patients received contrast agent adapted to their body weight ( gadobutrol 0.1 mmol/kg; Gadovist, Bayer HealthCare GmbH, Leverkusen, Germany) with a flow rate of 1.5 mL/s using a power injector followed by a saline flush of 20 mL. For DCE imaging, a series of 3 axial T1-weighted VIBE Dixon sequences was acquired after bolus administration and application of CARE Bolus (Siemens Healthcare, Erlangen, Germany) using the standard clinical protocol with the following parameters: field of view, 216 x 380 mm²; matrix, 182 x 320; voxel size, 1.2 x 1.2 x 3.0 mm³; echo time (TE),
2.39 milliseconds; repetition time (TR), 6.66 milliseconds; slice thickness, 3 mm; flip angle, 10 degrees; parallel imaging factor, 4 (CAIPIRINHA 2 × 2 with 3D shift 1); and TA, 16 seconds.

**Denoising Technique**

The used prototypical iterative denoising performs adaptive filtering on channel-combined, complex-valued image volumes using the same raw data as for DCEDE as described in previous works.14–16 The input comprises a spatially varying noise distribution, which is determined based on adjustment information of the raw thermal noise and the noise propagation through the image reconstruction. The implementation exploits that the reconstruction is linear up to the noise-robust estimation of GRAPPA kernels, so that the noise distribution can be accurately estimated at each step of the reconstruction process before the nonlinear filtering step. The denoising process utilizes a bank of wavelet priors that are optimally combined according to Stein’s Unbiased Risk Estimator, relying on the supplemented noise information.17 Conventional edge enhancement is applied in a final step to compensate for any perceived loss in sharpness resulting in the enhanced and denoised imaging dataset (DCEDE). All reconstructions were performed on saved raw data using an inline implementation and the retrospective reconstruction functionality of the MR system on the scanner console. Processing time was approximately 1 minute.

**Image Analysis**

All imaging studies were reviewed by 2 radiologists with 3 and 8 years of experience in abdominal MRI, respectively. DCEDE and DCEDE evaluation was performed in a blinded random-order reading without access to clinical patient data using a dedicated workstation (Centricity PACS RA1000; GE Healthcare, Milwaukee, WI). Only DCE imaging sequences were available for reading.

Imaging datasets were reviewed regarding the following parameters using a Likert scale ranging from 1 to 4 with 4 being the best: image noise (1, excessive levels of noise; 2, intermediate level of noise; 3, low level of noise; 4, no noise), artifacts (1, excessive artifacts; 2, intermediate level of noise; 3, low level of noise; 4, no artifacts), sharpness of hepatic arteries (1, very weak contrast, course not detectable; 2, weak contrast, course partially not detectable; 3, good contrast, course detectable; 4, excellent contrast, course excellently detectable), sharpness of all vessels (1, vessel contours not detectable; 2, severely blurred vessel contours; 3, slightly blurred vessel contours; 4, excellent sharpness of vessel contours without blurring), sharpness of liver edges (1, liver contours not detectable; 2, severely blurred liver contours; 3, slightly blurred liver contours; 4, excellent sharpness of liver contours without blurring), overall image quality (1, insufficient quality; 2, poor image quality; 3, good image quality; 4, excellent image quality). Furthermore, diagnostic confidence of the readers was rated on the same Likert scale (1, undiagnostic, repetition of examination recommended; 2, severely impaired confidence; 3, good confidence; 4, excellent confidence).

**Lesion Detectability**

In addition, the presence of hepatic lesions and their localization was noted. In case of multiple lesions, only the localization of the largest 5 lesions was documented. The maximum axial diameter of the largest lesion was determined, and detectability was rated on the same Likert scale as mentioned previously (1, lesions margins not detectable; 2, blurred lesions margins; 3, good detectability; 4, excellent detectability). No further characterization regarding the dignity of these lesions was performed, as only DCE imaging was available for study reading.

**Signal-to-Noise Ratio Maps**

To illustrate the effect of iterative denoising on the local noise distribution, exemplary SNR maps were calculated from the raw data. Because this required estimation of the noise propagation through the complete nonlinear reconstruction process, a stepwise estimation with analytically known noise propagation, as done for the input to the adaptive image filtering, was no longer possible. Therefore, a pseudoreplica method was used, like in previous publications.18–20 For the estimation of the noise maps, a total of 64 replicas were used. For each replica, Gaussian noise with a standard deviation of 1% of the thermal noise level was added to the original raw data. From the resulting images, a statistical noise map was derived.

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**TABLE 1. Patients’ Characteristics**

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patients</td>
<td>n = 50</td>
</tr>
<tr>
<td>Mean age ± SD</td>
<td>60 ± 17 y</td>
</tr>
<tr>
<td>Range</td>
<td>22–85 y</td>
</tr>
<tr>
<td>Sex</td>
<td>Male: n = 26; female: n = 24</td>
</tr>
<tr>
<td>Indication for MRI examination</td>
<td></td>
</tr>
<tr>
<td>Cholangiocellular carcinoma</td>
<td>n = 7</td>
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<tr>
<td>Post-LTX</td>
<td>n = 5</td>
</tr>
<tr>
<td>Breast carcinoma</td>
<td>n = 4</td>
</tr>
<tr>
<td>Melanoma</td>
<td>n = 4</td>
</tr>
<tr>
<td>Colorectal carcinoma</td>
<td>n = 4</td>
</tr>
<tr>
<td>Other malignant carcinoma</td>
<td>n = 11</td>
</tr>
<tr>
<td>Inflammatory disease</td>
<td>n = 7</td>
</tr>
<tr>
<td>Other nonmalignant disease</td>
<td>n = 8</td>
</tr>
<tr>
<td>Liver MRI findings</td>
<td></td>
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<tr>
<td>Inconspicuous</td>
<td>n = 19</td>
</tr>
<tr>
<td>Metastatic disease</td>
<td>n = 12</td>
</tr>
<tr>
<td>Inflammatory disease</td>
<td>n = 7</td>
</tr>
<tr>
<td>Cholangiocellular carcinoma</td>
<td>n = 3</td>
</tr>
<tr>
<td>Benign focal liver lesions</td>
<td>n = 2</td>
</tr>
<tr>
<td>Other malignant findings</td>
<td>n = 2</td>
</tr>
<tr>
<td>Other nonmalignant findings</td>
<td>n = 5</td>
</tr>
</tbody>
</table>

**TABLE 2. Evaluation of Image Quality Parameters and Diagnostic Confidence in Standard DCE Datasets (DCE) and Denoised and Enhanced Datasets (DCEDE)**

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Reader 1</th>
<th>Reader 1</th>
<th>Reader 1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reader 2</td>
<td>Reader 2</td>
<td>Reader 2</td>
</tr>
<tr>
<td>Noise</td>
<td>3 (3–3)</td>
<td>3 (3–3)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Artifacts</td>
<td>4 (4–4)</td>
<td>4 (4–4)</td>
<td>0.317</td>
</tr>
<tr>
<td>Arterial contrast and course of hepatic arteries</td>
<td>3 (3–3)</td>
<td>4 (4–4)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Sharpness of vessels</td>
<td>3 (3–4)</td>
<td>4 (4–4)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Sharpness of liver edges</td>
<td>3 (3–4)</td>
<td>4 (4–4)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Overall image quality</td>
<td>3 (3–4)</td>
<td>4 (4–4)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Diagnostic confidence</td>
<td>3 (3–4)</td>
<td>4 (4–4)</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>
Statistical Evaluation
Commercially available statistical software was used for analysis (SPSS Statistics Version 26; IBM, Armonk, NY). Parametric variables are displayed using mean ± standard deviation. Nonparametric variables are displayed using median and interquartile range in parentheses. The Wilcoxon signed-rank test was applied for ordinal scaled paired data. Bland-Altman analysis was used to assess lesion size. Intraclass correlation coefficient (ICC) for continuous data and linearly weighted Cohen κ for ordinal scaled variables were used to analyze interreader agreement. P values below 0.05 were regarded as significant.

RESULTS

Study Group Characteristics
All 50 patients could successfully be evaluated. The mean patient age was 60 ± 17 years (range, 22–85 years). Twenty-six patients were male. Most patients underwent abdominal MRI due to suspicion of malignant carcinoma (n = 30). Most MRI examinations (n = 19) were inconspicuous, whereas in 12 examinations, metastatic disease was found. Further details are shown in Table 1.

Image Quality Analysis
Cohen κ for interreader agreement of DCES (0.88) and of DCEDE (0.77) was substantial to perfect. Detailed results of interreader agreement are shown in the Supplementary Material, http://links.lww.com/RLI/A601. Therefore, in the following, only the results of reader 1 are displayed. All detailed findings are shown in Table 2 and in the Supplementary Material, http://links.lww.com/RLI/A601.

Noise levels were rated to be significantly superior in DCEDE with a median of 4 (3–4) compared with DCES with a median of 3 (3–3) (P < 0.001). However, there was no significant difference regarding the extent of artifacts between DCEDE and DCES (both median of 4 [4–4]; P = 0.317). The arterial contrast and visual assessment of anatomy of hepatic arteries were also evaluated to be better in DCEDE versus DCES with a median of 4 (4–4) versus 3 (3–3) (P < 0.001). The visualization of vessels was rated sharper in DCEDE with a median of 4 (4–4) compared with DCES with a median of 3 (3–4) (P < 0.001). Similar results were obtained for the sharpness of liver edges with a median of 4 (4–4) in DCEDE versus a median of 3 (3–4) in DCES (P < 0.001). Overall image quality was also rated significantly higher in DCEDE with a median of 4 (4–4) compared with DCES with a median of 3 (3–4) (P < 0.001). The diagnostic confidence was also rated to be superior in DCEDE with a median of 4 (4–4) versus DCES with a median of 3 (3–4) (P < 0.001). Figure 1 illustrates an example of improved image quality.

Lesion Detectability
Twenty-nine examinations revealed focal liver lesions. There was no significant difference regarding lesion size with a median of 18 mm (12–26 mm) in DCES and 18 mm (12–27 mm) in DCEDE for reader 1 (P = 0.091) as well as a median of 19 mm (12–27 mm) in DCES and 18 mm (12–27 mm) in DCEDE for reader 2 (P = 0.477). Intraclass correlation coefficient was excellent (0.99) for both readers between DCES and DCEDE measurements. Lesion detectability was also rated to be superior in DCEDE with a median of 4 (4–4) versus a median of 3 (3–4) in DCES for both readers (both P < 0.001; Table 3). Figures 2 and 3 show examples for improved lesion detectability.

Table 3: Lesion Detectability and Lesion Size in Standard DCE Datasets (DCES) and Denoised and Enhanced Datasets (DCEDE)

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>DCES</th>
<th>DCEDE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lesion size, mm</td>
<td>Reader 1</td>
<td>Reader 2</td>
</tr>
<tr>
<td>Lesion detectability</td>
<td>18 (12–26)</td>
<td>19 (12–27)</td>
</tr>
</tbody>
</table>

DISCUSSION
This study investigated the impact of a novel iterative denoising and edge enhancement technique in DCE MRI of the abdomen. Our results show that image quality, noise levels, and diagnostic confidence can be significantly improved in DCEDE compared with DCES. Furthermore, depiction of arteries as well as hepatic lesions was rated significantly better in DCEDE.

Dynamic contrast-enhanced imaging is an integral part in abdominal MRI, especially in hepatic and pancreatic MRI. Dynamic contrast-enhanced imaging is vital for further characterization of focal liver lesions as well as for risk stratification regarding pancreatic lesions.
for example, in intraductal papillary mucinous neoplasia according to the recommendations of the Fukuoka guidelines.\textsuperscript{22–24} The behavior of focal liver lesions is decisive for differentiation and further classification of focal benign and malignant liver lesions, for example, hemangioma, focal nodular hyperplasia, or hepatocellular carcinoma. Another role of DCE imaging is anatomic visualization of vessels (especially arteries) for surgical planning. A necessary requirement for DCE imaging of the abdomen is GRE imaging involving several breath-holds to avoid motion artifacts. However, this acquisition technique is prone to motion artifacts in patients who are unable to perform breath-holds of sufficient length, particularly in elderly, severely ill, or pediatric patients.\textsuperscript{25}

The most common approach for TA reduction is parallel imaging. However, due to the decrease of SNR with increasing parallel imaging factor, the extent of TA reduction through parallel imaging is mostly limited to the factor of 4.\textsuperscript{26,27} This aspect is improved by the presented iterative denoising and edge enhancement approach in our study. The presented SNR maps (Fig. 4) show that the DCE\textsubscript{DE} images provide a more homogeneous and slightly higher SNR compared with DCE\textsubscript{E}, despite the application of edge enhancement that is related to increase in noise. In particular, our presented method improves the nonuniformly distributed noise commonly observed in parallel imaging as noise bands.\textsuperscript{28}

Despite the decreased noise levels, there was, however, no significant impact of the denoising algorithm on motion artifacts. However, this was also not expected as the raw data of both reconstructions was the same. Regarding motion artifacts, the most practical solution seems to further decrease TA and breath-hold time. As noise levels as well as SNR were superior in DCE\textsubscript{DE} compared with DCE\textsubscript{E}, even higher parallel imaging factors might be possible. Further options to shorten TA include increase of bandwidth with compensation of the SNR loss using iterative denoising. However, further studies are necessary to investigate these approaches.

Another method to shorten TA is compressed sensing.\textsuperscript{29} However, the vessel to tissue contrast is superior by using this acquisition technique; the main drawback of this method consists of unrealistic and unnatural image impression in many cases.

Previous reported methods to avoid motion artifacts caused by breathing also involve free-breathing acquisitions or radial imaging, for example, for liver imaging or diagnosis of gastric cancer.\textsuperscript{12,30–33} However, these methods are still not well established and sufficiently validated. A further disadvantage of free-breathing technique is prolongation of TA. This limits this approach for DCE imaging as fast scanning time is vital for proper evaluation of lesions’ contrast behavior.

This presented technique can also be applied using 3-T scanners and in other body areas, because the denoising method is adaptive and independent of image contrast. It should be beneficial in all low-SNR scenarios, for example, with increased spatial resolution and/or reduced acquisition time. The only prerequisite is that the primary image reconstruction is linear so that a noise map can be calculated, which is typically straightforward for Cartesian acquisitions with parallel imaging reconstruction.

Compared with the development of new sequences and acquisition techniques, the major advantage of our presented iterative denoising and edge enhancement approach consists of its easy applicability. Technologists do not have to undergo teaching, and further instructions to successfully use this technique as the acquisition sequence parameters
remain the same. Therefore, this method can easily be introduced into the clinical workflow without interruptions.

Because of the importance of GRE imaging of the abdomen and DCE imaging in particular, future developments, especially regarding possible deep learning reconstruction algorithms, will be of utmost importance as it was recently shown in turbo spin echo imaging of the knee. Deep learning reconstructions of GRE imaging might therefore be the solution in the future to obtain swift and precise DCE images of high quality.

Several limitations of our study merit consideration. First, our study was conducted using a retrospective study design. Furthermore, as this study investigated the feasibility and implementation of iterative denoising for DCE imaging only, no other sequences were reconstructed using the algorithm. In this context, a profound analysis of the impact of the algorithm on the contrast behavior of different benign and malignant liver lesions was not feasible. Also, no systematic quantitative analysis of SNR and contrast-to-noise ratio measurements could be performed using regions of interest because due to the related technique after denoising no reliable results can be obtained via region of interest measurements. Therefore, we provided exemplarily a set of noise maps to demonstrate the improvement of SNR.

In conclusion, iterative denoising and edge enhancement can be successfully applied in DCE GRE imaging of the abdomen with improvement of image quality, visibility of vessel anatomy, noise levels, and diagnostic confidence.

REFERENCES


