Objective: The aim of the study was to evaluate image quality of a dynamic hepatic magnetic resonance (MR) imaging strategy based on advanced parallel acquisition combined with rhythmic breath-hold and gadoxetate disodium enhancement.

Materials and Methods: Twenty-seven patients (21 male/6 female; mean age, 57.3 years) were enrolled in this institutional review board–approved study and underwent MR imaging at 3 T. The sequence (T1 3-dimensional gradient-recalled echo; acceleration factor, 4; reconstruction mode; controlled aliasing in parallel imaging resulting in higher acceleration factors; acquisition time, 10.4 seconds) was repeated at 8 fixed time points within the 3 minutes after contrast agent injection. Image quality was evaluated on a 5-point scale (1, excellent; 5, nondiagnostic). Dynamic sequences were classified according to perfusion phases and contrast characteristics. Artifacts and position of the liver in the z axis were recorded and analyzed.

Results: Overall image quality was found to be 1.44 (95% confidence interval, 1.18–1.71). Contrast was scored as excellent in 25 of 27 patients for central vessels and 22 of 27 patients for peripheral vessels. Adequate-quality arterial-phase images were obtained in all 27 patients. Double arterial and single arterial phases were acquired in 13 of 27 and 14 of 27 patients (n = 6 arterial dominant, n = 8 early arterial phases), respectively. In 1 (3.7%) of 27 patients, severe respiratory artifacts were seen during an early arterial phase. Artifacts were observed in 21 of 27 patients and rated as mild in 19 of these. Compromised quality was related to receiver coils (17 of 29), parallel imaging (6 of 29), breathing (3 of 29), and other causes (3 of 29). The position of the liver throughout the dynamic phases was highly constant, with a greatest mean shift of +2.9 mm throughout the first dynamic acquisition.

Conclusions: Advanced parallel acquisition with rhythmic breath-hold and gadoxetate injection allows arterial phase imaging without breathing artifacts; a decelerated yet normal breathing pattern results in very robust breath-hold depth.

Key Words: liver, MR, magnetic resonance, sequences, 3-dimensional

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Conflicts of interest and sources of funding: Dr Alexander Huppertz has been a full time employee of Siemens AG until December 2014. His function has been associate director of the Imaging Science Institute, a scientific cooperation between the Charité–University Hospitals of Berlin and Siemens Healthcare in form of a private-public partnership (PPP). Dr Dominik Nickel is a full time employee of Siemens AG (ongoing relationship). Dr Carsten Schwenke gave statistical support in planning and reporting of this project and performed the statistical analysis on an honorary basis. All other authors have no competing interests to declare.

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ORIGINAL ARTICLE

D ynamic, especially arterial phase, imaging plays an essential role in hepatic magnetic resonance (MR) imaging for both tumor detection and tumor characterization1–3 as well as for precise visualization of vascular anatomy. The arterial contrast can be delivered by gadolinium-based extracellular contrast agents (ECCAs), which have been the standard for more than 20 years, and by hepatocyte-specific contrast agent gadoxetate disodium,3–5 which is in increasing use because of its inherent superiority in lesion-to-liver contrast.

The differences between the 2 strategies have been assessed in detail and have revealed (a) significant differences in favor of ECCA for central arteries during the arterial phases,6 (b) similar signal-to-noise ratio (SNR) of liver parenchyma,1–3 and (c) comparable enhancement patterns for focal liver lesions.3 Achieving high-quality arterial phase imaging with gadoxetate is more challenging and requires precise timing and specific examination protocols.2–8 The main reasons for this are the differences in relaxivity,4 the differing dosages (gadoxetate being typically administered at a quarter of the dose compared with ECCA), and the consequently smaller volume of gadoxetate.7,8,10 These factors lead to a compact bolus, which can be substantially shorter than the data acquisition time for high spatial resolution arterial data sets3,11,12 and can result in truncation artifacts13,14 due to sudden changes in contrast intensity at the time of central k-space filling. Another more recently reported observation compromising image quality throughout arterial-phase imaging is the presence of movement artifacts due to an insufficient breath-hold maneuver; these were attributed to transient dyspnea.15–19

We have introduced an improving breathing maneuver in combination with shortened acquisition times (without compromises in spatial resolution) based on a novel algorithm of parallel acquisition (controlled aliasing in parallel imaging resulting in higher acceleration [CAIPIRINHA]).20,21 Basic physiology studies have shown that voluntary breath-holding requires suppression of powerful involuntary mechanisms gating respiratory rhythm.22 This seems to be the main reason why even healthy subjects have difficulty in holding their breath for more than a few seconds. Our rhythmic breath-hold technique resembles a physiological yet slowed-down respiratory rhythm; this allows simplification and standardization of the examination protocol, and individual timing was not required.

The purpose of our prospective study was to evaluate the quality of the images obtained by this novel dynamic hepatic MR imaging strategy based on advanced parallel acquisition combined with rhythmic breath-hold and gadoxetate enhancement.

MATERIALS AND METHODS

Study Population

The protocol of this prospective study conformed to Good Clinical Practice. Institutional review board approval was obtained, and all patients gave written informed consent. Inclusion criteria were focal liver lesions scheduled for surgery or suspected hepatic metastases in patients with known extrahepatic malignancies. Exclusion criteria were contraindications to MR imaging or to the injection of gadoxetate and concurrent uncontrolled medical conditions (eg, recent stroke, myocardial infarction). The study was supported by research grants from Bayer HealthCare. The investigators had exclusive control of all data in this study, manuscript drafting, and submission.

Twenty-seven patients (21 male, 6 female), with a mean age of 57.3 years (19–79 years) and mean (SD) body mass index of 26.2 kg/m² (3.9 kg/m²; 18–34.3 kg/m²), were included; no patients were excluded.
Voxel size, mm  Minimum, 1.2
Slice oversampling, % 25%
Phase oversampling, % 10%
Bandwidth, Hz 600
Acquisition time, s 10.4
Base resolution, % 80
Base resolution, mm 320
Field of view, % 78.2

MR Imaging

Magnetic resonance imaging was performed using a 3 T system (Magnetom Skyra; Siemens Healthcare, Germany) and matrix coils (32-channel spine + two 18-channel body coils). T1-weighted 3-dimensional gradient-recalled echo sequences with fat saturation were acquired before and 20, 40, 60, 80, 100, 120, 150, and 180 seconds after injection of gadoxetate (Eovist; Bayer HealthCare, Germany) at 0.025 mmol/kg body weight. An automated power injector (Spectris Solaris; Bayer Healthcare) was used for a bolus administration (injection speed 1 mL/s) followed by a saline chaser of 20 mL. Sequence parameters are shown in Table 1. An improved parallel acquisition technique (PAT) algorithm for volumetric imaging (CAIPIRINHA), modifying the k-space acquisition pattern and adapting image reconstruction correspondingly, was applied.20,21,23

On the basis of respiratory physiology, an absolute voluntary breath-hold maneuver of ~20 seconds might easily interfere with the powerful involuntary central respiratory rhythm.22 A rhythmic breath-hold technique resembling a decelerated, yet normal, breathing pattern was therefore established (Fig. 1). Before the start of the MR examination and directly before the injection of contrast agent, patients were instructed orally (with a short explanation in 4–5 sentences) about the workflow of the dynamic sequence and the rhythm of the breath-holding maneuvers. During the acquisition, patients’ breath-hold was monitored by using a respiratory belt system. All other sequences performed during the MR examination were performed in conventional breath-hold or by using respiratory gating.

Qualitative Analysis

A qualitative analysis was performed in consensus by 2 readers (with 15 and 5 years of experience in abdominal/vascular MR imaging, respectively) blinded to any clinical information. Overall image quality was rated on a 5-point scale (1, excellent; 2, good; 3, moderate, no impairment of image interpretation; 4, limited, diagnostic quality questionable; 5, nondiagnostic).

Contrast enhancement throughout dynamic data sets was rated separately for central and peripheral vessels and was classified as 1, excellent (strong vessel enhancement); 2, good (vessel enhancement sufficient for detection of intravascular pathologies); 3, moderate (minimally decreased contrast enhancement impairing detection of intravascular pathologies); 4, limited (vessel of interest not completely enhanced); and 5, nondiagnostic (vessel of interest not identifiable). Central vessels included the aorta, the celiac axis, the mesenteric artery, the left and right portal vein, and the distal hepatic veins. Similarly, contrast enhancement of focal liver lesions was evaluated (from 1, excellent, to 5, nondiagnostic).

Perfusion phases were classified as too early (hepatic arteries not enhanced), early arterial phase (hepatic arteries-only phase), hepatic arterial–dominant phase (early enhancement of the portal vein with persistently strong enhancement of the arteries), portal venous phase (enhancement of portal vein and hepatic veins), transitional phase (parenchymal signal intensity [SI] almost equal to enhancement of the liver veins), and contrast reverse (intrahepatic vessel SI lower than liver parenchyma).24

The presence of artifacts was assessed on a 3-point scale: 1, absent; 2, mild (no relevant impairment of image interpretation); and 3, prominent (relevant impairment of image interpretation). Occurring artifacts were related to (1) breathing/motion, (2) pulsation, (3) surface receiver coils, (4) classical wrap-around, (5) spatial aliasing/PAT, (6) strong signal change (ice-cube artifact), and (7) metal.25 For a detailed analysis of artifacts, the patient’s girth at the level of the liver was calculated by measuring patient diameter in the right-left and anterior-posterior directions and applying the formula:

\[
\left( d_i - d_p \right) / 2 \times \pi
\]

Quantitative Analysis

For SI evaluations, 2 separate regions of interest (ROIs) were recorded at comparable slice positions by 1 single investigator (U.L.F.) to

FIGURE 1. Respiratory slope of rhythmic breath-hold throughout acquisition of the dynamic sequences. Figure 1 can be viewed online in color at www.investigativeradiology.com.
determine SI and its SD: one in the tissue of interest (aorta, splenic artery, portal vein, intrahepatic vein, liver parenchyma, for the right and left lobe separately, or, if present, in a hypothetically vital area of focal lesions) and the other one in the paraspinal muscle (2-region approach).

Several factors in PAT have an important influence on the estimation of SNR because statistical and spatial distribution of noise is influenced by coil geometry, phase-encoding direction, and acceleration factors. Nevertheless, SNR comparisons for different tissues remain valid because the constant factor will cancel out when one calculates a relative change. Therefore, noise was defined as the SD of an ROI placed in the paraspinal muscle at the same slice position as the ROI of the vessel or parenchymal structure of interest. Enhancement ratio (ER), SNR, and contrast-to-noise ratio (CNR) were calculated as follows:

\[
ER = \left( \frac{SI_{\text{lesion postcontrast}} - SI_{\text{lesion precontrast}}}{SI_{\text{lesion precontrast}}} \right) \times 100
\]

\[
SNR = \frac{SI_{\text{parenchyma or vessel}}}{\text{noise}}
\]

\[
CNR = \frac{SI_{\text{parenchyma or vessel}} - SI_{\text{portal vein}}}{\text{noise}} = \frac{SI_{\text{lesion precontrast}}}{\text{noise}}
\]

Enhancement ratio evaluation was done on a per-lesion basis (1 or more lesion types by patient, measurements on most representative lesion of each type), and lesions were classified as hypervascular or hypovascular. In addition, lesions were counted (maximum of 10 lesions per patient).

Depth of breath-hold and its constancy over dynamic sequences were evaluated by identifying the position of the liver dome and caudal liver pole on the z axis and comparing the postcontrast with the precontrast position.

Statistical Analysis

Spearman rank correlation coefficient was used for correlation analysis of artifacts and patient's girth. Strength of correlation was assessed as follows: strong, \( r \geq 0.751 \); moderate, \( 0.501 \leq r < 0.751 \); weak, \( r < 0.501 \). Mixed models were used to assess the SNRs, the change from baseline in CNR, and z axis shift of liver dome and caudal liver pole compared with the respective precontrast observations over time, taking into account the correlation of repeated measurements per patient. Owing to deviation from normality, logarithmic transformations were used for SNRs and CNR. Descriptive statistics were analyzed by calculating least squares means with 95% confidence intervals (CIs). All statistical tests were performed using SAS 9.2 2-sided at a significance level of 5% (SAS Institute Inc, Cary, NC).

RESULTS

Lesions were seen in 23 patients, among whom surgery or biopsy revealed a single lesion entity in 21 patients and 2 differing lesion entities in 2 patients. Final histopathology diagnosis comprised metastasis of colorectal cancer in 13 patients, cholangiocellular carcinoma (CCC) or metastasis of CCC (\( n = 3 \)), hepatocellular carcinoma (HCC, \( n = 2 \)), metastasis of neuroendocrine carcinoma (\( n = 2 \)), metastasis of malignant melanoma (\( n = 1 \)), metastasis of follicular thyroid carcinoma

![Image](https://investigativeradiology.com/image.png)
n = 1), sclerosed hemangioma (n = 1), focal nodular hyperplasia (n = 1), and adenoma (n = 1). In 4 patients, no focal hepatic lesions were detected. The remaining 23 patients had a total of 106 focal liver lesions (1–10 lesions/patient; mean diameter, 47 mm; range, 5–173 mm; SD, 39 mm).

Qualitative Analysis

Overall image quality was rated as excellent (score 1) in 18 of 27 patients, good (score 2) in 6 of 27 patients, and moderate (score 3) in 3 of 27 patients. In a 69-year-old man, the first dynamic phase showed severe breathing artifacts, whereas all other 7 dynamic sequences including the arterial-dominant phase were of good image quality; therefore, overall quality was scored as 2.

In central vessels, contrast enhancement was rated excellent in 25 of 27 patients (Figs. 2–4) and good in 2 of 27 patients. Contrast enhancement of the peripheral vessels was rated as excellent in 22 of 27 patients (Figs. 2–4), good in 3 of 27 patients, and moderate in 2 of 27 patients. Enhancement of focal lesions was rated excellent in 22 of 23 patients and good in 1 of 23 patients. Seven lesions were classified as hypervascular (2/2 HCC, 2/2 neuroendocrine carcinoma, 1/1 thyroid carcinoma metastasis, 1/3 CCC, 1/1 focal nodular hyperplasia) and 18 lesions as hypovascular (Fig. 5).

The evaluation of perfusion phases is given in Table 2 and revealed acquisition of double arterial phases in 13 of 27 patients and single arterial phase in 14 of 27 patients, respectively. At least 1 arterial phase without severe respiratory motion artifacts was acquired in all 27 patients. In patients with single arterial phase, enhancement was classified as “arterial dominant” in 6 of 14 patients and “early arterial/hepatic arteries-only phase” in 8 of 14 patients.

Artifacts

In 6 of the 27 examinations, no artifacts were detected (Fig. 3). Mild artifacts not compromising diagnostic information were present in 19 of 27 patients (Fig. 2), and prominent artifacts compromising diagnostic quality were present in 2 of 27 patients. Prominent artifacts were due to respiratory motion during the arterial phase in 1 patient and surface coil combined with parallel imaging artifacts in another patient compromising all precontrast and dynamic data sets. In 14 of 21 examinations with artifacts only, 1 type of artifact was detectable, and 7 of 21 examinations showed several types of artifacts. Artifacts were mainly related to surface coils (n = 17, Fig. 2) and spatial aliasing/PAT (n = 6, Fig. 4). Other types of artifacts were due to breathing/motion (n = 3), pulsation (n = 2), and metal (n = 1). Classic wraparound and ice cube tray artifacts were not observed. Breathing artifacts were observed singularly in 1 dynamic data set (first dynamic data set, n = 2; second dynamic data set, n = 1), whereas all other 26 of 29 artifacts were observed throughout all dynamic data sets including precontrast imaging. The correlations of spatial aliasing/PAT and of surface coil artifacts with patient's girth were found to be strong (r = 0.77 and r = 0.90, respectively).

Quantitative Analysis

Enhancement ratio of hypervascular lesions showed a maximum 40 seconds after contrast agent administration, whereas ER for hypovascular lesions showed a plateau between 80 and 180 seconds (Fig. 5A).

Greatest SNRs in the aorta and the splenic artery (Fig. 5B) were seen 20 and 40 seconds after contrast agent administration (difference...
Not statistically significant). Highest SNR in the portal vein was seen after 40 seconds with a plateau lasting up to 80 seconds. Highest absolute CNR between portal vein (seen as surrogate marker for hypovascular lesions) and liver parenchyma was seen after 40 seconds.

Overall, z axis shifts of the liver dome and the caudal liver pole were very small (Fig. 6). The greatest z axis shift of the liver dome was noted during the first dynamic phase (+2.3 mm; SD, 6.9 mm) followed by the second dynamic phase with −2.1 mm (SD, 8 mm). The greatest caudal liver shift in z axis was noted during the third dynamic phase −2.8 mm (SD, 11.1 mm) followed by the first dynamic phase +2.9 mm (SD, 7.6 mm). The least squares mean change from baseline of 0.028 (95% CI, −0.777 to 0.833) for the liver dome and of −0.053 (95% CI, −0.856 to 0.751) for the caudal liver pole across the time points was not significantly different from 0 (P = 0.9439 and 0.893, respectively).

DISCUSSION

In terms of accomplishment of high-quality arterial phase imaging with gadoxetate, 3 challenging factors have been identified: (1) significant contrast enhancement change during center of k-space filling, causing truncation artifacts; (2) inaccurate synchronization of bolus and scanner; and (3) breathing artifacts.

The risk of truncation artifacts can be reduced by lowering the injection speed to 1 mL/s, and, thereby, stretching the contrast bolus and, of course, by shorter acquisition times. Reducing the acquisition time to almost a half while preserving a high spatial resolution is the key characteristics of the CAIPIRINHA reconstruction algorithm.19–21 Owing to its more efficient use of the coil sensitivity variations, g-factor–related noise enhancement in the parallel imaging reconstruction is reduced, and therefore, the advantages of CAIPIRINHA’s 2-dimensional PAT algorithm over conventional 1-dimensional PAT led to an improved SNR and a reduction in artifacts.27,28 Our evaluation revealed that severe non-motion-related artifacts compromising diagnostic quality are very rare: artifacts were mainly mild, not compromising image interpretation, and they included surface receiver coil–related artifacts and spatial aliasing/PAT artifacts in 59% and 19% of examinations, respectively, which accords with the results of other recent studies.27,28

Timing can be optimized by implementing individual timing strategies, especially care bolus techniques. Drawbacks are a high protocol complexity, a prolonged examination time, and the risk of respiration artifacts caused by intensive noise of the sequence combined with closely spaced breath commands and breath-hold. In opposition to that, our strategy with rhythmically repeated acquisitions is a standardized protocol and therefore less dependent on the operator. The results of Park et al29 using the CAIPIRINHA sequence in gadoxetate-enhanced 3 T MR imaging with image parameters (very similar to ours except for individual timing of their single arterial phase by bolus-triggering) can be used as comparator. Park et al29 reported no artifacts in 71.2% of patients (57/80), comparable to our “excellent” score in 66.7% (18/27), mild artifacts and no impairment of diagnostic quality in 25% (20/80), comparable to our “good” and “moderate” scores in 33.3% (9/27), but still with impaired diagnostic quality in 3.8% of patients (3/80). Introducing our rhythmical breath-hold strategy, we were able to avoid completely dynamic data sets of nondiagnostic or questionable image quality. In addition, our protocol offers the advantages of the kinetic protocols of breast or prostate imaging.30 Thereby, independently even of modified hemodynamics in, for example, liver cirrhosis,31 the acquisition of precise kinetic data on liver lesions is possible, which is of major importance in the diagnostics of HCC and in making the challenging distinction between HCC and dysplastic nodules.32

The actual basis for high diagnostic confidence (ie, focal lesion conspicuity of the CAIPIRINHA sequence at 3 T) is at least comparable to more...
conventional generalized autocalibrating partially parallel acquisition; this has already been reported in a comparative study. Nevertheless, apart from simple acquisition of kinetic data, we have to admit that a repeated acquisition time of 20 seconds is not enough to acquire early arterial and arterial-dominant phase in the same patient with robustness and that we are not able to predict subtype of arterial phase acquisition. Our results reveal at least 1 arterial phase without motion artifacts in 100% of patients and are, thereby, comparable to those of a triphasic single breath-hold approach, which yielded similar results in 98% of patients. However, in specific indications, such as the early detection of HCC, one might consider adapting the protocol accordingly and shortening intervals, especially within the first 10 to 45 seconds after administration of the contrast agent.

To define strategies that eliminate breathing artifacts, a more profound understanding of the artifact’s origin seems obligatory. Severely degraded arterial-phase data sets in up to 14% of patients after injection of gadoxetate have been reported. The observation was interpreted as a motion artifact due to a possibly drug-related “transient

FIGURE 5. Enhancement ratios (A) and SNRs (B) throughout dynamic acquisition. A, ER in hypervascular and hypovascular lesions after contrast agent administration. ER of hypervascular shows a maximum 40 seconds after contrast agent administration, whereas ER for hypovascular lesions shows a plateau between 80 and 180 seconds after contrast agent administration. B, SNR in vessels and liver parenchyma: SNR analysis reveals maximal enhancement in the aorta and the splenic artery at 20 and 40 seconds after contrast agent administration. Highest SNR in the portal vein is seen at 40 seconds with a plateau up to 80 seconds after contrast agent administration. The highest absolute difference between SNR of portal vein, seen as surrogate marker for hypovascular lesions, and liver parenchyma is seen 40 seconds after contrast agent administration. Figure 5 can be viewed online in color at www.investigativeradiology.com.

### TABLE 2. Perfusion Phase Determination of Dynamic Sequences After Bolus Injection of Gadoxetate

<table>
<thead>
<tr>
<th>Dynamic Series Number</th>
<th>Time Post CA Injection, s</th>
<th>Too Early Timing</th>
<th>Early Arterial (Arteries Only) Phase</th>
<th>Arterial-Dominant Phase</th>
<th>Portal Venous Phase</th>
<th>Transitional Phase</th>
<th>Inverse Contrast Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>7</td>
<td>16</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>0</td>
<td>5</td>
<td>15</td>
<td>7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>26</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
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</tr>
<tr>
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<td>0</td>
<td>0</td>
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</tr>
<tr>
<td>7</td>
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<td>0</td>
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<td>7</td>
</tr>
<tr>
<td>8</td>
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<td>0</td>
<td>0</td>
<td>10</td>
<td>17</td>
</tr>
</tbody>
</table>

Gray-shaded cells represent the median at each time point.

CA indicates contrast agent.
The limitations of these prospective and retrospective studies were a potential patient selection bias, and an off-label dosing scheme with significantly higher doses compared with those approved by the US Food and Drug Administration, even though the phenomenon still seems to occur with on-label and below-label dosing. Irrespective of that, our strategy to reduce breathing artifacts was developed by taking into account basic facts about respiratory physiology: as the central respiratory rhythm seems to continue throughout breath-holding, powerful involuntary mechanisms normally override voluntary breath-holding and thus define the breakpoint. Consequently, for many patients, breath-hold times of more than 20 seconds are hardly attainable. The technique with repeated breath-holds of approximately 10 seconds resembles a decelerated, yet normal, breathing pattern and is in a way comparable to the breathing pattern chosen throughout breast-stroke swimming. Thereby, we obtained very robust breath-hold depth and were able to reduce the rate of severe breathing artifacts to 3.7%, which was lower than found in a previous study by Pietryga et al, who reported a triple arterial phase acquisition throughout a single breath-hold: an adequate late arterial phase quality in a large number of patients was reported by the use of CAIPIRINHA, but the percentage of patients with severe breathing artifacts was still 10.7% and increased progressively during the sequential arterial phases, which emphasizes the strategy's drawback of an overly long 23-second breath-hold maneuver that results in an (involuntary) restart of respiration during the second half of the acquisition.

Nevertheless, we learned from our results that there might be still a possibility of improving our technique: taking into account the fact that the highest z-axis shift occurred throughout the first dynamic phase and observing that isolated breathing artifacts still occur during first or second dynamic data set (possibly caused by insufficient adaptation to the respiratory rhythm at the beginning of the acquisition), it might be useful to initiate the breathing pattern several cycles before the acquisition of postcontrast sequences, thus allowing the patient a certain degree of habituation. Despite this, our study design was not able to exclude fully the possibility that the isolated breathing artifacts might have been drug related.

In its current form, our strategy seems likely to become applicable in clinical routine in the near future. On the contrary, other recently proposed sequence designs with further improved temporal footprint (eg, echo sharing or non-Cartesian k-space filling or acquired without breath-hold) are associated with very large data sets and require dedicated hardware and software, specific evaluation tools, and long evaluation times, although they indicate the future of further reduced acquisition times while providing at least comparable image quality.

**Limitations**

Our study has several limitations. We did not perform a comparison with conventional liver-imaging strategies, that is, bolus timing and conventional breath-hold techniques. We included a relatively small number of patients, which limits the generalizability of our findings. Additionally, we did not perform a direct comparison with conventional liver-imaging strategies, such as bolus timing and conventional breath-hold techniques. Finally, our study design did not fully exclude the possibility that the isolated breathing artifacts might have been drug related. Nevertheless, we learned from our results that there might be still a possibility of improving our technique: taking into account the fact that the highest z-axis shift occurred throughout the first dynamic phase and observing that isolated breathing artifacts still occur during first or second dynamic data set (possibly caused by insufficient adaptation to the respiratory rhythm at the beginning of the acquisition), it might be useful to initiate the breathing pattern several cycles before the acquisition of postcontrast sequences, thus allowing the patient a certain degree of habituation. Despite this, our study design was not able to exclude fully the possibility that the isolated breathing artifacts might have been drug related.

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number of patients with mixed histopathologies, and our consensus reading did not allow any measurement of interobserver variability.

**Summary Statement**

Overall, we conclude that fixed-delay dynamic acquisitions allow arterial phase imaging with gadoxetate disodium without severe breathing artifacts in most patients and can thereby provide precise kinetic information on hepatic lesions and a decentered, yet normal breathing pattern, resulting in very robust breath-hold depth.

**REFERENCES**