MAJOR PAPER

Reduction of Ringing Artifacts in the Arterial Phase of Gadoxetic Acid-enhanced Dynamic MR Imaging

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(Received July 9, 2011; Accepted December 7, 2011)

Purpose: We assessed what MR imaging parameters affected ringing artifacts during the arterial phase of gadoxetic acid-enhanced dynamic magnetic resonance (MR) imaging.

Materials and Methods: We tested various parameters, including imaging matrices, choice of either sequential or elliptical centric phase-encoding scheme, scanning time, and contrast injection rate using new simulation software on a personal computer and visually evaluated clinical MR images retrospectively using a 4-point scale to assess ringing artifacts.

Results: The simulation study revealed that square matrices, short scanning time, slow injection rate, and sequential view ordering effectively reduced ringing artifacts, findings confirmed in clinical practice using gadoxetic acid-enhanced MR imaging. Significantly fewer artifacts resulted using a slow injection rate ($P < 0.05$) and using square matrices in the arterial ($P < 0.05$), portal ($P < 0.01$), and hepatocytic ($P < 0.05$) phases.

Conclusion: Choice of square matrix, slower injection rate, shorter scanning time, and sequential view ordering could reduce ringing artifacts.

Keywords: *dynamic MR imaging, gadoxetic acid, ringing artifact*

Introduction

Gadoxetic acid (gadolinium ethoxybenzyl diethylenetriaminepentaacetic acid; Gd-EOB-DTPA)-enhanced magnetic resonance (MR) imaging has been used to diagnose focal hepatic lesions worldwide.^{1–3} Except when breath-hold failure has caused spatial misregistration, the technique has been highly useful with injection of a small volume of medium. However, particularly during arterial phase acquisition, use of a small volume may produce “ringing artifacts” that interfere with detection and characterization of focal hepatic lesions (Fig. 1). To avoid this problem, we numerically simulated artifacts in various conditions using custom-made software and then applied countermeasures deduced from analysis to the daily practice of gadoxetic acid-enhanced MR imaging.

Methods

Computer Simulation: To analyze ringing arti-

facts, one author programmed simulation software on a personal computer (Visual Studio 2008, Microsoft, Redmond, MA, USA) Input consists of an arbitrarily drawn schematic image, typically of human anatomy, and the MR scan parameters for 3-dimensional (3D) gradient echo imaging; the pro-

Fig. 1. Ringing artifacts often occur during the arterial phase of gadoxetic acid-enhanced magnetic resonance (MR) imaging (arrows).

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gram segments the image into parts by color; and a time-intensity curve or constant intensity value can be assigned to each part. In this study, we drew a schema mimicking an axial liver section with segments representing the liver parenchyma, portal vein, hepatic vein, liver cyst, aorta, and inferior vena cava and roughly simulated the dynamic changes in signal intensities of the liver, aorta, portal vein, and inferior vena cava using concocted time-intensity curves with reference to time-density curves in previous computed tomographic (CT) examination.⁴ Various parameters, such as imaging matrices, choice of phase-encoding scheme (either sequential or elliptical centric), scanning time, and contrast injection rate can also be selected arbitrarily. After we input these modeling data, the program calculated a simulated object image at every sampling point in time (Fig. 2a) and performed 2-dimensional (2D) Fourier transform to create corresponding k-space images (Fig. 2b). A line of data, or view, was taken from each of the k-space images as the specified view order scheme dictated upon a given sampling point in time, put into the corresponding view in the synthesized “raw data” (Fig. 2c), and finally reconstructed back to a simulated image (Fig. 2d). Changes in the time-intensity curves and scan and data acquisition parameters resulted in different Fig. 2a and 2b images. Choice of phase-encoding scheme, either sequential or elliptical centric view ordering, heavily influenced the Fig. 2c image.

Although 3D data acquisition was taken into account to calculate the sampling points in time and their phase-encoding view number, object simulation through the spatial frequency space was performed with a 2D model. We adopted this simulation simplification to accept hand-drawn 2D schematic images as input and, more pragmatically, to mitigate computational resource requirements and accommodate the simulator program to an ordinary PC with a reasonable interactive response.

Clinical MR imaging: We performed gadoxetic

acid-enhanced MR imaging using a 1.5-tesla scanner (Signa HD TS version 12, GE Healthcare, Buckinghamshire, UK). This study followed the Declaration of Helsinki principles and was approved by our institutional review board. Written informed consent from patients was waived because of the retrospective study design.

We identified 220 patients with suspected focal liver lesions who underwent gadoxetic acid-enhanced MR imaging at our institution from February to September 2008. All patients underwent imaging with a transverse T_1 -weighted fast spoiled gradient echo (FSPGR) sequence (in- and opposed-phase imaging), precontrast baseline and gadoxetic acid-enhanced dynamic fat-suppressed T_1 -weighted gradient echo imaging with 3D acquisition sequence (liver acquisition with volume acceleration [LAVA]; repetition time [TR]/echo time [TE], 3.2 to 3.4 ms/1.4 to 1.6 ms; flip angle, 12° ; bandwidth, 83.33 kHz; matrix size, 320×192 or 256×256 ; slice thickness/gap, 4.4 mm/2.2 mm; sequential view ordering; zero-fill interpolation (ZIP), 2; and number of slices, 80 to 100, so that scanning time was 16 to 20 s), followed by T_2 -weighted imaging, diffusion-weighted imaging (DWI), and gadoxetic acid-enhanced hepatocytic phase (LAVA; 20 min after injection). We applied parallel imaging technique (array spatial sensitivity encoding technique [ASSET]) to all pulse sequences (ASSET factor, 2). During data acquisition, bellows were placed around the patient's abdomen to monitor breath-hold on the operator screen.

For gadoxetic acid-enhanced dynamic scans, contrast medium dose was 0.025 mmol/kg (0.1 mL/kg); the average amount injected was 6.1 mL. We sampled 140 consecutive patients with rapid (2-s injection duration) or slow (4-s injection duration) injection rate, so that the average injection speed was 3.0 mL/s for 70 patients (47 men, 23 women; aged 27 to 83 years, mean, 64.7 years; 19 with normal liver function, 51 with chronic hepatitis or cirrhosis) and 1.5 mL/s for the other 70 (49 men, 21

Fig. 2. Sample images from simulation steps. Simulated object image at a sampling point (a), corresponding k-space image (b), simulated “raw data” image (c), and final simulated image (d).

women; aged 23 to 82 years, mean, 63.7 years; 21 with normal liver function, 49 with chronic hepatitis or cirrhosis). Bolus injection was followed by 30-mL saline flush administered at the same injection rate as gadoxetic acid using a power injector (Sonic Shot GX, Nemoto Kyorindo, Tokyo, Japan) to clear the intravenous line. We used fluoroscopic triggering technique to determine the timing of the arterial-phase image, which was 6 s after the arrival of the contrast medium in the abdominal aorta.

The next consecutive 80 patients received injection at a constant rate of 4 s; image matrices were rectangular (320×192) for 40 patients (23 men, 17 women; aged 41 to 80 years, mean 66.9 years; 12 with normal liver function, 28 with chronic hepatitis or cirrhosis) and square (256×256) for the other 40 patients (26 men, 14 women; aged 36 to 81 years, mean 65.7 years; 12 for normal liver function; 28 for chronic hepatitis or cirrhosis). Bolus injection of gadoxetic acid was followed by sequential acquisition of arterial, portal (one minute after start of injection), and late (3 min)-phase images.

By consensus, 2 radiologists with 10 and 20 years' experience in body MR imaging visually compared imaging artifacts of the precontrast baseline, arterial phase, and hepatocytic phase between the rapid and slow injection rate groups using a 4-point scale (Fig. 3) (4, no artifact; 3, mild; 2, moderate; one, severe). Similarly, they compared

imaging artifacts in the arterial, portal, and hepatocytic phases between the groups with rectangular and square matrices.

Statistical analyses: For 4-point scores in clinical MR imaging data, we performed statistical analysis on a personal computer (Windows XP) using Statcel (Yanai H eds. OMS Publishing, Saitama, Japan), working on Microsoft Excel. We used Kruskal-Wallis test to compare artifacts among the 3 phases, Wilcoxon's signed-rank test to compare artifacts between any 2 phases in the same conditions, and Mann-Whitney's U-test to compare artifacts between groups with either rapid and slow injection rate or rectangular and square matrices. $P < 0.05$ was considered statistically significant.

Results

Computer simulation: Figure 4 shows the results for time-intensity curves and imaging data. The simulation showed 2 causes for ringing artifacts. The first was a steep change in gadolinium concentration during the arterial phase (Fig. 4b). The worst case scenario was premature imaging timing with elliptical centric phase order that missed gadolinium enhancement at the crucial low frequency views (Fig. 4c). Few artifacts occurred when gadolinium concentration was almost constant (3 and 20 min) (Fig. 4e, f). The other cause

Fig. 3. Visual inspections evaluated on a 4-point score. **a:** no artifact (score 4); **b:** mild artifact (score 3); **c:** moderate artifact (score 2); and **d:** severe artifact (score 1).

Fig. 4. Relationship between scan timing after gadoxetic acid injection and appearance of artifacts. Continuous lines in color are time-intensity curves of various organs (a). Dark-green dots represent sampling points from low (toward the top in the graph) to high spatial frequency (toward the bottom, a–f). The right-hand figures are simulated images with artifacts. The longitudinal line of each graph shows signal intensity, and the transverse line shows time elapsed after gadoxetic acid injection. The image matrix size is 256×256 . View ordering is elliptical centric, and scanning time was set to 18 s. Aortic peak time is set to 20 s after gadoxetic acid injection. At 15 s after injection, the aorta is blurred as the steeply rising time-intensity curve of the aorta (red) crosses the elliptical centric view-ordered sampling-point curve (b). Note that intrahepatic vessel blurring is the worst at 27 s, where the steeply rising time-intensity curve of the portal vein (orange) crosses the sampling-point curve, but the aorta is already stable (c). At 60 s, the vessels are well opacified, and artifacts decrease (d). At 3 (e) and 20 min (f), intensities of vessels are almost constant, and few artifacts are observed. The length of scanning time is the same in (e) and (f) as in (a–d); only the time scale was different.

was mismatch in frequency and phase-encoding direction matrices, or truncation artifact. Comparison between rectangular (320×192) and square (256×256) matrices demonstrated ringing artifacts dramatically decreased at 256×256 (Fig. 5a), and shorter scan duration produced fewer ringing artifacts (Fig. 5b). Similarly, sequential view ordering and slow injection rate yielded fewer artifacts (Fig. 5c, d).

Clinical MR imaging: Patient background (age, gender, presence of liver damage) did not differ significantly between the rapid (mean 3.0 mL/s) and slow (mean 1.5 mL/s) injection groups or the rectangular (320×192) and square (256×256) matrix groups. For 70 consecutive patients each, slower injection produced significantly fewer artifacts than rapid injection ($P < 0.05$; Table 1). MR images with square matrices showed significantly fewer artifacts in the arterial ($P < 0.05$), portal ($P < 0.01$), and hepatocytic phase ($P < 0.05$; Table 2), and

those with 320×192 matrices demonstrated significantly fewer artifacts in the hepatocytic phase than arterial ($P < 0.05$) and portal ($P < 0.01$) phases.

Discussion

Ringing artifacts are derived from truncation artifacts in a narrow sense and phase ghost from organs and vessels. Truncation artifacts result from the rectangular phase and frequency encoding steps in k-space.⁵ A steep change in gadolinium concentration during k-space data acquisition, particularly noted in the arterial phase, produces phase ghosts.^{6–8} These phenomena are emphasized with rapid injection rate, longer scanning time, and elliptical centric view ordering. In the arterial phase of dynamic MR imaging, change in gadolinium concentration is inevitable, and this artifact might be a fateful event of dynamic MR imaging. The ap-

Fig. 5. Simulated effects of scan parameters on ringing artifact. Each pair of images is a result of software simulation. All scans started 27 s after injection. Scanning time was basically set to 18 s in these simulations. (a) Square matrices (256×256) showed fewer artifacts than rectangular matrices (320×192). (b) Two scanning times (18 and 6 s) were set to this simulation. Artifacts were fewer at shorter (6 s) than longer (18 s) scanning time, even when rectangular matrices were used. (c) Artifacts were fewer with sequential than elliptical centric view ordering, even when rectangular matrices were used. (d) Artifacts were fewer with a slower than more rapid injection rate in PC simulation, in which the slower rate was set to twice the width of time-intensity curves of the more rapid injection and to half the peaks of the aorta and portal vein as that used for the rapid injection.

proved dose of gadoxetic acid (0.025 mmol/kg) is one-fourth that of conventional gadolinium compounds. Therefore, the short duration of the gadoxetic acid bolus produces a steeper change in gadolinium concentration than conventional gadolinium compounds. The matching of peak concentration with proper k-space data acquisition may be difficult in the case of gadoxetic acid-enhanced MR imaging. A fast injection rate could produce greater aortic peak enhancement. However, this mech-

anism may apply to the enhancement on conventional dynamic CT or dynamic MR imaging⁹ but not on gadoxetic acid-enhanced MR imaging. In addition, an experimental study revealed better arterial enhancement using slower injection (one versus 2 mL/s).¹⁰

Our clinical data showed significant reduction in ringing artifacts using slow injection. In addition, fewer artifacts were apparent in precontrast baseline and hepatocytic phase than arterial phase, probably because less perturbation in registered signal intensities across the raw data space contributed to less complication in spatial registration. A slow-flow injection method was recently shown to provide better matching between the homogenous peak-concentration “bolus” of contrast medium and low spatial frequency sampling period.¹¹ In refer to ref. 11 study, the combination of fluoroscopic triggering and slow injection rate reduced the artifacts in gadoxetic acid-enhanced MR imaging. Our clinical MR imaging also adopted fluoroscopic triggering to adjust scan timing, and our findings supported their results. Increasing the volume of contrast medium and lengthening peak concentration during k-space data acquisition could also reduce artifacts.¹² However, a dilution method may increase preparation time because it requires examiners to take care to avoid contamination risk, but it may also represent off-label use without evidence of safety. Our clinical study also showed a significant reduction in artifacts in square compared to rectangular matrices, which the PC simulation confirmed. Truncation in k-space represents abrupt signal discontinuity in the spatial frequency domain, and the adverse effect of truncation on the reconstructed image worsens with an untimely surge in signals of the organs, especially the blood vessels. It is important to understand the trade-off between larger matrix and shorter scanning time, both of which lead to reduced ringing. Naturally, the choice of square matrices may increase scanning time, but imaging parameters should be selected to balance time and quality.

Our dynamic MR imaging parameters are: fixed injection duration (4 s; mean injection rate, 1.5 mL/kg) followed by 30-mL saline flush at the same injection rate as gadoxetic acid using a power injector, fluoroscopic triggering technique to determine the timing of the arterial-phase image, 256×256 matrices, 4.4-/2.2-mm slice thickness/gap, sequential view ordering, and 80 to 100 slices, so that the scanning time is 16 to 20 s using a 3D gradient echo sequence (LAVA). In our clinical studies, artifacts possibly caused by other imaging parameters such as ASSET or ZIP could be neglected, because only

Table 1. Comparison between scores of rapid and slow injection rate

	rapid 2 seconds injection [N = 70]			slow 4 seconds injection [N = 70]		
	baseline	arterial	hepatocyte	baseline	arterial*	hepatocyte
score 4	46	36	48	47	46	50
score 3	22	23	19	22	21	17
score 2	2	9	3	1	3	3
score 1	0	2	0	0	0	0
mean $\pm$ SD	3.6 $\pm$ 0.5	3.3 $\pm$ 0.8	3.6 $\pm$ 0.6	3.7 $\pm$ 0.5	3.6 $\pm$ 0.6	3.7 $\pm$ 0.6

In rapid injection group, there was a significant difference among precontrast, arterial phase, and hepatocyte phase ($p < 0.05$), although no difference was found in slow injection group.

* Artifacts in the arterial phase with slow injection rate were significantly less than with rapid injection rate ($p < 0.05$). In precontrast baseline and hepatocyte phase, no difference was found between rapid and slow injection rate.

Table 2. Comparison between scores of rectangular (320×192) and square (256×256) matrices

	320×192 [N = 40]			256×256 [N = 40]		
	arterial	portal	hepatocyte*	arterial	portal	hepatocyte
score 4	16	15	25	27	30	33
score 3	21	22	13	13	9	7
score 2	0	2	1	0	1	0
score 1	3	1	1	0	0	0
mean $\pm$ SD	3.3 $\pm$ 0.8	3.3 $\pm$ 0.7	3.6 $\pm$ 0.7	3.7 $\pm$ 0.5**	3.7 $\pm$ 0.5 [#]	3.8 $\pm$ 0.4**

* For rectangular (320×192) matrices, hepatocyte phase showed significantly less artifact than arterial ($p < 0.05$) and portal phase ($p < 0.01$). For square (256×256) matrices, no significant difference was found among three phases.

** MR images with square matrices showed significantly less artifacts in the arterial and hepatocyte phase than with rectangular matrices ($p < 0.05$).

[#] MR images with square matrices showed significantly less artifacts in the portal phase than with rectangular matrices ($p < 0.01$).

imaging matrices or length of injection was altered.

Our study had some limitations. First, we did not compare image quality between longer and shorter scanning times or between elliptical centric and sequential view ordering in patients. Nevertheless, though we did not test the effects of these parameters clinically, the simulation results favoring shorter scanning time and sequential view order seem reasonable because these scanning schemes lead to smoother transitions in contrast concentration over the phase-encoding views ordering. Second, patients underwent MR imaging as routine clinical examinations, so we could not compare parameters in the same patient group, and finally, failure of breath-hold might be included in clinical studies, though we applied respiratory monitoring during data acquisition.

Conclusion

Our PC simulation and clinical MR imaging data showed that ringing artifacts could be reduced by selecting square matrix, slower injection rate, shorter scanning time, and sequential view ordering. When formulating protocols for dynamic contrast MR imaging, we should consider these choices to counter undesired artifacts.

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