Published in final edited form as:

J Magn Reson Imaging. 2014 January ; 39(1): . doi:10.1002/jmri.24105.

Clinical Evaluation of CAIPIRINHA: Comparison Against a GRAPPA Standard

Katherine L. Wright, B.S.^{1,2}, Michael W. Harrell, B.S.³, John A. Jesberger, B.S.², Luis Landaras, M.D.³, Dean A. Nakamoto, M.D.³, Smitha Thomas, M.D.³, Dominik Nickel, Ph.D.⁴, Randall Kroeker, Ph.D.⁴, Mark A. Griswold, Ph.D.^{1,2,3}, and Vikas Gulani, M.D., Ph.D.^{1,2,3}

¹Dept. of Biomedical Engineering, Case Western Reserve University, Cleveland, OH

²Case Center for Imaging Research, Case Western Reserve University and University Hospitals Case Medical Center, Cleveland, Ohio

³Case Center for Imaging Research, Case Western Reserve University and University Hospitals Case Medical Center, Cleveland, Ohio

⁴Siemens Healthcare, Erlangen, Germany

Abstract

Purpose—To evaluate image quality when using a CAIPIRINHA sampling pattern in comparison to a standard GRAPPA sampling pattern in patients undergoing a routine 3D breath-held liver exam. CAIPIRINHA uses an optimized phase encoding sampling strategy to alter aliasing artifacts in 3D acquisitions to improve parallel imaging reconstruction.

Methods—Twenty patient volunteers were scanned using a 3D VIBE acquisition with an acceleration factor of four using a CAIPIRINHA and standard GRAPPA sampling pattern. CAIPIRINHA and GRAPPA images were evaluated by three radiologists in a two alternative forced choice test, and the Wilcoxon signed rank test was performed.

Results—The CAIPIRINHA sampling pattern was preferred in an average of 68% of the comparisons, and the Wilcoxon signed rank test showed a significant improvement in CAIPIRINHA images ($p=0.014$). This analysis indicates that in the given sample set, CAIPIRINHA preference over the GRAPPA standard was statistically significant.

Conclusion—This work shows that for an acceleration factor of four, a CAIPIRINHA accelerated VIBE acquisition provides significantly improved image quality in comparison to the current GRAPPA standard. This allows a further reduction in imaging time for similar spatial resolutions, which can reduce long breath-hold requirements in abdominal imaging, and may be particularly helpful in patients who cannot provide requisite breath-holds with current protocols.

Keywords

CAIPIRINHA; Body Imaging; Parallel Imaging; GRAPPA; Sampling Strategy

INTRODUCTION

Image acquisition time is among the most important factors in clinical MRI. Long imaging times lead to patient discomfort, repeated breath-holds, increased motion artifacts and exams with accompanying increased costs. These considerations particularly affect body imaging,

where long breath-holds are required to capture MR images without respiratory motion artifacts. Parallel imaging(1–3) has made large advances in imaging speed with wide ranging clinical impact (4–6). Parallel imaging reduces imaging time by undersampling in the phase encoding direction by an acceleration or reduction factor (R), where every R phase encoding k-space lines are acquired. This undersampling leads to aliasing artifacts, and images are reconstructed using spatial encoding information from an array of receive coils to recover an unaliased image. The well-known limitations of parallel imaging reconstructions are a decrease in signal-to-noise ratio (SNR) that depends heavily on the geometry of the coil array used and residual aliasing artifacts at high acceleration factors, which lead to a loss in image quality (2).

In volumetric scans, MR data can be undersampled in both the phase and partition encoding directions(7,8), taking advantage of coil sensitivity variations in multiple dimensions and thus making possible higher overall reduction factors. However, the fundamental limitations of the coil array remain. Any time the array has poor performance encoding one or more directions, the end result will also be poor if parallel imaging is performed in those directions. CAIPIRINHA (Controlled Aliasing In Parallel Imaging Results IN Higher Acceleration) (9–11) is a parallel imaging technique that modifies aliasing artifacts during acquisition of multi-slice or 3-dimensional (3D) data to mitigate this basic dependence on the coil array geometry. The pattern of aliasing in 3D acquisitions is optimized by altering the phase encoding sampling strategy, specifically by applying gradient offsets during set points of data acquisition. This change in phase encoding results in modified aliasing and reduces the quantity or severity of aliased pixels, which allows for a more robust parallel imaging reconstruction with fewer residual aliasing artifacts (9–12). Clinically, this could allow for acquisition of higher quality images even at high acceleration factors, which is especially attractive for application in patients with breath-hold difficulties or those with poor compliance.

While CAIPIRINHA has been shown to improve SNR and reduce residual aliasing artifacts in previous studies, its clinical merit in improving overall image quality has not been explored. Here, we evaluate this potential improvement in image quality when using a CAIPIRINHA sampling pattern in comparison to a standard GRAPPA (3)sampling pattern in a clinical population of patients undergoing routine 3D breath-held liver exams.

METHODS

CAIPIRINHA Theory

The use of a CAIPIRINHA sampling pattern to acquire volumetric data has been previously shown to alter aliasing artifacts for a more robust parallel imaging reconstruction(10). In order to evaluate the expected improvement in image quality by using a CAIPIRINHA sampling pattern, data were acquired using a standard undersampling pattern and a CAIPIRINHA pattern as depicted in Figure 1. A standard GRAPPA undersampling pattern with a reduction factor of 2 in both phase and partition encoding directions is shown in Figure 1A, and a CAIPIRINHA undersampling pattern with a reduction factor of 2 in both phase and partition encode directions and a sampling shift of 1 is shown in Figure 1B. For simplification, volumetric acceleration factors will be noted as:

$$R = R_{PE} \times R_{PAR}^{(\Delta)}, \quad (1)$$

where R is the total reduction factor, R_{PE} is the reduction factor in the phase encoding direction, R_{PAR} is the reduction factor in the partition encoding direction, and Δ is the sampling shift. Therefore, the data acquired in this study had a total reduction factor of $R = 4$, and both the standard sampling pattern of $2 \times 2^{(0)}$ and the CAIPIRINHA sampling pattern

of $2 \times 2^{(1)}$ were used. The use of the $2 \times 2^{(1)}$ CAIPIRINHA pattern was chosen for its similar parameters to standard GRAPPA, except for the added reordering shift. Furthermore, the selection of the $2 \times 2^{(1)}$ sampling pattern, as opposed to other CAIPIRINHA sampling patterns, was based on initial datasets on normal volunteers (10).

Data Acquisition

In this IRB-approved and HIPAA compliant study, 20 patient volunteers scheduled for a routine abdominal MRI exam were scanned following informed written consent. Patient demographic data and study type are described in Table 1. All data were collected on a Siemens Avanto 1.5 Tesla scanner with a standard 6-channel body matrix receive coil and spinal array coil (using between 6 and 12 channels) over a four month period. Only patients with suspected abdominal pathology were selected for the study. Data acquisition was performed during a quiescent period in the clinical protocol at 3 to 5 minutes after injection of contrast, during which no imaging is routinely performed, and thus routine imaging for these subjects was not disturbed. Because of this limited time window, we limited this study to the two fundamental sampling patterns to assess whether CAIPIRINHA had any positive effect on image quality ($2 \times 2^{(0)}$ data were acquired following $2 \times 2^{(1)}$).

All images were acquired using a fat suppressed 3D Volumetric Interpolated Breath-hold Examination (VIBE) sequence (3D FS gradient-echo)(13). Both GRAPPA and CAIPIRINHA accelerated datasets were acquired with the following parameters: partition encoding in the cranio-caudal dimension, phase encoding anterior-posterior, repetition time 5.11 ms, echo time 2.27 to 2.29 ms, bandwidth 300 Hz/pixel, flip angle 13° , field of view range $289 \times 370 \times 180$ mm to $335 \times 370 \times 240$ mm, and spatial resolution of $1.4 \times 1.4 \times 3.0$ mm to $1.5 \times 1.5 \times 3.0$ mm. The volumetric coverage (field of view and number of partitions) were altered in each subject based on the anatomy, which yielded an average acquisition time of 7.7 seconds per data set with a range of 7.3 seconds to 11.5 seconds per data set. The scanning parameters were kept uniform for the GRAPPA and CAIPIRINHA accelerated datasets in each individual subject.

Image Evaluation

Three radiologists blinded to the sources of the data and overall goal of the study (one fellow with 1 year experience in body imaging and two attending level sub-specialty trained radiologists with over five years experience in body imaging) were asked to evaluate images for both the GRAPPA and CAIPIRINHA cases. Images were analyzed in DICOM (Digital Imaging and Communications in Medicine) format in a darkened room on a Siemens workstation with *Syngo* software (Siemens, Erlangen, Germany). A side-by-side comparison of the CAIPIRINHA and GRAPPA images was presented for each patient. Radiologists were allowed to scroll through each volumetric image individually for a patient, and simultaneous side-by-side and slice-by-slice comparison of the CAIPIRINHA and GRAPPA data was possible. Images were fully anonymized and randomized. Furthermore, the viewing plane (left or right) on which each data set was viewed was randomly selected, such that no preference was given to placing either acquisition type consistently on one side of the screen.

The image comparison was presented to the raters as a two alternative forced choice test (2AFC), in which one of the two image sets presented for a patient must be chosen as superior. The raters were asked to select their preferred image set based on overall image quality and clinical preference (i.e., which image set would be preferred in a clinical diagnostic setting). They were given the option to revisit and re-grade previously read images, and were given an unlimited time frame to grade each image set. The readers were able to read the compilation of images in less than one hour.

Statistical Analysis

Statistical analysis was performed using SPSS (IBM, Endicott, New York). Data from the 2AFC test was analyzed using a Wilcoxon signed rank test(14). This analysis was used to distinguish whether the images acquired using a CAIPIRINHA sampling pattern and the GRAPPA sampling pattern significantly differed from one another ($\alpha=0.05$). Additionally, Cohen's kappa coefficient (κ) values were calculated to determine inter-rater reliability (15,16). κ is a measure of inter-rater agreement for qualitative analyses, utilized in this case to determine agreement among the radiologists on superiority or inferiority for any one specific set of images.

RESULTS

Images were reconstructed from GRAPPA and CAIPIRINHA sampling patterns, and representative single slices from 3D volumes are shown in Figures 2–4 with a $2\times 2^{(1)}$ sampling pattern in Figures 2A, 2C, 3A, and 4A and a $2\times 2^{(0)}$ sampling pattern in Figures 2B, 2D, 3B, and 4B. Increased noise or residual aliasing artifacts are highlighted in Figures 3 and 4 with arrows. In these Figures, the shown slices have been selected from similar anatomical regions to ease visual comparison. Figure 2 shows two slices from the same subject for both the CAIPIRINHA and GRAPPA sampling patterns. In this subject, the CAIPIRINHA acquisition was preferred by all three radiologists over the standard GRAPPA acquisition. In Figure 3, a single slice is shown for both sampling patterns. Again, all three radiologists preferred the CAIPIRINHA images as well. However, in a minority of patients, the location of the noise or residual aliasing artifacts in the CAIPIRINHA images was unfavorable compared to those in the analogous GRAPPA images. As seen in Figure 4, the noise and aliasing modification of CAIPIRINHA were unfavorable, resulting in a net reader preference for the GRAPPA images.

The radiologists' 2AFC results are summarized in Table 2. For the total of 20pairs of volumetric images, radiologists chose the images using a CAIPIRINHA sampling pattern in an average of 68% of the comparisons (65% for radiologists 1 and 2 and 75% for radiologist 3). A Wilcoxon signed rank test of the 2AFC data for all three radiologists showed a significant difference ($p = 0.014$). This analysis indicates that in the given sample set, CAIPIRINHA preference over the GRAPPA standard was statistically significant.

Raters 1 and 2 had identical 2AFC selections, and Rater 3 had the same selections as raters 1 and 2 in 18 of the 20 image comparisons. This resulted in a Kappa (κ) coefficient value of 1 between raters 1 and 2, and a κ coefficient value of 0.76 between raters 1 and 3 and between raters 2 and 3. Raters 1 and 2 were the more experienced, attending radiologists, while Rater 3 was a board certified radiologist, but still in fellowship training.

DISCUSSION

While using a CAIPIRINHA sampling strategy has been previously shown to reduce SNR losses and residual aliasing artifacts, these improvements have not been explored in a clinical evaluation. In this study, data were collected using a standard GRAPPA and CAIPIRINHA undersampling pattern in order to qualitatively compare the resulting images for diagnostic image quality. Three radiologists assessed each pair of volumetric images in 20 subjects, and selected the superior image in a two alternative forced choice test. These data demonstrated a statistically significant improvement in image quality when using a CAIPIRINHA $2\times 2^{(1)}$ sampling pattern over a standard $2\times 2^{(0)}$ GRAPPA pattern.

Images shown in Figures 2–4 demonstrate representative image quality for data collected with CAIPIRINHA and GRAPPA sampling patterns. For each of these sampling strategies,

aliasing artifacts will vary based on the size of the object being imaged, the spatial variation in coil sensitivities, and the positioning of the imaging volume. Therefore, a single sampling pattern may not be superior in all imaging exams or applications. This can be seen by the discrepancy between Figures 2–3 and Figure 4. Image quality improved in Figures 2 and 3 with the CAIPIRINHA sampling pattern, while Figure 4 shows a representative example with better image quality using the GRAPPA sampling pattern. It is important to note that in our experience the example in Figure 4 occurs in a minority of acquisitions, but it is shown here to demonstrate the variability of aliasing artifacts for the same sampling pattern in different exams, and their effects on radiologist preference. One potential solution to this problem that has been suggested in the literature is to use a sampling strategy that is optimized for each subject. This can be achieved by obtaining an additional pre-scan to evaluate the aliasing in each subject and then selecting the sampling strategy accordingly (17), though this strategy would have the deleterious effect of adding to the scan time. This solution has not been evaluated in the present study, but could be explored in the future to further optimize the integration of CAIPIRINHA into the clinical routine.

The comparison between CAIPIRINHA and GRAPPA sampling strategies is further described in the radiologists' ratings shown in Table 2. In these 20 comparative datasets, an average of 68% of the images acquired with a CAIPIRINHA sampling pattern had superior image quality in comparison to the GRAPPA standard. This difference was statistically significant, which indicates that the $2 \times 2^{(1)}$ sampling pattern offers a better image quality for the same amount of acquired data. There was excellent inter-observer agreement between the three readers, with an average κ of 0.84. The κ value of 0.76 between readers 1 and 3 and readers 2 and 3 is categorized as substantial rater agreement, and the κ value of 1 between readers 1 and 2 is categorized as perfect agreement (see categorization details by Landis, et al. (15)). Perfect agreement was seen between the two attending-level radiologists, and very little difference was seen between the fellow trainee and the more experienced readers, with the fellow preferring CAIPIRINHA slightly more often than the attending radiologists.

While this sampling strategy can be applied to any arbitrary sequence, an axial VIBE acquisition was used in this study. This exam is used in all abdominal MR protocols at our institution, with a standard R=2 GRAPPA sampling pattern. These data are acquired in a volumetric exam with high spatial resolution, and therefore typically involve a long breath-hold (at least 18 seconds) for the patient. At our institution, approximately 10 percent of patients fail to provide full breath-holds, resulting in various degrees of motion-related artifacts. The results indicated that in a large majority of patients in whom higher acceleration factors are needed (i.e. patients who are identified as having difficulties with breath-holds on initial pre-contrast imaging), utilizing a CAIPIRINHA sampling could yield the higher acceleration while maintaining better image quality than GRAPPA. This would allow for a reduction in breath-holding times in volumetric liver imaging without sacrificing spatial coverage or resolution, while improving patient comfort and compliance and minimizing loss of image quality.

The main limitation of this study is the limited focus on the R=4 undersampling patterns. Different sampling patterns have been explored in previous works (9,10,12), and may be beneficial in certain applications. The pattern chosen for comparison here was selected from multiple possible patterns by comparing initial results on normal volunteers. The comparisons performed were limited to minimize time loss for both patients and radiologists. Further comparisons could be performed in the future for selecting sampling strategies could be explored for more applications, different acquisition planes, and acceleration factors.

In conclusion, this work shows that for a total acceleration factor of 4, a $2 \times 2^{(1)}$ CAIPIRINHA accelerated VIBE acquisition provides significantly improved image quality in comparison to the current GRAPPA standard. Clinically, this may allow for a further reduction in imaging time for similar spatial resolutions, which is particularly important in abdominal scans for patients who may not be able to comply with long breath-hold requirements in critical timed post-contrast images.

Acknowledgments

Grant Support: NIH 1KL2RR024990, NIH 1RO1HL094557, CWRU Summer Research

REFERENCES

1. Sodickson DK, Manning WJ. Simultaneous acquisition of spatial harmonics (SMASH): fast imaging with radiofrequency coil arrays. *Magn Reson Med*. 1997; 38(4):591–603. [PubMed: 9324327]
2. Pruessmann KP, Weiger M, Scheidegger MB, Boesiger P. SENSE: sensitivity encoding for fast MRI. *Magn Reson Med*. 1999; 42(5):952–962. [PubMed: 10542355]
3. Griswold MA, Jakob PM, Heidemann RM, Nittka M, Jellus V, Wang J, Kiefer B, Haase A. Generalized autocalibrating partially parallel acquisitions (GRAPPA). *Magn Reson Med*. 2002; 47(6):1202–1210. [PubMed: 12111967]
4. Schoenberg, S.; Dietrich, O.; Reiser, M., editors. *Parallel Imaging in Clinical MR Applications*. Berlin: Springer; 2007.
5. Deshmane A, Gulani V, Griswold MA, Seiberlich N. Parallel MR imaging. *J Magn Reson Imaging*. 2012; 36(1):55–72. [PubMed: 22696125]
6. Margolis D, Bammer R, Chow L. Parallel Imaging of the Abdomen. *Top Magn Reson Imaging*. 2004; 15:197–206. [PubMed: 15480001]
7. Weiger M, Pruessmann KP, Boesiger P. 2D SENSE for faster 3D MRI. *MAGMA*. 2002; 14(1):10–19. [PubMed: 11796248]
8. Blaimer M, Breuer FA, Mueller M, Seiberlich N, Ebel D, Heidemann RM, Griswold MA, Jakob PM. 2D-GRAPPA-operator for faster 3D parallel MRI. *Magn Reson Med*. 2006; 56(6):1359–1364. [PubMed: 17058204]
9. Breuer FA, Blaimer M, Heidemann RM, Mueller MF, Griswold MA, Jakob PM. Controlled aliasing in parallel imaging results in higher acceleration (CAIPIRINHA) for multi-slice imaging. *Magn Reson Med*. 2005; 53(3):684–691. [PubMed: 15723404]
10. Breuer FA, Blaimer M, Mueller MF, Seiberlich N, Heidemann RM, Griswold MA, Jakob PM. Controlled aliasing in volumetric parallel imaging (2D CAIPIRINHA). *Magn Reson Med*. 2006; 55(3):549–556. [PubMed: 16408271]
11. Yutzy SR, Seiberlich N, Duerk JL, Griswold MA. Improvements in multislice parallel imaging using radial CAIPIRINHA. *Magn Reson Med*. 2011; 65(6):1630–1637. [PubMed: 21287592]
12. Deshpande, V.; Nickel, D.; Kroeker, R.; Kannengiesser, S.; Laub, G. Optimized Caipirinha acceleration patterns for routine clinical 3D imaging. *Proc of the 20th Annual Meeting of the Int Soc Magn Reson Med*; 2012. p. 104
13. Rofsky N, Lee V, Laub G, Pollack M. Abdominal MR Imaging with a Volumetric Interpolated Breath-hold Examination1. *Radiology*. 1999; 212(3):876–884. [PubMed: 10478260]
14. Wilcoxon F. Individual comparisons by ranking methods. *Biometrics Bulletin*. 1945; 1(6):80–83.
15. Landis JR, Koch GG. The measurement of observer agreement for categorical data. *Biometrics*. 1977; 33(1):159–174. [PubMed: 843571]
16. Shrout PE, Fleiss JL. Intraclass correlations: uses in assessing rater reliability. *Psychol Bull*. 1979; 86(2):420–428. [PubMed: 18839484]
17. Breuer, F.; Blaimer, M. Finding the optimal sampling pattern in 2D parallel imaging for a given receiver coil configuration. *Proc of the 13th Annual Meeting of the Int Soc Magn Reson Med*; 2005. p. 2665

Figure 1. Sampling patterns used to achieve a total reduction factor of $R=4$. Figure 1A shows a $2 \times 2^{(0)}$ standard GRAPPA pattern, and Figure 1B shows a $2 \times 2^{(1)}$ CAIPIRINHA pattern.

Figure 2.

Two slices from a VIBE acquisition in a single volunteer which were sampled using an acceleration factor of $2 \times 2^{(1)}$ (Figures 2 A and C), and an acceleration factor of $2 \times 2^{(0)}$ (Figures 2 B and D). Figures 2 A and C were preferred over Figures 2 B and D by all 3 radiologists.

Figure 3.

A single slice from a VIBE acquisition in a single volunteer which were sampled using an acceleration factor of $2 \times 2^{(1)}$ (Figure 3 A), and an acceleration factor of $2 \times 2^{(0)}$ (Figure 3 B). Figure 3A was preferred over Figure 3 B by all 3 radiologists. Arrows indicate residual aliasing artifacts.

Figure 4.

A single slice from a VIBE acquisition in a single volunteer which were sampled using an acceleration factor of $2 \times 2^{(1)}$ (Figure 4 A), and an acceleration factor of $2 \times 2^{(0)}$ (Figure 4 B). Figure 4 B was preferred over Figure 4 A by all 3 radiologists. Arrows indicate residual aliasing artifacts.

Table 1

Summary of Patient Demographic Data and Study Type.

Subject	Age	Weight (kg)	Contrast Agent	Contrast Agent Dose (mmol/kg)	Study Type
1	54	70	Optimark	0.1	Routine Liver
2	59	100	Optimark	0.1	Routine Liver
3	33	100	Optimark	0.1	Enterography
4	74	82	Eovist	0.025	Routine Liver
5	80	82	Eovist	0.025	Routine Liver
6	30	57	Eovist	0.025	Routine Liver
7	83	82	Eovist	0.025	Routine Liver
8	35	95	Optimark	0.1	Routine Liver
9	35	68	Optimark	0.1	Routine Pancreas
10	64	91	Eovist	0.025	Routine Liver
11	51	86	Multihance	0.1	Routine Liver
12	58	50	Optimark	0.1	Routine Liver
13	57	84	Optimark	0.1	Routine Liver
14	20	101	Optimark	0.1	Routine Liver
15	20	101	Multihance	0.1	Routine Liver
16	23	77	Optimark	0.1	Routine Liver
17	31	64	Optimark	0.1	Routine Liver
18	52	100	Optimark	0.1	Routine Liver
19	54	70	Optimark	0.1	Routine Liver
20	44	70	Optimark	0.1	Routine Liver

Table 2

Summary of radiologists' assessments of the CAIPIRINHA and GRAPPA images using a two alternative forced choice test.

Acquisition	Rater 1	Rater 2	Rater 3	Mean Rater Percentage per Method
GRAPPA ($2 \times 2^{(0)}$)	7	7	5	32%
CAIPIRINHA ($2 \times 2^{(1)}$)	13	13	15	68%
CAIPIRINHA Percentage per Rater	65%	65%	75%	