CAIPIRINHA-accelerated T1w 3D-FLASH for small-bowel MR imaging in pediatric patients with Crohn's disease: assessment of image quality and diagnostic performance

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Background: **The "Controlled Aliasing In Parallel Imaging Results In Higher Acceleration" (CAIPIRINHA) technique greatly accelerates T1w 3D fast low angle shot (FLASH) scans while maintaining high image quality. We studied image quality and conspicuity of inflammatory lesions on CAIPIRINHA-accelerated imaging for pediatric small-bowel magnetic resonance imaging (MRI).**

Methods: **Forty-four consecutive patients (mean 14±3 years, 18 girls) underwent small-bowel MRI (MR enterography, MRE) at 1.5 T including diffusion-weighted imaging (DWI), contrast-enhanced CAIPIRINHA 3D-FLASH and standard 2D-FLASH imaging. Crohn's disease (CD) was confirmed in 26 patients, 18 patients served as control. Independent blinded readings were performed for grading of image quality and conspicuity of CD lesions on CAIPIRINHA FLASH and standard FLASH images in comparison to a reference standard comprising imaging and endoscopic data.**

Results: **CAIPIRINHA FLASH yielded significantly higher image quality with good inter-observer agreement (κ=0.68) and showed better visual delineation in 40% of the assessed bowel lesions, as compared to standard FLASH. There was full agreement for identification of CD patients between CAIPIRINHA and standard FLASH. CAIPIRINHA FLASH detected two small-bowel lesions that were not seen on standard FLASH. DWI revealed additional inflammatory lesions inconspicuous on contrast-enhanced imaging. MRE showed an overall diagnostic accuracy of 93%.**

Conclusion: **We present first evidence that CAIPIRINHA greatly accelerates T1w imaging in paediatric MRE without trade-off in image quality or lesion conspicuity and is thus preferable to standard FLASH imaging.**

World J Pediatr 2016;12(4):455-462

Key words: **CAIPIRINHA;**
Crohn's disease;
FLASH;
pediatrics;
small-bowel MRI

Introduction

Crohn's disease (CD) is a common chronic inflammatory bowel disorder with pediatric patients comprising about one-fourth of all cases at primary diagnosis.[1,2] While ultrasonography is the diagnostic method of first choice in children with CD,[3] it may not cover the full range and extent of gastrointestinal CD manifestations and of coexisting extra-intestinal pathologies. Computed tomography[4,5] is increasingly replaced by magnetic resonance imaging (MRI) as the preferred cross-sectional imaging modality in young CD patients.[6] Reported sensitivity and specificity of small bowel MRI for detecting inflammatory bowel disease range between 60% and 92%.[7-12] Repeated breath-holding and prolonged immobilization in the MR scanner, however, are not well tolerated by many young patients, frequently resulting in motion artefacts and degraded image quality.[13] Novel acquisition techniques, such as "Controlled Aliasing In Parallel Imaging Results In Higher Acceleration" (CAIPIRINHA) greatly accelerate MR imaging beyond the effect of standard parallel imaging techniques[14] and allow the acquisition of a full stack of abdominal images at almost "CT-like" speed within 15 to 20 seconds during a single breath-

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doi: 10.1007/s12519-016-0047-5
Online First July 2016

hold. CAIPIRINHA-accelerated scans show high image quality in volunteers and adult patients[15-18] and in pediatric abdominal MRI.[13] In this study, we analyzed data on image quality and diagnostic performance of CAIPIRINHA 3D-FLASH imaging in pediatric CD patients undergoing routine small-bowel MRI.

Methods

We retrospectively identified all 44 pediatric patients who had clinical routine small-bowel MRI including both standard FLASH and CAIPIRINHA FLASH imaging on a 1.5 Tesla Magnetom AERA scanner (Siemens Medical, Erlangen, Germany, Syngo VD13) at our institution between January 2013 and September 2014. Informed written consent had been obtained from the legal guardians and, if possible, from the patients for all diagnostic procedures. A waiver was granted by the Institutional Review Board for the retrospective analysis of data presented in this study. All study work was conducted in accordance with the Declaration of Helsinki of 1964, as revised in 2000.

Patients

All 44 consecutive patients (mean age 14±3 years, range 9 to 18 years, 18 girls) had clinical work-up and treatment at the Department of Pediatrics of our institution. The study group comprized 26 CD patients and 18 patients without chronic inflammatory bowel disease.

In the CD study group (*n*=26), 16 patients (mean age 13±3 years) were newly diagnosed with CD and all had concurrent gastroscopy, ileocolonoscopy, endoscopic biopsy and histological evaluation of biopsy specimen. Duration of abdominal symptoms prior to diagnosis ranged from six weeks to 24 months with a median of seven months. In 10 patients with known CD, mean course of disease was 4 to 84 months (median 36 months). Of these, eight patients underwent MRI for acute exacerbation of abdominal symptoms under anti-inflammatory treatment and for suspected progressive CD, one patient for clinically suspected small bowel obstruction and one patient for suspected abdominal wall abscess.

Eighteen patients (mean age 14±3 years) without history or clinical signs of chronic inflammatory bowel disease underwent MR enterography (MRE) for a variety of clinical conditions. Three patients were on post-treatment follow up of abdominal tumours (*n*=3, carcinoid of the appendix, colonic small round blue-cell tumour, prolapse of juvenile colonic polyp). The remaining 15 patients underwent MRI for recurrent abdominal pain of non-clarified etiology in the presence of juvenile rheumatic arthritis (*n*=2), mismatch repair cancer syndrome (*n*=1), Muckle-Wells syndrome (*n*=1), prolonged non-resolving mesenterial lymphadenopathy (*n*=2), preceding laparoscopic appendectomy (*n*=2), and chronic recurrent abdominal symptoms including pain, diarrhoea and vomiting (*n*=7).

MRI examination

MRE was performed according to our institutional routine imaging protocol, as previously described in detail,[19] supplemented with CAIPIRINHA-accelerated T1w 3D-FLASH imaging. The scanning protocol, performed with oral administration of 250 to 1500 mL (median 1000 mL) 2.5% mannitol solution and with gastrointestinal hypotonia (a weight-adapted dose of 20-40 mg butylscopolamine (Buscopan) comprised high-resolution T2w Half-Fourier Acquisition Single-shot Turbo spin Echo (HASTE), diffusion-weighted (DWI, single-shot echoplanar imaging with b values of 50 and 800 s/mm^2) and T1w contrast-enhanced fat-saturated (ce-T1w FS) sequences. Post-contrast scans were acquired at 1 to 3 minutes after i.v. administration of a weight-adapted standard dose of gadoterate meglumine (Dotarem, Guerbet, Paris, France) in 25 patients and gadopentetate dimeglumine (Magnograf; Marotrast, Jena, Germany) in 19 patients. For study purposes, post-contrast imaging included a standard T1w 2D FLASH FS and a CAIPIRINHA-accelerated

Table 1. Typical MRI scan parameters used in this study

Variables	Standard 2D-FLASH	CAIPIRINHA 3D-FLASH	DWI, b=50/800	T2w HASTE
TR, ms	86.0	6.1	8800	1000
TE, ms	3.8	3.0	88	102
Flip angle, °	90	10	90	160
Scan orientation	Transverse	Transverse	Transverse	Transverse
In-plane resolution, mm	1.3×1.3	1.0×1.0	1.5×1.5	1.0×1.0
Slice thickness, mm	5	3-5	4	4
FOV, mm	250	250	250	350
iPAT	-	Acceleration factor 4	-	Acceleration factor 2
Breath-hold	22 s	15 s	Free-breathing	21 s
Scan time	4 min 3 s	15 s	5 min 27 s	21 s

TR: repetition time; TE: echo time; FOV: field of view; iPAT: integrated parallel acquisition techniques.

T1w 3D FLASH FS scan acquired in random order at 2 to 3 minutes after i.v. contrast injection. Typical scan parameters are outlined in Table 1. Additional coronal scans were performed, as clinically necessary (Fig. 1).

Image analysis

All readings were performed on a certified radiology work station (Syngo Plaza, Siemens Medical, Erlangen). The first reader, a resident in radio-oncology with basic training in MR imaging (LM), and the second reader, a board-certified consultant pediatric radiologist with 10 years experience in abdominal MRI (NH), first performed a consensus reading blinded to all clinical and patient data, assessing the extent of small bowel distention and colonic distension by oral contrast on the three point Likert scale, overall image quality of CAIPIRINHA 3D-FLASH scans and standard 2D-FLASH scans on a five point Likert scale and the presence of the CD manifestations. Bowel segments were rated as normal in the absence of pathological wall thickening (exceeding 3 mm wall thickness in distended segments) and of segmental signal increase on contrast-enhanced T1w and on DWI (b=800) in combination with low signal on the corresponding apparent diffusion coefficient (ADC) map. After two weeks, a second consensus reading was completed by the same two readers with full access to all available data (imaging, clinical and endoscopic data) to establish the diagnostic reference standard.

Assessment of overall image quality was based on the presence or absence of diagnostic image quality and the presence of artefacts. Overall image quality of CAIPIRINHA 3D-FLASH *vs.* standard 2D-FLASH was graded on a modified 5-item Likert scale as previously published.[13]

Inter-observer agreement on overall image quality was studied by the means of a third, independent and blinded, reading performed by an experienced resident radiologist with special training in pediatric MR imaging (HN) three months after the consensus reading.

Finally, the second reader performed a quantitative analysis on bowel wall thickness, bowel wall signal and intraluminal signal on CAIPIRINHA FLASH, standard FLASH and diffusion-weighted images (b=800) with quantitative ROI measurements (average of three measurements) of distended inflamed and non-inflamed adjacent bowel segments, as described previously,[19] and calculated signal intensity ratios of unaffected *vs.* inflamed bowel wall and bowel wall *vs.* lumen. Conspicuity of inflammatory bowel lesions in the small and the large bowel was also compared between CAIPIRINHA FLASH and standard FLASH based on the visual preference.

Estimation of sample size

The primary goal of this study was to determine the level of agreement for the identification of patients with inflammatory bowel disease using the standard sequence (2D-FLASH) and the study sequence (CAIPIRINHA 3D-FLASH). Based on the null hypothesis of moderate agreement (κ_0=0.50) *vs.* a postulated very good agreement ($\kappa_1 \geq 0.90$) on kappa analysis, the a priori estimation of sample size computed with PASS 12 for Windows indicated a necessary sample size of n=36, with a test power of 80%, α=0.05 and expected 75% test-positive cases in the study cohort.

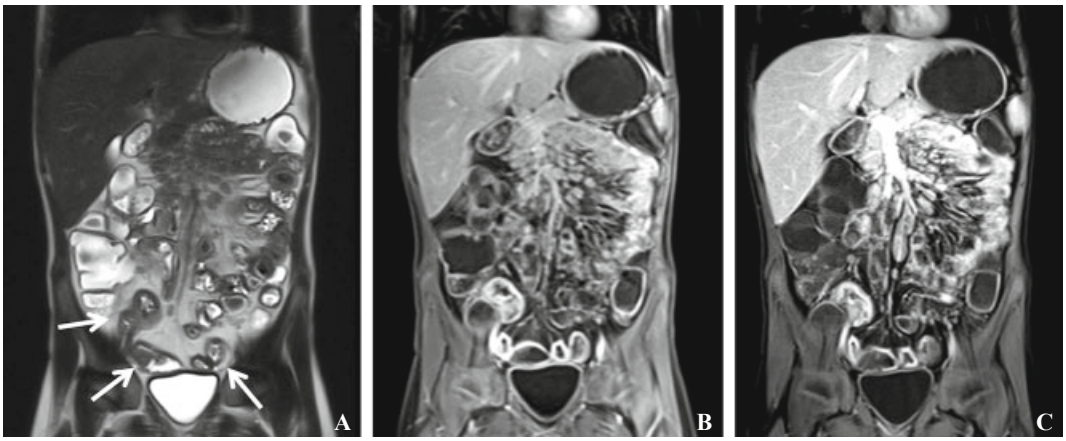

Fig. 1. Patient (11-year-old, male) with primary diagnosis of Crohn's disease and endoscopically confirmed highly active terminal ileitis. Coronal T2w HASTE (**A**) as well as contrast-enhanced standard T1w 2D-FLASH (**B**) and T1w 3D-CAIPIRIHA FLASH (**C**) consistently visualise the extensive inflammatory wall lesions of the ileum and at the ileocoecal junction (arrows). Although overall image quality of both standard and CAIPIRINHA-accelerated FLASH imaging was graded as excellent, organ and vessel contours are yet more clearly delineated with CAIPIRINHA FLASH.

Further statistical analyses

Descriptives and data following normal distribution are shown as mean and standard deviation. Image quality was compared between study sequence and standard sequence using the Wilcoxon matched-pair signed-rank test. Inter-observer variability in assessing overall image quality was studied with a kappa analysis of two independent blinded readings. Between-groups comparison for quantitative data was conducted with the Wilcoxon non-parametric test for related samples. Proportions on cross-tabs were tested with the Chi-square test. All statistical tests were performed as two-sided tests with α=0.05 and were computed with the IBM SPSS 21 software package for Windows.

Results

Consensus reading establishing the diagnostic standard

All MRI studies were successfully completed. In total, 308 bowel segments were evaluated in 44 study participants, with inflammatory lesions being present in 73 (24%) segments on MRI and/or endoscopy. Using all available clinical and imaging information, we identified two false-negative and one true-negative cases among the 26 CD patients and one false-positive case in the control group. Thus, diagnostic accuracy of MRI for identifying the presence of inflammatory bowel disease on a per patient basis was thus 41/44= 93%.

Consensus reading on overall image quality

All MRI scans showed diagnostic image quality. Bowel distention was rated as good in 27 (61%) and 20 (45%), as sufficient in 15 (34%) and 17 (39%) and as poor in 2 (5%) and 7 (16%) patients for small bowel and large bowel, respectively. Overall image quality was significantly higher with CAIPIRINHA FLASH, compared to standard FLASH (Wilcoxon signed rank test, P<0.001) (Table 2). Degraded image quality was noted in 3 (7%) of standard FLASH scans, but in none of the CAIPIRINHA FLASH scans. In all examinations, image quality of CAPIRINHA FLASH was superior or equal to standard FLASH. In eight patients with less-than-good image quality on standard FLASH (IQ 2+3), good or excellent image quality was seen with CAIPIRINHA acceleration. In one 15-year-old patient, who poorly cooperated with breath-holding and showed degraded image quality (IQ2) on standard FLASH, at least satisfactory image quality (IQ3) was obtained with CAIPIRINHA FLASH.

Table 2. Cross-table presenting the results of the consensus reading on overall image quality (IQ) of 2D-FLASH standard technique and CAIPIRINHA-accelerated 3D-FLASH imaging ranging from 1 (insufficient for diagnosis) to 5 (excellent image quality, little or no artefacts)[13]

		3D-FLASH CAIPIRINHA					∑
		IQ 5	IQ 4	IQ 3	IQ 2	IQ 1	
2D-FLASH standard	IQ 5	20					20
	IQ 4	9	6				15
	IQ 3	4	2	0			6
	IQ 2	0	2	1	0		3
	IQ 1	0	0	0	0	0	0
	∑	33	10	1	0	0	

Inter-observer variability in overall image quality

Inter-observer kappa comparing the image quality score of the consensus reading of two observers *vs*. the independent blinded reading of a third observer was κ=0.68, indicating good inter-observer agreement. Consistent with the results of the consensus reading, the third observer rated the image quality of all CAIPIRINHA 3D-FLASH scans as either equal or superior to standard 2D-FLASH.

Diagnostic performance of DWI, standard 2D-FLASH and CAIPIRINHA 3D-FLASH

All 23 true-positive CD patients showed inflammatory bowel lesions on DWI. In one of these patients, both standard FLASH and CAIPIRINHA FLASH failed to demonstrate signs of ileitis, while DWI and endoscopy were positive for inflammation.

In per-segment analysis of 69 small-bowel segments, DWI correctly diagnosed all 43 affected small bowel segments, as compared to the diagnostic standard, while standard FLASH missed two inflamed upper small bowel segments (Fig. 2) and one lesion at the ileocoecal junction due to overlying motion artefacts. With CAIPIRINHA FLASH, all upper small bowel lesions were correctly identified. The one ileocoecal lesion diagnosed on DWI and confirmed by endoscopy, was occult with both T1w scan techniques for a lack of discernible wall thickening and contrast enhancement in the presence of motion artefacts.

In the 161 large bowel segments assessed, DWI yielded false-negative findings in five segments and false-positive signal increase of one non-distended segment in the transverse colon, as compared to colonoscopy. Standard FLASH was false-negative in 11 segments and CAIPIRINHA FLASH in 10 segments, both sequences missing inflammatory colonic involvement in three patients in the presence of a positive diagnostic reference standard. Abdominal wall abscess (n=1) and stenotic small bowel segments (n=2) were correctly identified on all sequences (Fig. 3).

While the findings on standard FLASH and on CAIPIRINHA FLASH were not fully consistent on per-segment analysis of inflamed bowel wall, there was full

agreement (100%) between the consensus reading of standard and study sequence with regard to the presence of inflammatory bowel lesions on per-patient analysis, supporting the study hypothesis of excellent agreement with $\kappa_1 \geq 0.90$.

Qualitative comparison of lesion conspicuity on standard 2D-FLASH *vs.* CAIPIRINHA 3D-FLASH

Conspicuity of one inflammatory bowel lesion per patient, if present, was assessed in 21 small bowel and eight large bowel segments. Based on the subjective visual preference of the readers, CAIPIRINHA FLASH was preferred to standard FLASH in nine (43%) and seen of equal quality in twelve cases of small bowel lesions. Among eight patients with large bowel lesions,

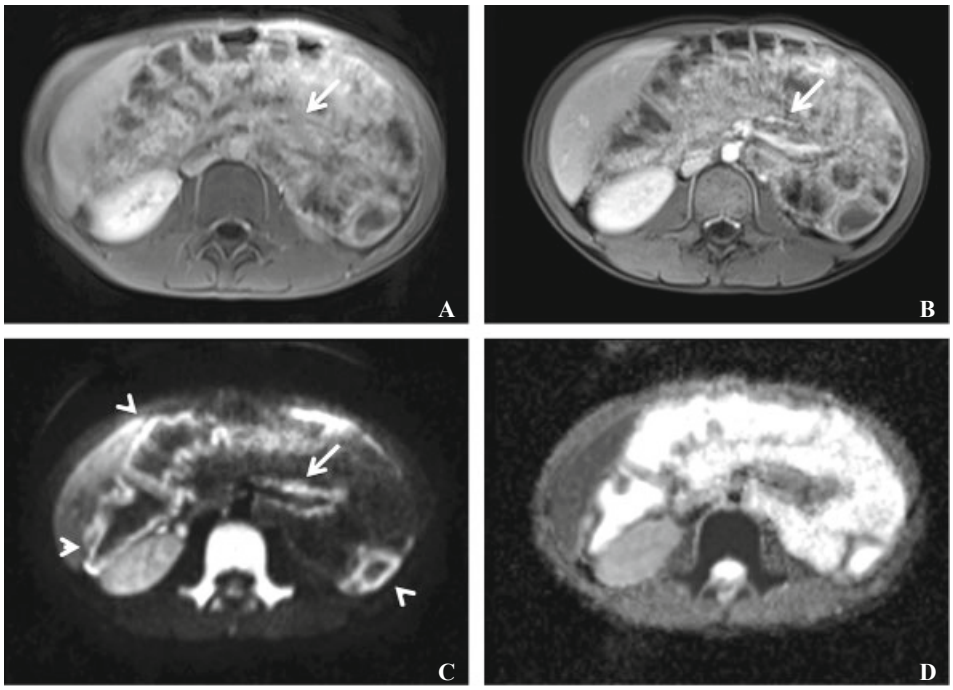

Fig. 2. Patient (10-year-old, male) with primary diagnosis of Crohn's disease. Extensive colitis and terminal ileitis were seen on endoscopy. Standard 2D-FLASH imaging (**A**) fails to visualise the jejunal skip lesion (arrow) seen as transmural contrast enhancement on CAIPIRINHA FLASH (**B**) and high signal on DWI b=800 (**C**) with corresponding low ADC (**D**). The high signal of the large bowel wall on DWI (arrow heads) indicating colonic wall inflammation remains without correlating signal alterations on contrast-enhanced imaging. CAIPIRINHA FLASH shows more homogeneous fat saturation along the anterior abdominal wall as compared to standard FLASH.

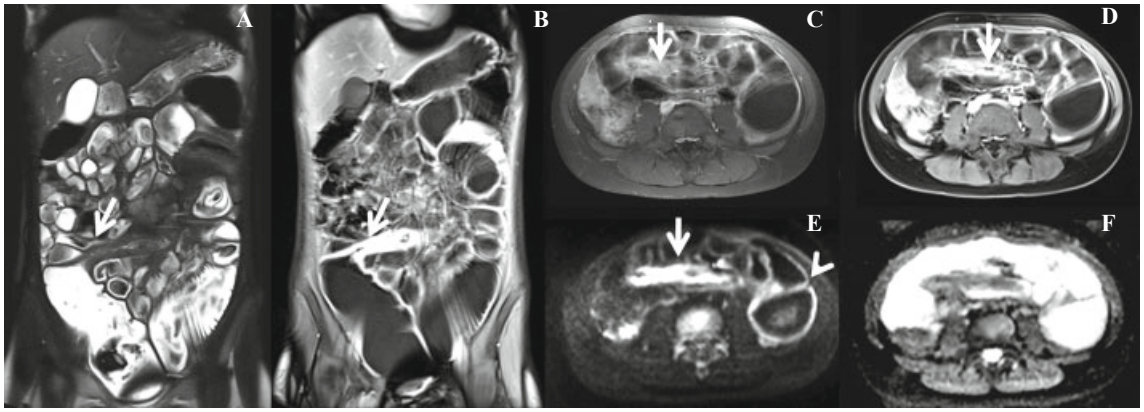

Fig. 3. Patient (16-year-old, female) with Crohn's disease for five years. Long-standing non-compliance with anti-inflammatory treatment recently led to an acute relapse with abdominal pain for four weeks. Coronal T2 HASTE (**A**) and contrast-enhanced CAIPIRINHA FLASH (**B**) show segmental narrowing of the lower jejunum (arrow) in the presence of massive dilatation of proximal small bowel indicating functionally relevant stenosis. Transverse cross-sections confirm stenotizing segmental jejunal inflammation, which is less visible on standard FLASH (**C**) than on CAIPIRINHA FLASH (**D**), DWI (**E**) and the ADC map (**F**). The dilated proximal small bowel loops in the left middle abdomen show high signal on DWI (**E**, arrowhead) in the absence of wall thickening, possibly due to chronic subileus.

Table 3. Quantitative analysis of wall thickness and signal intensity ratios (SIR) of small and large bowel segments on standard 2D-FLASH and CAIPIRINHA-accelerated 3D-FLASH

Variables	2D-FLASH standard	3D-FLASH CAIPIRINHA	*P*
Small bowel			
Normal wall thickness, mm	1.8±0.2	1.8±0.1	0.346
Inflamed wall thickness, mm	5.4±1.8	5.3±1.6	0.913
SIR inflamed wall *vs.* lumen	4.4±1.4	4.1±1.1	0.571
SIR inflamed wall *vs.* normal wall	1.6±0.4	1.8±0.8	0.841
Large bowel			
Normal wall thickness, mm	1.9±0.2	1.9±0.2	0.280
Inflamed wall thickness, mm	4.5±0.8	4.4±0.6	0.695
SIR inflamed wall *vs.* lumen	3.1±0.8	3.7±1.5	0.250
SIR inflamed wall *vs.* normal wall	1.5±0.3	1.6±0.2	0.383

SIR: signal intensity ratio.

CAIPIRINHA FLASH was preferred in three cases (38%), leaving five ties. CAIPIRINHA FLASH was not seen as inferior to standard FLASH in any of the assessed bowel wall segments.

Quantitative comparison of standard 2D-FLASH and CAIPIRINHA 3D-FLASH

Quantitative data comparing 2D-FLASH and CAIPRINHA 3D-FLASH is presented in Table 3. Notably, none of the assessed quantitative parameters showed a statistically significant difference. The restricted diffusivity in inflamed bowel segments corresponded to a lower ADC with virtually no overlap between normal and diseased bowel segments.

Discussion

Our study results demonstrate first evidence that, in terms of image quality and acquisition time, highly accelerated CAIPIRINHA T1w 3D-FLASH consistently outperforms standard 2D-FLASH in small-bowel MRI scans. To our knowledge, this finding is novel, as there is no previously published data available on the diagnostic performance of CAIPIRINHA-FLASH in patients with Crohn disease, pediatric or adult. Fast scanning with CAIPIRINHA acceleration requires only one 15-second breathhold for a full stack of abdominal images, suffers less motion artefacts and considerably reducs total scanning time. These findings strongly recommend CAIPIRINHA 3D-FLASH for implementation in small-bowel MRI protocols.

MR imaging is the modality of choice in children with inflammatory bowel disease when ultrasonography does not provide all necessary information.[20] One of the remaining setbacks of MRI, that is long acquisition time, can be overcome with modern acceleration techniques. The CAIPIRINHA technique,[14] which is now commercially available on clinical MRI scanners, combines three-dimensional volume acquisition with k-space under-sampling in both encoding directions and the shifting of sampling positions in order to reduce aliasing artefacts.[21] Recent studies on CAIPIRINHA acceleration showed advantages in terms of image quality[15,18] and visualization of arterial liver perfusion.[16,17] Our data now demonstrates that high acceleration factors used in CAIPIRINHA do not compromise conspicuity of inflammatory bowel wall lesions. Rather on the contrary, less artefacts from patient bulk motion, respiratory and bowel movement as well as improved fat saturation all favour CAIPIRINHA. The over-all diagnostic accuracy seen in our study group was high and in line with previously reported data.[7-12] Superior image quality with CAIPIRINHA FLASH is a consistent finding in our study with good inter-observer agreement, considering that the readers had not performed any previous "calibration reading" to reduce variability. In our study group, CAIPIRINHA FLASH identified all patients with inflammatory bowel lesions that show pathological findings on standard FLASH, detected a number of additional bowel lesions and reliably visualised all CD-related complications, such as abscess and small-bowel stenosis. Quantitative evaluation of wall thickness in normal and inflamed bowel segments, of relative signal intensity of normal wall *vs.* inflamed wall and of inflamed bowel wall *vs.* bowel lumen did not show statistically significant differences for standard and accelerated FLASH imaging. All patients in our study cohort underwent scheduled routine imaging and were in generally good clinical condition. We expect the benefits of fast scanning to be even more pronounced in an emergency setting and in very young, or very old patients.

Though not adressed in this study, ultra-fast scanning may also provide for dynamic contrast-enhanced imaging studies with high temporal resolution for research purposes and may provide new insight into the dynamics of inflammation-induced hyperperfusion of diseased bowel wall, although attempts to correlate parameters of dynamic contrast enhancement with disease activity in pediatric CD patients have so far produced equivocal results.[22]

At this point, it is important to emphasise the need for sufficient bowel distention. Most of our patients cooperated well with oral contrast administration. In order to maintain a low level of invasiveness, we do not routinely perform enteroclysis via gastric or duodenal tubes for small-bowel MRI. We routinely inform patients and their guardians on the importance of oral contrast for diagnostic accuracy and usually are able to secure a sufficiently high level of patient compliance. Consequently, a good or at least sufficient overall degree of distention was achieved in small (96%) and

large (84%) bowel in the majority of our patients. In our experience, poor loop distention frequently results in apparent thickening and signal increase of the collapsed bowel segment, mimicking inflammation on both standard FLASH and CAPIRINHA FLASH, and, unlike previously reported by Ousalah et al from adult patients,[23] also on DWI. Although we did not attempt a detailed analysis in this respect as part of the present study, we performed quantitative assessment in distented bowel segments only.

Diffusion-weighted MRI (DWI) is another recent addition to paediatric small-bowel MR imaging protocols.[19,24,25] DWI relies on intrinsic tissue contrast based on altered diffusivity without the need of i.v. contrast agent and provides quantitative data, the ADC. Prediction of response to infliximab treatment based on DWI data was reported from an adult cohort with Crohn's disease.[25] In this study, we performed and analysed DWI as an important part of our diagnostic standard of comparison. As in an earlier study,[19] DWI detected additional CD manifestations in this study cohort in correlation with endoscopically confirmed Crohn segments. We therefore use, and recommend, DWI as a routine supplement to standard MR sequences in small-bowel scans. A combination of high-resolution T2w HASTE, DWI and fast post-contrast scans with CAIPIRINHA facilitates high-quality small-bowel scans in children within less than 10 minutes total acquisition time.

Some limitations of our study warrant discussion. Our findings may be affected by the retrospective study design and the relatively small number of study participants and should be verified in a larger prospective trail. Secondly, it is notoriously difficult to establish a reliable diagnostic reference standard for small-bowel imaging studies. Large portions of the intestine remain inaccessible to endoscopy. Where available, endoscopy is confined to mucosal manifestations and intramural or extramural disease may not be detected. Ultrasonography is recognized as useful and accurate in children with inflammatory bowel disease, yet a segment-by-segment correlation of ultrasound and MRI findings in a clinical setting seems hardly feasible. We therefore relied on a comprehensive reference standard taking full advantage of all clinical and imaging data available, with many, but not all, of our patients having had concurrent endoscopy. Our clinical small-bowel protocols do not routinely include fast dynamic T1w 3D scanning (e.g. VIBE FLASH) after i.v. contrast application, as used in dynamic liver scans, therefore we could not compare volumetric scan with and without CAIPIRINHA acceleration, as may be appropriate. In general, however, our clinical experience with VIBE imaging of the pediatric abdomen is such that these images frequently suffer from severe artefacts, too. Finally, although the readers were blinded to clinical and imaging data when performing the per-sequence study analysis, CAIPIRINHA FLASH and standard FLASH images each come with characteristic visual features, which defeat the attempt to blind the experienced reader to the particular sequence. This, however, is a general problem and hard to avoid when comparing quality and imaging characteristics across different scan techniques.

In conclusion, pediatric patients undergoing small bowel scans can expect substantial benefits from highly accelerated 3D MR imaging. CAIPIRINHA T1w 3D-FLASH imaging greatly reduces total acquisition time and the number of breath-holds and, as a novel finding from our study, reduces artefacts and detects additional inflammatory bowel wall lesions, as compared to standard FLASH imaging.

Funding: No external sources of funding were used for this study.
Ethical approval: A waiver was obtained from the local Institutional Review Board for this retrospective study.
Competing interest: Prof. Köstler H receives research support from Siemens Medical (Erlangen, Germany). The Department of Diagnostic and Interventional Radiology, represented by Prof. Bley T, receives ongoing MRI research support from Siemens Healthcare (Erlangen, Germany). Prof. Bley T receives ongoing research support from the "Deutsche Forschungsgemeinschaft, DFG" for MRI research. Prof. Bley T had past consulting activities for HeartFlow, GSK and MSD and received past payments for lectures for Bayer, Bracco, Guerbet, and Siemens. All these fundings and activities are not related to the research work presented in this manuscript. The project did not receive external sources of funding. The other authors have no conflict of interest to declare.
Contributors: NH is the guarantor of the presented work. LM and NH conceived and planned the study. LM, DA, HN and NH collected imaging and clinical data and performed the data analysis. BT contributed to data interpretation. PT and KH were responsible for developing MRI sequences. All authors participated in drafting and revising the manuscript and approved the submitted version.

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Received December 25, 2015
Accepted after revision March 13, 2016