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DANTE-prepared 3D FLASH: A fast isotropic-resolution MR approach to morphological evaluation of the peripheral arterial wall at 3 Tesla

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Abstract

Purpose—To develop and assess a sequence using DANTE dark-blood preparation combined with FLASH readout (DANTE-FLASH) for rapid isotropic-resolution 3D peripheral vessel wall imaging at 3T.

Materials and Methods—Numerical simulations were first conducted to optimize imaging parameters for maximizing the wall-lumen contrast. The sequence, implemented at 3T, was then assessed in the bilateral superficial femoral arteries of 8 healthy volunteers and 3 patients who were undergoing non-contrast-enhanced MRA due to known peripheral artery disease. Conventional 2D dark-blood turbo spin echo (DB-TSE) was performed as a reference in all subjects. Image quality on a 5-point scale, apparent wall signal-to-noise ratio, apparent wall-lumen contrast-to-noise ratio, wall thickness, wall area and lumen area were assessed or measured in all healthy subjects. Additionally, the agreement in the depiction of wall thickening or luminal stenosis between DANTE-FLASH and DB-TSE, or MRA was assessed using a 4-point scale in the patient study.

Results—DANTE-FLASH allowed for a 30-cm-long coverage within 4 min, whereas DB-TSE took about 7 min for a 9-cm-long coverage. Good image quality was obtained by DANTE-FLASH (score>3). The wall thickness, wall area, and lumen area were all comparable (t-test; $p = 0.334$, 0.224 and 0.136) and showed excellent agreement between DANTE-FLASH and DB-TSE (intra-class correlation = 0.81 , 0.85 , and 0.98). The atherosclerotic plaques and luminal stenosis identified by DANTE-FLASH were in accordance with the findings by 2D DB-TSE or MRA.

Conclusion—DANTE-FLASH is a 3D dark-blood MR sequence allowing for rapid isotropic-resolution imaging of the peripheral vessel wall at 3T.

Keywords

Peripheral vessel wall; Dark-blood MRI; DANTE preparation

Peripheral artery disease (PAD) has become a public health issue worldwide. Two hundred and two million people were living with PAD in 2010 and the number of individuals with PAD increased by 28.7% in low-income or middle-income countries and 13.0% in high-income countries from 2000 to 2010 (1). The major cause of PAD is atherosclerosis, an inflammatory arterial wall disease that gradually narrows and blocks the arteries, resulting in intermittent claudication and gangrene in the lower extremities and even amputation (2–4). Although critical luminal stenosis is the immediate cause of severe PAD symptoms and has become the most important diagnostic imaging marker, luminal narrowing may be absent in patients with severe atherosclerosis due to positive arterial wall remodeling (5,6). Thus, direct depiction of arterial wall morphology would be of importance for early detection of PAD (6).

Dark-blood MR imaging has emerged as a noninvasive imaging modality for directly assessing vessel wall thickness and plaque burden (7–9). Several dark-blood MR techniques have been proposed for peripheral vessel wall imaging, including spatial pre-saturation dark-blood two-dimensional (2D) turbo spin-echo (DB-TSE) (6), motion-sensitized driven equilibrium (MSDE) prepared three-dimensional (3D) fast low-angle shot (FLASH) (8), and 3D variable-flip-angle TSE (SPACE) (10). The application of 2D DB-TSE is restricted by its poor slice resolution, long scan times, and limited spatial coverage (10).

As 3D imaging techniques, MSDE prepared FLASH (MSDE-FLASH) and SPACE are advantageous over 2D DB-TSE with respect of voxel isotropy and spatial coverage efficiency, which is particularly valuable for the thin and large-spatial-extent peripheral vessel wall. However, these two methods have inherent drawbacks. MSDE-FLASH, although fast due to the FLASH readout, is sensitive to the B_1 field inhomogeneity because of the typically used large field of view (FOV) and large-flip-angle radio-frequency (RF) pulses in the MSDE preparation (11,12). This issue can be exacerbated at higher magnetic field strengths such as 3 Tesla (3T). As a result, the quality of flow signal suppression and wall delineation may not be consistently satisfactory throughout the long arterial segment. Compared to MSDE-FLASH, SPACE requires a longer time of repetition (TR) and/or lower turbo factor for adequate signal-to-noise ratio (SNR) and thus renders relatively long scan times (10). This may increase the likelihood of involuntary motion during scanning and hence motion-related artifacts.

Recently, a new dark-blood preparation, DANTE (Delay Alternating with Nutation for Tailored Excitation), was employed for suppressing blood signal and demonstrated successfully in carotid vessel wall imaging (13,14). The preparative module exploits a series of low-flip-angle RF pulses interspersed with dephasing gradients to generate intravoxel phase dispersion among flowing spins to suppress flow signal. Compared to the MSDE preparation, DANTE permits less T2-decay effect and thus higher SNR of the vessel wall (14) and, more importantly, is theoretically insensitive to B_1 field inhomogeneity due to the

use of low-flip-angle RF pulses. Hence, DANTE would be well suitable for dark-blood peripheral vessel wall imaging at 3T.

In this work, a sequence combining the DANTE preparation with the FLASH readout (DANTE-FLASH) was developed and implemented at 3T. Volunteer studies were performed to assess the feasibility of DANTE-FLASH to achieve fast isotropic-resolution peripheral vessel wall imaging.

MATERIALS AND METHODS

Sequence

The sequence diagram of the DANTE-FLASH technique is shown in Figure 1. The DANTE preparative module consists of a train of hard RF pulses interspersed with dephasing gradients. The durations of RF pulse, dephasing gradient and the gap between the RF pulse and the dephasing gradient are 200 μ s, 1000 μ s and 10 μ s, respectively, resulting in an inter-pulse duration of 1220 μ s. In order to realize optimal outer-wall definition, a chemically-selective fat saturation module follows the DANTE module to suppress perivascular fat signal. Centric phase-encoding ordering is used in the 3D FLASH readout to maximize dark-blood and fat saturation effects.

Numerical Simulations

As discussed in (13), the dark-blood efficiency of the DANTE module highly depends on its RF pulse flip angle, pulse train length, and the zeroth-gradient moment between two adjacent RF pulses. In this work, a large zeroth gradient moment (amplitude = 20 mT/m and duration = 1000 μ s) was chosen to avoid visible banding artifacts on static tissues. The DANTE flip angle and pulse train length underwent optimization for maximizing the contrast between the vessel wall and lumen. In addition, the flip angle and turbo-factor of the FLASH readout may also affect the resultant image contrast and therefore needed to be optimized.

In order to simplify numerical simulations, the flip angle and pulse train length of the DANTE module were first optimized for three combinations of the FLASH flip angle and turbo factor. As shown in Table 1, Group A and B had the same readout flip angle and different turbo factors, whereas Group B and C had different readout flip angles and the same turbo factor. The simulations were used to understand how the DANTE flip angle and pulse train length modulate the wall-lumen contrast and help select optimal parameters of the DANTE module.

The optimized DANTE flip angle (15°) and pulse train length (150) were then employed in additional simulations where the flip angle and turbo factor of the FLASH readout were varied. The simulations were used to understand how the contrast was modulated by the FLASH readout and help determine optimal readout parameters.

In all simulations, a constant TR of 1600 ms was used to accommodate the time for executing individual modules (i.e. DANTE, fat saturation, and FLASH readout) and for extra magnetization recovery. Steady-state signal evolution was obtained after 5 iterations of

TR. The wall-lumen contrast was primarily determined by the center k_y line and defined as the difference in the normalized longitudinal magnetization between the vessel wall and lumen immediately before the corresponding RF excitation. The T1/T2 values of the vessel wall and arterial blood used in simulations were 1412/50 ms and 1935/275 ms, respectively (15). The FLASH readout echo spacing was 8.9 ms, the same as in *in vivo* imaging experiments. Additionally, an approximation signal evolution (13) was used in order to simplify the numerical simulations, and thus the blood flow velocity was not considered in the simulations. The simulation program was coded in Matlab (Mathworks, Natick, MA).

In vivo Experiments

Volunteer studies approved by our institutional review board (IRB) were performed to assess the feasibility of DANTE-FLASH to achieve fast 3D isotropic-resolution peripheral vessel wall imaging. Written informed consent was obtained from all subjects.

Healthy Volunteer Study—Eight healthy volunteers (1 male, 7 females, aged 29–39 years) who had no history of PAD were recruited in the study. Imaging was performed using a 3T clinical whole-body MR system (MAGNETOM Verio, Siemens AG, Germany) with two 6-channel body matrix coils combined with spine coils to cover a region from the pelvis to knees. Subjects were placed supine and feet first in the scanner with the thighs at the iso-center.

After localizing the subject's SFAs using a multi-slice 2D time-of-flight sequence, DANTE-FLASH was performed in an oblique coronal orientation to acquire 3D vessel wall images of both SFAs. Based on numerical simulations, the parameters for the DANTE module included: flip angle = 15° , pulse train length = 150. The parameters for the FLASH readout included: echo spacing/TE = 8.9/3.8 ms, flip angle = 8° , isotropic resolution = $0.72 \times 0.72 \times 0.72 \text{ mm}^3$, longitudinal coverage = 30 cm, bandwidth = 131 Hz/pixel, parallel imaging (GRAPPA) acceleration factor = 2, partial Fourier factor in slice direction = 7/8, TR = 1600 ms. According to numerical simulations, a small flip angle and a large turbo factor can be used to realize fast data acquisition without considerable contrast-to-noise ratio (CNR) penalty. Thus, two shots per slice, i.e. a turbo factor of 131, were used in the imaging protocol. The scan time for DANTE-FLASH was 3.5 min.

Following the DANTE-FLASH scan, conventional multi-slice 2D DB-TSE with spatial pre-saturation bands was performed as a reference standard (10). The slices were prescribed perpendicular to the SFA segment in one randomly selected leg. Three scans were successively conducted to image the proximal, middle, and distal segments of the SFA. Imaging parameters were as follows: TR/TE = 900/6.9 ms, slice thickness = 3.0 mm, in-plane resolution $0.72 \times 0.72 \text{ mm}^2$, bandwidth = 338 Hz/pixel, number of average = 2, 10 contiguous slices per scan, and scan time = 2.2 min.

Patient Study—The developed DANTE-FLASH sequence was also added to the clinical examination of three PAD patients (three men, aged 61, 66 and 76 years) who were undergoing an IRB approved non-contrast MRA research scan using flow-sensitive dephasing-prepared balanced steady-state free precession (FSD-MRA) (16,17). All patients had symptoms of intermittent claudication without critical limb ischemia. After FSD-MRA,

a DANTE-FLASH scan was performed, covering bilateral SFAs, followed by one multi-slice 2D DB-TSE scan that was prescribed at the region of the most severe stenosis detected by FSD-MRA. Imaging parameters for both dark-blood sequences were the same as in the healthy volunteer study.

Image Analysis

Healthy Volunteer Study—All images acquired from healthy volunteers using DANTE-FLASH and 2D DB-TSE were loaded to a workstation (Leonardo; Siemens AG, Germany). To avoid any measurement bias due to the difference in location and spatial resolution, cross-sectional images with the location and slice thickness matched to those in DB-TSE scans were created from 3D DANTE-FLASH images using multi-planar reformation (MPR). In each subject, 15 paired 2D cross-sectional images were randomly selected from the three SFA segments for the following comparisons between the two sequences.

Two radiologists with over 10 years of experience in cardiovascular MR who were blinded to the scan protocols reviewed independently all randomized images. Image quality was rated on a 5-point scale: 0, non-diagnostic due to poor vessel wall delineation; 1, incomplete vessel wall delineation due to appreciable juxtaluminal flow artifacts and/or local wall signal voids; 2, moderate vessel wall delineation due to presence of mild flow artifacts and/or wall signal dropout; 3, good vessel wall delineation with adequate blood suppression and homogeneous wall signal; 4, excellent vessel wall delineation due to high vessel wall signal and clean lumen.

In addition, the vessel wall signal intensity (S_w), vessel wall thickness and area, lumen signal intensity (S_l) and area were measured using VesselMass (Vessel Mass, Leiden University Medical Center, The Netherlands) by a reader (G. X.) with over 5 years of experience in cardiovascular MR. In each image, the wall and lumen boundaries were first determined by Canny edge detection and then manually outlined for reducing the measurement bias resulting from different window levels. All measurements were then obtained using region-of-interest (ROI) analysis.

Due to the use of parallel imaging, noise could not be simply measured in the air region for the DANTE-FLASH scans. Similar to the previous work by Zhang et al (10), noise (σ_n) was measured as the standard deviation of signals from an ROI ($> 25 \text{ mm}^2$) manually drawn in the surrounding vastus medialis muscle. The apparent SNR of the wall and lumen (defined as $S_{w(l)}/\sigma_n$) as well as the apparent wall-lumen CNR (defined as $[S_w - S_l]/\sigma_n$) were then calculated.

Patient Study—All images acquired from the three patients were also loaded to the same workstation. For the comparison between DANTE-FLASH and 2D DB-TSE, cross-sectional images with matched location and slice thickness were assessed side-by-side by a radiologist (X. L.) with over 10 years of experience in cardiovascular MR. The agreement in the depiction of wall thickening between the two sequences was qualitatively evaluated with two major criteria, i.e. the severity and distribution of wall thickening. In addition, the 3D images acquired by DANTE-FLASH were fused into the FSD-MRA images. The agreement in the depiction of luminal stenosis between the two sequences was qualitatively evaluated

by the same radiologist with two major criteria, i.e. the severity and distribution of luminal stenosis. The above two agreement analyses were both rated on a 4-point scale (1 = poor and 4 = excellent).

Statistical Analysis

Because the sample size of the patient study was small, statistical significance testing was performed only in the healthy volunteer study using SPSS (v.14.0, SPSS Inc, Chicago, IL). First, the average of the each subject's image quality scores obtained from the two radiologists was calculated and Wilcoxon signed rank test was used to see if the scores were significantly different between DANTE-FLASH and DB-TSE. Second, the difference between them in the apparent SNR, apparent CNR, vessel wall thickness, vessel wall area, and lumen area were determined using two-tailed paired Student's t-tests. A p value of <0.05 was considered to indicate statistical significance in all above tests. Third, the agreement in vessel wall thickness, vessel wall area, and lumen area between the two techniques were respectively assessed by the intra-class correlation and Bland-Altman methods (18).

RESULTS

Numerical Simulations

Figure 2 (a) – (c) show the simulation results corresponding to the three groups of the fixed FLASH readout parameters (i.e. group A, B and C in Table 1). Despite different FLASH readout, flip angles and turbo factors, the wall-lumen contrast exhibits similar trends with respect to the DANTE flip angle and pulse train length on simulations. The larger the flip angle is, the shorter the pulse train length is needed for maximizing the contrast, and vice versa. In this work, a DANTE flip angle of approximately 15° and a pulse train length of approximately 150 were deemed in all three scenarios to consistently achieve maximal contrast.

The contrast between the vessel wall and lumen is also affected by the parameters of the FLASH readout as shown in Figure 2(d). A smaller flip angle is favorable to the contrast. Notably, the contrast does not considerably decrease as the turbo factor increases at a small flip angle. Therefore, a small flip angle ($5\text{--}10^\circ$) and a large turbo factor (>100) of FLASH readout can be used in DANTE-FLASH to achieve fast data acquisition while maintaining a high contrast. The two parameters were then chosen as 8° and 131 for *in vivo* studies.

In vivo Experiment

Healthy volunteer study—DANTE-FLASH allowed for a 30-cm-long craniocaudal spatial coverage within 4 min, whereas DB-TSE took nearly 7 min for a 9-cm-long coverage. Good image quality (score > 3) was obtained by DANTE-FLASH, even though it was significantly lower than that of DB-TSE (average score: 3.09 ± 0.24 v.s. 3.43 ± 0.19 , $p = 0.012$). The lower score of DANTE-FLASH was due to its generally lower wall signal in comparison with DB-TSE. Representative images are shown in Figure 3. The image in the first column is a curved MPR from the DANTE-FLASH scan, which demonstrates the large longitudinal spatial coverage offered by the technique. The second column shows five slices

(slice thickness = 3 mm) reconstructed from the DANTE-FLASH scan at the location of the five yellow dashed lines marked on the MPR. These slices correspond to the superior, middle and inferior parts of the femoral artery. The third column shows the corresponding 2D slices acquired by 2D DB-TSE. Generally, both DANTE-FLASH and 2D DB-TSE were able to suppress arterial blood signal. However, DB-TSE sometimes exhibited mild residual flow artifacts in the arteries (yellow arrows), although these artifacts did not completely eliminate the contrast between the lumen and vessel wall and thus wall/lumen contouring was still readily achievable. Also, note that in contrast to DB-TSE, DANTE-FLASH has dramatically clean lumen in the rather-slow-flow veins (red arrows).

Table 2 summarizes the statistical analyses of the comparison in apparent wall SNR, apparent lumen SNR, apparent wall-lumen CNR, wall thickness, wall area, and lumen area. Although the apparent wall SNR and wall-lumen CNR of DANTE-FLASH were 39% and 53% lower than those of the 2D DB-TSE, they were visually adequate to depict the vessel wall and lumen according to the aforementioned image quality assessment. The wall thickness, wall area, and lumen area were not significantly different (t-test: $p = 0.334$, 0.224 and 0.136 , respectively). Bland-Altman plots (Figure 4) and intra-class correlation analysis (ICCs = 0.81, 0.85 and 0.98) also revealed good agreement between the two techniques.

Patient Study—The agreement in the depiction of wall thickening between DANTE-FLASH and DB-TSE was excellent (score = 4 for 1 patient) or good (score = 3 for 2 patients). Figure 5 shows the representative cross-sectional images acquired by DANTE-FLASH and DB-TSE from a patient. The lower apparent SNR associated with DANTE-FLASH appeared not to affect the visualization of plaque morphology (green arrows). Clean lumens not only in the artery but also in the slow-flow vein (yellow arrows) on DANTE-FLASH images indicated the superior blood-nulling capability of the DANTE preparation.

Likewise, the agreement in the depiction of luminal stenosis between DANTE-FLASH and FSD-MRA is excellent (score = 4 for 1 patient) or good (score = 3 for 2 patients). This can be well appreciated on the fused image (a3-5 and b3-5) in Figure 6 whereby the patient had diffuse atherosclerotic plaques in both legs. Compared to FSD-MRA (a1 and b1), DANTE-FLASH (a2 and b2) not only showed the luminal obstructions but also depicted the thickened vessel wall associated with plaques.

DISCUSSION

In this work, the DANTE module is combined with the FLASH readout to achieve fast isotropic-resolution peripheral vessel wall imaging at 3T. The feasibility of using the technique to evaluate the peripheral vessel wall was successfully demonstrated.

Relatively slow blood flow and desired large imaging coverage and high spatial resolution are the major challenges for dark-blood peripheral vessel wall MR imaging (6). Herein, the DANTE module is exploited to ensure adequate blood signal suppression. DANTE has flow sensitivity over a broad velocity range for dark-blood preparation (13), which translates to a consistently good quality of flow signal suppression even if the blood flow is rather slow in the stenotic peripheral arteries. This is demonstrated in Figure 5 whereby both arterial and

venous blood flows are completely suppressed. In addition, DANTE is inherently suited for large longitudinal coverage as it is insensitive to B_1 field inhomogeneity and, more importantly, independent of the inflow effect. On the other hand, the use of 3D FLASH readout allows for both time-efficient coronal acquisition and sampling (19). With the above combination as well as the parallel imaging approach, imaging of the bilateral SFAs vessel wall with sub-millimeter, isotropic spatial resolution and a 30-cm longitudinal coverage is feasible in a short time of less than 4 min. The same coverage, in contrast, would demand over 20 minutes for the commonly used method - 2D multi-slice DB-TSE. Hence, it is anticipated that DANTE-FLASH would potentially be suitable for fast screening of PAD in a clinical setting.

Compared with the 2D DB-TSE, the SNR of the peripheral vessel wall was lower on DANTE-FLASH images. This may be attributed to the following three reasons. First, the SNR of TSE is intrinsically higher than that of FLASH. Second, the dark-blood mechanisms employed in 2D DB-TSE and DANTE-FLASH are different. In 2D DB-TSE, spatial pre-saturation bands are simply applied outside of the imaging slab thus imparting minimal signal attenuation in the interrogated vessel wall. In contrast, DANTE-FLASH relies on the DANTE module that not only suppresses the signal from flowing blood but also attenuates the signal from static tissues including the vessel wall. Third, the scan protocols for both techniques were different in this work. For instances, the number of averages was two in 2D DB-TSE scans but one in DANTE-FLASH scans; accelerated data acquisition with GRAPPA and Partial Fourier were not used in the DB-TSE scans. Nevertheless, DANTE-FLASH has yielded adequate signal to accurately depict the vessel wall as demonstrated by in vivo experiment results. Excellent agreement with DB-TSE with respect to wall and lumen morphological measurements suggests the great promise of DANTE-FLASH to be a clinical tool for accurate screening of PAD and potentially for longitudinal study of plaque progression and regression.

The preliminary patient study results have demonstrated the superiority of DANTE-FLASH in PAD screening. Both atherosclerotic plaques and obstruction locations in the peripheral arteries can be detected by DANTE-FLASH. As PAD is a progressive circulation disorder, early positive remodeling of the vessel wall and plaque formation are useful imaging markers for early detection of PAD. Therefore, DANTE-FLASH that directly visualizes the vessel wall and plaque is presumably a more accurate modality for diagnosis of PAD compared to the 3D MRA methods that only provide the information of stenosis.

There are two limitations in this work. First, in order to simplify the numerical simulations, the approximation approach in (13) was used to simulate the signal evolution of spins during the DANTE preparation. In this approximation approach, the blood flow velocity was not considered in the simulations. Nevertheless, such an approach is valid for simulations as the exact formation and approximation have been proven to be in agreement (13). Second, only three patients were recruited to provide a qualitative evaluation of the developed method. To elucidate its clinical value, a large-scale patient studies on, for example, diagnostic performance and reproducibility are highly needed and will be our future work.

In conclusion, DANTE-FLASH is a 3D dark-blood peripheral vessel wall MR sequence at 3T. Through the volunteer studies in this work, the technique demonstrates striking performance in blood signal suppression, spatial coverage, quality of vessel wall delineation, and time efficiency. Its potential for fast screening of PAD merits a systematic clinical validation.

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Figure 1.

The sequence diagram of DANTE-FLASH. A DANTE module for dark-blood preparation is followed by spoiler gradients, chemically-selective fat saturation pulse (FATSat), and a 3D FLASH readout with centric phase-encoding ordering. $TR = 1600$ ms, $t = 1220$ μ s, $T_{ES} = 8.9$ ms and $T_{recovery} = 251.1$ ms were used according to the *in vivo* study protocol in this work.

Figure 2.

(a–c) Simulations for the wall-lumen contrast versus the DANTE flip angle and pulse train length for three FLASH readout scenarios, i.e. flip angle/turbo factor = $8^\circ/80$, $8^\circ/130$, and $12^\circ/130$. The contrast exhibits similar distributions despite different FLASH readout parameters. Maximum contrast can be achieved using a DANTE pulse flip angle of approximately 15° and a pulse train length of approximately 150 for all three scenarios. (d) Simulations for the wall-lumen contrast versus FLASH readout parameters with fixed DANTE pulse flip angle and pulse train length (i.e. 15° and 150). A smaller flip angle (5 – 10°) is favorable to the contrast. Notably, the contrast does not considerably decrease as the turbo factor increases at a small flip angle.

Figure 3.

Representative images of the left femoral artery from a healthy subject. The image in the first column is a curved MPR from the DANTE-FLASH scan. The second column shows five slices (slice thickness = 3mm) reconstructed from the DANTE-FLASH scan at the locations of the five yellow dashed lines marked on the MPR. Images in the third column are the corresponding 2D slices acquired by DB-TSE. Both DANTE-FLASH and DB-TSE were able to suppress arterial blood signal. However, DB-TSE that sometimes exhibited mild residual flow signal in the arteries (yellow arrows) and always strong signal in the rather-slow-flow veins (red arrows).

Figure 4.

Bland-Altman plots of the difference between the measurements of DANTE-FLASH and DB-TSE scans in: (a) wall thickness, (b) wall area and (c) lumen area.

Figure 5.

Representative plaque images from a patient's left and right femoral arteries. Each of these cross-section images shows the atherosclerotic plaques (green arrows) clearly. The lower SNR associated with DANTE-FLASH is not considerably affecting the visualization of plaque morphology. Extremely clean lumens not only in the artery but also in the slow-flow vein (yellow arrows) on DANTE-FLASH images indicate the superior blood-nulling capability of the DANTE preparation.

Figure 6.

Representative clinical study results by FSD-MRA (a1 and b1) and DANTE-FLASH (a2 and b2). Cross-section slices at the locations of the yellow dashed lines marked on the MPR of DANTE-FLASH are shown in a3 and b3. The corresponding slices of the FSD-MRA are shown in a4 and b4. Compared to FSD-MRA, DANTE-FLASH not only shows the obstruction locations but also depicts the vessel wall and plaques. The fused images demonstrate excellent match of the narrowed lumen well between DANTE-FLASH and FSD-MRA (a5 and b5).

Table 1

Three representative groups of FLASH readout parameters for simulations

Parameters	Readout Flip Angle	Readout Turbo Factor	Echo Spacing	TR
Group A	8°	80	8.9 ms	1600 ms
Group B	8°	130	8.9 ms	1600 ms
Group C	12°	130	8.9 ms	1600 ms

Table 2

Image quality comparison between DANTE-FLASH and DB-TSE

Method	Apparent Wall SNR	Apparent Lumen SNR	Apparent Wall-Lumen CNR	Wall Thickness (mm)	Wall Area (mm ²)	Lumen Area (mm ²)
DANTE-FLASH mean±std	7.6±1.4	4.6±1.1	3.1±0.8	1.4±0.2	24.5±5.0	14.5±5.4
DB-TSE mean±std	12.5±3.9	6.6±2.8	5.8±2.7	1.4±0.2	23.9±5.1	14.2±5.8
<i>p</i> value (Paired t test)	<0.05	<0.05	<0.05	0.334	0.224	0.136