Noncontrast-enhanced Peripheral MRA: Technical Optimization of Flow-Spoiled Fresh Blood Imaging for Screening Peripheral Arterial Diseases

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Flow-spoiled fresh blood imaging, a noncontrast peripheral MR angiography technique, allows the depiction of the entire tree of peripheral arteries by utilizing the signal difference between systolic- and diastolic-triggered data. The image quality of the technique relies on selecting the right triggering delay times and flow-dependent read-out spoiler gradient pulses. ECG triggering delays were verified using manual subtraction and automated software. The read-out spoiler gradients pulses were optimized on volunteers before utilizing the flow-spoiled fresh blood imaging technique to screen for peripheral arterial disease. Thirteen consecutive patients with suspected peripheral arterial disease underwent both flow-spoiled fresh blood imaging and 16-detector-row computed tomography angiography examinations. A total of 23 segments were evaluated in the arterial vascular system. Using computed tomography angiography as the reference standard, 56 diseased segments were detected with 22 nonsignificant stenoses (≤50%) and 34 significant stenoses, 15 of which were totally occluded. Flow-spoiled fresh blood imaging had a sensitivity of 97%, a specificity of 96%, an accuracy of 96%, a positive predictive value of 88%, and a negative predictive value of 99%. With such a high negative predictive value, flow-spoiled fresh blood imaging has the potential to become the safest noninvasive screening tool for peripheral arterial disease, especially for patients with impaired renal function. Magn Reson Med 65:595–602, 2011. © 2010 Wiley-Liss, Inc.

Key words: noncontrast-enhanced MR angiography (MRA); flow-spoiled fresh blood imaging (FS-FBI); peripheral artery diseases; peripheral run-offs; MR arteriography; 16-detector-row computed tomography angiography (CTA)

INTRODUCTION

Contrast-enhanced MR angiography (CE-MRA) has been widely accepted for daily examinations since it was introduced in 1993 in the study by Prince et al. (1). Multistage CE-MRA in peripheral run-offs by means of bolus synchronization allows the depiction of the entire vascular tree in a relatively short scanning time and is widely accepted as part of daily clinical practice (2,3). However, since the US Food Drug Administration issued warnings linking gadolinium-based contrast agents used in MR and nephrogenic systemic fibrosis, contrast-enhanced MRA is no longer considered safe for patients with impaired renal function (4,5). The clinical need for noncontrast-enhanced MRA examinations for patients with moderate to severe renal insufficiency has dramatically increased.

In Japan, the volume of MR contrast medium allowed per patient is limited to 20 cc according to the Japanese Ministry of Health Labor and Welfare, although the cost of the contrast medium in this quantity exceeds the cost of an MR examination (6). This limitation, along with the nephrogenic systemic fibrosis issue, motivated us to develop noncontrast MRA (NC-MRA) techniques like fresh blood imaging (FBI) (6) and flow-spoiled fresh blood imaging (FS-FBI) (7) in Japan, even when CE-MRA was considered the standard worldwide. In 2002, Urata et al. reported the comparison study of FS-FBI vs. CE-MRA in patients with peripheral diseases (7). Recently, Lim et al. presented a clinical evaluation of NC-MRA in the distal lower extremities using a similar technique (8).

Multidetector row computed tomography has been proposed as an alternative technique to conventional digital subtraction angiography. Several groups have reported that 16-detector-row CT angiography (CTA) has a high diagnostic ability to evaluate the aortoiliac and lower extremity arteries (9–11). Multidetector row computed tomography also provides excellent, three-dimensional (3D), high-resolution images. However, because it requires iodine-based contrast material and ionizing radiation, it is not considered to be a totally safe technique for use in all patients. In a screening setting, the ideal technique must be safe and accurate, have a good negative predictive value (NPV), and be cost effective. The safety of NC-MRA for all patients with no contraindication for MRI is obvious.

The purposes of this study are to present the technical aspects of the NC-MRA technique FS-FBI and to evaluate the accuracy of the technique at 1.5T compared with 16-row CTA. The CTA technique was used as the reference standard as it is widely available, relatively inexpensive, fast, and has demonstrated clinical value (9–11). The evaluation of cost-effectiveness of NC-MRA is not within the scope of this study. For potential use in peripheral arterial disease (PAD) screening, we optimized the FS-FBI sequence parameters to create a good balance.
between image quality and acquisition time. Furthermore, the advantages and the pitfalls of FS-FBI are discussed in detail.

MATERIALS AND METHODS

FS-FBI Background

FS-FBI is an ECG-gated, 3D half-Fourier, Fast Spin Echo sequence using RO spoiler gradient pulses (12). The technique utilizes the physiological signal change of an artery during a cardiac cycle. The method relies on the flow void signal because of the rapid arterial flow during systole as opposed to the high-signal intensity of slow flow during diastole. Because their flow is relatively slow and nonpulsatile, venous signals are high in both diastole and systole-triggered images. By subtracting the systole-triggered image from the diastolic image, an artery-only image is obtained. FS-FBI offers the possibility to further separate arteries from veins using flow-dependent RO spoiler pulses. To improve the blood-to-tissue contrast, a short tau inversion recovery (STIR) of 190 msec was applied for fat suppression and some background suppression. Note that although the use of STIR to suppress fat signal is not mandatory because of the subtraction of the images, it is helpful for the analysis of source images, especially diastolic images, as we will further discuss.

To reduce blurring in the phase-encoding (PE) direction, each partition of the 3D sequence was acquired in two shots. To avoid T1 saturation effects, the repetition time was set to three or four heartbeats (R-R intervals) (13). A 2D ECG-prep scan (single slice with multiple phases) was used to determine the appropriate systolic and diastolic trigger times for the 3D partitions. Our system permits continuous acquisition of both systolic and diastolic images during a single scan, automatic subtraction of diastolic from systolic images, and automatic maximum intensity projection (MIP) processing. This continuous acquisition of the diastolic and systolic images without interruption minimizes the risk of patient motion producing image misregistration.

The RO flow spoilers are mainly useful in vessels with a relatively small flow velocity difference between systole and diastole. This phenomenon is primarily observed in peripheral or slow flow vessels.

For thoracic and abdominal vessels, the original FBI technique (13) depicts vessels in bright blood with diastolic triggering only; systolic-triggered arterial signal is dark due to the fast flow. However, in peripheral vessels, because of the slow flow, the technique depicts all vessels (both arteries and veins) in bright blood even in systolic-triggering, thus making it difficult to separate arteries from veins (13). Using FS-FBI in peripheral run-offs, the RO direction is chosen to be parallel with the vessel orientation (generally head-foot) to enhance the intrinsic dephasing effect in the direction of flow (12). By applying the RO flow-spoiled gradient pulses in both systolic and diastolic acquisitions, a greater flow dephasing effect can be obtained, thus resulting in a larger arterial signal drop in systole compared to diastole, even in slow flow arteries (12). This technique is based on the assumption that the RO flow-spoiled gradient pulses have less effect during diastole where blood is considered to be relatively stationary.

It is important to realize when interpreting so-called “arteries-only” MIP images that they are actually flow-difference images between systole and diastole. Therefore, evaluation of both the diastolic source and subtracted MIP images is recommended. The diastolic images show all vessels (both arteries and veins) in bright blood. To improve vessel conspicuity, STIR fat saturation is typically used to reduce the background signal. With the subtracted images, the use of STIR fat saturation has no real advantage; however, when reviewing the diastolic images and/or the systolic images, it becomes necessary for the observation of the vessels.

Patients

This preliminary study was approved by our institutional review board and informed consent was obtained. A total of 13 consecutive patients (10 men [mean age, 72 years] and three women [mean age, 69 years]) with suspected PAD were included in this study. All patients underwent both FS-FBI and 16-detector row CTA examinations. The FS-FBI examination was performed before CTA. The mean delay between FS-FBI and CTA was 13 days (range: 1–45 days). The exclusion criteria for the FBI examination included patients with irregular heart rates and/or metal implants, whereas that for the CTA examination included patients with allergies to contrast agents and/or renal failure.

IMAGING PARAMETERS

FS-FBI

All MR examinations were performed using 1.5-T clinical imagers (EXCELART and EXCELART/Vantage™ with Atlas, Toshiba, Tokyo, Japan). A quadrature torso SPEEDER coil was used for aortoiliac, femoral, and popliteocrural studies in the EXCELART system. After each station (iliac, femoral, popliteocrural), patients were asked to physically reposition themselves without moving the coil. In the EXCELART/Vantage Atlas system, two SPEEDER coils, allowing 100-cm coverage, were used for the three-station examination without requiring repositioning of the patients or coils. The patient’s legs were properly positioned, i.e., horizontally in line with the abdomen, and were comfortably strapped to constrain motion. Patients were instructed before the examination not to move during the MR scan, and both systolic and diastolic triggered FBI images were acquired sequentially without any pause in between. Before the FS-FBI 3D acquisition, a 2D ECG prep scan using single shot half-Fourier FSE with single slice and multiple phases was acquired to determine the appropriate diastolic and systolic ECG delay times (12). The ECG prep scan was performed using an incremental delay of 50 msec relative to the R wave trigger with a sufficient number of increments to cover the entire cardiac cycle. The typical ECG prep scan parameters were as follows: TR = 3 RR intervals; effective TE (Teff) = 80 msec; echo train spacing (ETS) = 5 msec; flip angle/refocusing angle = 90/130 degree, matrix = 128 × 256; section
thickness = 80 mm; FOV = 37 × 37 cm; a single shot of 128 PE lines with parallel imaging (SPEEDER or SENSE) factor (SF) of 2.0; and ~14 to 22 repeats for a total scan time of 30 to 40 sec, depending upon the heart rate. The ECG-Prep scan was performed on all patients and volunteers because the triggering delay times vary on an individual basis.

The 3D FS-FBI acquisition parameters were as follows: TR = 3 RR intervals; TEeff = 80 msec; inversion time (TI) = 190 msec; ETS = 5 msec; flip angle/refocusing angle = 90/170–180 degree, matrix = 256 × 256 (interpolated to 512 × 512); section thickness = 4 mm (interpolated to 2 mm); about 30–40 slice partitions; bandwidth = 651 Hz/pixel, FOV = 37–50 × 37–50 cm; 2 shots per 256 phase encode lines; parallel imaging factor of 2.0; and a total acquisition time (including both systolic and diastolic acquisitions) of 3–4 minutes. Selective pulses were used in both excitation and refocusing pulses. The IR pulse was applied for fat suppression. For each slice encoding, two shots are interleaved to fill k space to make up a 2D image. From the partial Fourier side of the k space 16 lines (TTeff 80 msec/ETS 5 msec) and the other side of 64 lines give a total echo train length of 80 lines per shot or 400 msec (80 lines × ETS 5 msec). The application of parallel imaging in the PE direction (SF = 2.0) gave a shot duration of 200 msec. After the 3D acquisition, the system automatically performs subtraction of the systolic source images from the diastolic source images and MIP processing.

Volunteer Studies

The image quality of FS-FBI relies on the difference in signal intensity between the systolic and diastolic triggering delays. To confirm the consistency of triggering delay times, the ECG prep images obtained in four healthy volunteers were analyzed using manual subtraction and FBI-Navi software (14). The FBI-Navi software calculates the arterial signal variation caused by the effects of systole and diastole for the ECG prep images. The manual subtraction of the ECG prep images was performed by selecting the image with the vessel with the lowest signal as a systolic triggering delay time; this image was then subtracted from all ECG prep images. Once the systolic and diastolic triggering delays were determined at the iliac station, other two stations were acquired using the same triggering delay times.

The effects of RO spoiler gradient magnitudes were studied in three different stations, (aortoiliac, femoral, and popliteocural), in two young male volunteers (21 years and 23 years of age, respectively), and in two older male volunteers (62 years and 64 years of age, respectively) to mimic the flow speed of the PAD patients according to age. To minimize the total examination time, the optimal RO gradient magnitude values were derived for each station and used as a fixed value in the patient studies.

Multidetector CTA

All images were acquired on a 16-detector row CT scanner (Aquilion 16; Toshiba, Tokyo, Japan). Noncontrast images were acquired before contrast administration. The delay time between the start of contrast administration and the start of scanning was obtained for each patient using a real-time monitoring technique (Realprep, software; Toshiba) for optimal intraluminal contrast enhancement. A nonionic, iodinated contrast medium (Iopamiron; Nihon Schering K.K., Osaka, Japan; 370 mg iodine per milliliter) was then administered via 18–21 gauge needles which had been placed in a superfi- cial vein located in the antecubital fossa. A 100 mL volume of contrast medium was administered using an automated injector (Nemoto Kyorindo Co., LTD, Dual Shot GX, Japan) at a flow rate of 3mL/sec and was followed by a 20 mL flush of saline administered at the same flow rate. Data acquisition was performed in a cranio-caudal direction using 16 mm × 1 mm collimation with a helical pitch of 15. Transverse sections were reconstructed with a section thickness of 1 mm at an interval of 0.6 mm. The reconstructed FOV was 30 to 37 cm and the matrix was 512 × 512.

All CTA data were transferred to a dedicated workstation (Virtual place, AZE, Japan), thus allowing the generation of various 3D reconstructions including MIP, multiplanar reformations, and volume rendering. For luminal analysis, cross sections and multiplanar reformations of diseased segments were also generated using the AZE vessel analysis package to overcome the well-known limitation of the MIP image analysis in the presence of wall calcification.

Image Analysis

All FS-FBI MR images of the 13 patients were interpreted by one board-certified radiologist (K.N. with 20 years of clinical experience in vascular MR imaging), who was unaware of the result of CTA, because the FS-FBI MRA images were evaluated first before the CTA examinations. However, the FS-FBI results were known to K.N., prior to evaluation of CTA. In addition, a radiological technologist (K.K.) reviewed the FS-FBI images independently and then evaluated together with K.N. for consensus.

The image quality of the FS-FBI images in all three stations was visually evaluated and compared to the CTA data. The arterial vascular system was divided into three main regions, i.e., the aortoiliac, femoral, and popliteocural. The aortoiliac region included seven segments: the infrarenal aorta, the right and left common iliac arteries, the internal iliac arteries, and the external iliac arteries. The femoral region included six segments: the right and left common femoral arteries, the superficial femoral arteries, and the deep femoral arteries. The popliteocural region included 10 segments: the right and left popliteal arteries, the anterior tibial arteries, the tibioperoneal trunks, the posterior tibial arteries, and the peroneal arteries. A total 299 segments (23 segments per patient) were examined.

For each modality independently, the degree of stenosis of an arterial segment was visually graded based on careful review of the MIPs and the source images. Stenosis of the arterial segment was graded separately for degree of stenosis using a four-point grading system;
grade 1 indicated a normal vessel or mild vessel irregularities (<10% luminal narrowing); grade 2 indicated moderate arterial stenosis (10–49% luminal narrowing); grade 3 indicated severe arterial stenosis (50–99% luminal narrowing); and grade 4 indicated occlusion.

A luminal narrowing was considered to be hemodynamically insignificant if it was less than 50%, and hemodynamically otherwise significant. Using CTA as our reference standard, we examined the sensitivity, specificity, accuracy, positive predictive value, and NPV of each hemodynamically significant stenosis finding.

RESULTS

Figure 1 shows the results of the ECG Prep scan using the manual subtraction method and the FBI-Navi plot. The manual subtraction method to determine the systolic and diastolic triggering delays were matched with those of FBI-Navi in all volunteer studies. It was easier to determine the systolic and diastolic triggering delays in the graph of signal intensity vs. delay times using FBI-Navi software than manual observation of the subtracted images. In the manual subtraction method, the systolic delay time was straightforward to ascertain due to the hypointense signal. However, the diastolic delay time was difficult to determine; with the high signal observed in a period of diastolic times, it was challenging to select a single delay by visual observation.

Next, the RO spoiler gradient was optimized for the younger (21 and 23 years) and older (62 and 64 years) volunteers separately by acquiring −10%, 0%, +10%, and +20% data at each station. For the younger volunteers, the RO spoiler gradient was found to provide better depiction of arterial vessels at −10% for aortoiliac, 0% for femoral, and +10% for popliteocrural regions. For the older volunteers, the RO spoiler gradient was suitable at 0% for aortoiliac, +10% for femoral, and +20% for popliteocrural regions. These settings were used in all of the patient studies. The results of the appropriate RO spoiler pulse strengths for young volunteers and patients are summarized in Table 1. In addition, Fig. 2 shows the sequence diagrams of the different RO spoiler pulses.

In our patient studies, diagnostic quality images were obtained from both modalities for all patients. Figure 3 shows a case with severe stenoses illustrating the representative image quality we obtained using both FS-FBI and CTA techniques. Figure 4 shows that the rotated
MIP images of Fig. 3a are acceptable for visualizing continuation of vessel trees for the purpose of screening. Fifty-six diseased segments were found among 13 patients with 22 nonsignificant stenoses as well as 34 significant stenoses, of which 15 were totally occluded. On the FS-FBI images, patients with calcification were easily evaluated for luminal diameters of vessels compared to the CTA images, as shown in Figs. 5 and 6. The FS-FBI images were not affected by the presence of calcifications, whereas CTA requires analysis of the multiplanar reconstructions and cross-sections at a postprocessing console.

Five normal or hemodynamically insignificant arterial stenoses detected on CTA were overestimated and were considered hemodynamically significant on the FS-FBI.

FIG. 2. Sequence diagrams showing different read-out spoiler gradient pulses. The read-out (RO) spoiler pulse strength was calculated as a percentage of one-half the area of the read-out gradient, which is equivalent to the area from the ramp up to the echo center of the read-out gradient. For the +10% gradient pulses, spoiler or dephasing pulse is applied in the RO direction. In contrary, −10% gradient pulses mean applying a partial flow-compensation in the RO direction. The echo train spacing (ETS) of 5 msec was used.

FIG. 3. A 66-year-old male with occlusions of the right superficial femoral artery and the right anterior tibial artery. Coronal MIP image of the entire vascular tree from the distal aorta to the crural region, obtained with (a) FS-FBI MRA and (b) CTA. Note the very good agreement between the two modalities for detecting normal to occluded segments with clear visualization of the collateral circulation.

FIG. 4. FBI-Image resolution. From left to right rotating the MIP images of Fig. 3a from 0° to 90° in 30° steps. Note that the chosen slice thickness in our protocol (reconstructed 2 mm) gives acceptable image quality not only on the coronal MIP but also on the oblique views. The larger portion of popliteocrural area shows clear depiction of occlusions in the right anterior tibial artery.
images. In two of the five segments, stenosis-like findings were observed in steep, bent portions which may have been caused by turbulent flow, resulting in signal loss, as shown in Fig. 5. One of the five segments was an internal iliac artery which showed poor image quality because of gastrointestinal peristalsis. All of the stenoses detected on CTA were also detected on FS-FBI (there were no false negatives). The sensitivity, specificity, accuracy, positive predictive value, and NPV for the detection of a significant stenosis (narrowing >50%) are summarized in Table 2.

DISCUSSION

Noncontrast-enhanced MR angiography techniques have been available since the early days of MRI. However, the prolonged acquisition time due to early hardware and software limitations, as well as the relatively poor image quality compared to that of CE-MRI, did not widely motivate research using contrast-free angiography for peripheral MRA. Until recently, 2D time of flight and phase contrast, both of which have been available for many years, were the two primary nonenhanced MRA techniques used in peripheral arteries despite their well-known limitations (i.e., limited coverage, poor image quality, and long acquisition time). Nearly abandoned, noncontrast-enhanced MRA is an active research field where several approaches based on hardware and software advances are being proposed and developed (15–20).

In this preliminary clinical study, we evaluated the FS-FBI technique using 16-detector row CTA as the reference standard. CE-MRA would be a more logical choice of reference standard, whereas the best reference standard would be digital subtraction angiography. CE-MRA...
Technical Optimization of FS-FBI for Screening PAD

was not selected for this study due to the limited amount of contrast media used for the three-station peripheral run-off study. In addition, CTA is more readily available than CE-MRA because it is less expensive, easier, and faster to use. Its clinical value for use in PAD has been demonstrated in the literature (21); however, recently Ouwendijk et al. demonstrated on 145 patients that vessel wall calcifications decrease the clinical utility of CTA, especially in patients with PAD (22).

In our volunteer studies, to reduce the total examination time, the RO spoiler gradient pulse was preliminarily investigated on both younger and older volunteers in the aortoiliac, femoral, and popliteal arteries. We found that the faster the flow, such as the aortoiliac compared to the femoral, the less flow spoiler gradient was necessary. Other than the choice of RO spoiler gradient, determination of the ideal systolic and diastolic triggering delay times is the most important methodological aspect of this technique. The technique relies on the systolic and diastolic signal difference. As shown in Fig. 1a, selecting one delay from the manually subtracted images by observing the arterial images is difficult due to the similarity in the arterial signal intensity between the 600 to 1000 msec triggering delays. On the contrary, the FBI-Navi in Fig. 1b shows the arterial signal intensity over the ECG phases in a 2D graph and simultaneously presents the subtracted image of the diastolic (dashed line) and systolic (solid line) image, as shown in Fig. 1c. Thus, the FBI-Navi data added confirmation of the results from the manual subtraction method.

For evaluation as a potential screening protocol, the FS-FBI acquisition was acquired on our MRI system with a balance between image resolution and acquisition time (3–4 min per stage, total examination time less than 30 min). However, one can easily increase the image resolution in the slice direction by increasing the number of slices with a trade-off of longer acquisition time. One may use the quick scan for screening; if any stenoses or occlusions are found, a follow-up high resolution acquisition may be acquired.

Like any subtraction-based technique, FS-FBI is intrinsically sensitive to patient motion. However, in this study, we did not experience any limitations due to patient motion. This can be attributed to good patient instruction, comfortable patient positioning with restraints, and continuous acquisition of diastolic and systolic images. Without a pause between systolic and diastolic FS-FBI acquisitions, patients maintain a constant position until the end of the scan.

As FS-FBI uses the flow difference of systole and diastole, it is primarily flow-dependent. In some areas, a drop in arterial signal was observed in the subtracted MIP images, often seen proximal to a severe stenosis. In these locations, the vessel may have slow flow that could not flow voided in the systolic image, resulting in some remaining signal in the systolic images. This causes signal loss after the diastolic and systolic subtraction, which could mislead the interpretation of the images and the diagnosis. Therefore, in cases of positive findings, evaluation of the diastolic images in conjunction with the subtracted MIP images is imperative to avoid overestimation of the degree of stenosis and detection of a false positive. Similarly, in intracranial MRA, the MIP images of 3D time of flight are evaluated first and then the source images are reviewed in case of finding irregularities.

The short echo spacing and a higher parallel imaging factor may help to minimize the turbulence or dephasing effect. In our study, it was somewhat more challenging to score the segments distal to a tight stenosis, showing decreased signal intensity when there is little flow change during the cardiac cycle. In addition, it is noteworthy that CTA, CE-MRA, and digital subtraction angiography allow visualization of the contrast-agent filling in the vessel lumen. On the other hand, FS-FBI depicts the arterial blood flow difference between diastole and systole. With proper interpretation, FS-FBI provides morphological information, with functional information regarding blood flow below a tight stenosis as future investigation.

In an earlier clinical study, Urata et al. reported in 2002 that the FS-FBI method was comparable to CE-MRA in 24 out of 44 regions, while 15 were inferior and 5 were superior among a total of 56 regions (18 iliac, 20 femoral, and 18 calf segments) in 26 patients with diagnosed or suspected arterial occlusive diseases (7). In the study, they indicated to it was important to evaluate the diastolic source images in addition to subtracted MIP images in cases with stenosis or bypass grafts due to the overestimation of stenoses in subtracted MIP images. Similarly, we have reviewed the diastolic source images when the subtracted MIP images presented stenoses or occlusions. On the contrary, in a recent report by Lim et al., the authors only evaluated the subtracted MIP images, which may explain their reported lower scores. Furthermore, their scores were lower than our scores in all aspects of accuracy, sensitivity, specificity, and NPVs in comparison with CE MRA and time-resolved MRA in the calf region, mostly due to serious image artifacts in

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<th>Region</th>
<th>Sensitivity</th>
<th>Specificity</th>
<th>Positive predictive value</th>
<th>Negative predictive value</th>
<th>Accuracy</th>
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<td>Aortoiliac (N = 91)</td>
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<td>96</td>
<td>90</td>
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<tr>
<td>Femoral (N = 18)</td>
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<td>98</td>
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<td>80</td>
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<td>Total (N = 299)</td>
<td>97</td>
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17 out of 36 patients (47%). Among patients with satisfactory diagnostic confidence, accuracy, sensitivity, and NPV were 92.2%, 92.4%, and 97.5, respectively. Another possible reason for their lower scores is motion artifact. This could be mitigated by proper patient handling and coaching before examination. In addition, Lim et al. indicated that they also encountered some blurring in the PE direction compared to contrast-enhanced MRA [8]. In our study, we used an echo train duration or single shot acquisition time of ~200 msec compared to their 325 msec. The shorter echo train length reduces the blurring effect by improving the point-spread function in the PE direction (23). Further reductions of the blurring effect can be achieved by increasing the parallel imaging factor using multiple RF coils.

In our study, FS-FBI demonstrated very high sensitivity and specificity. However, its positive predictive value was relatively low (88%). Because NC-MRA images are not only luminal images but are also dependent on the flow velocity, a one-to-one comparison with CTA using the same rules led to an overestimation of the degree of stenosis and the length of the diseased segment. These stenoses also tended to be overestimated when scored using the same rules as those used for techniques based on contrast filling. Therefore, in cases of positive findings, a careful analysis of the diastolic images is required.

When screening, it is crucial not to miss any disease. Therefore, with its high NPV of 99%, we believe that FS-FBI may become the tool of choice to rule out PAD in at-risk patients. For patients with severe renal malfunction, noncontrast FS-FBI is a readily available noninvasive and safe tool. In the case of a positive finding, a follow-up higher resolution image of the diseased segment can be acquired. Therefore, FS-FBI is also a valuable tool for use in the post-treatment follow-up of patients with PAD. Our preliminary clinical studies indicate the potential clinical benefit for diagnosing patients with PAD; however, further clinical assessment is required.

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