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T1-weighted Black-Blood Carotid Plaque Imaging Using Variable Flip-Angle 3D Turbo Spin-Echo: Comparison with 2D Turbo Spin Echo and 3D Turbo Field Echo Sequences

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Abstract：Purpose: To compare a T1-weighted, three-dimensional variable-flip-angle (3D-VRFA) turbo spin-echo (TSE) sequence with both a two-dimensional (2D)-TSE double inversion recovery (DIR) sequence and a 3D turbo field-echo (3D-TFE) DIR sequence in magnetic resonance black-blood carotid plaque imaging. Materials and Methods: Fifteen patients underwent black-blood plaque imaging including pulse-triggered axial T1-weighted (T1W) 2D-TSE, pulse-triggered sagittal 3D-TFE, and non-triggered coronal T1W 3D-VRFA sequences. The imaging quality of each sequence was visually graded on a three-point score. The signal ratio of the carotid plaque to the arterial lumen (RPL), and that of the carotid plaque to the adjacent muscle (RPM) was calculated in each sequence. Results: The score for the 3D-TFE was lower than that of 3D-VRFA. Although no significant differences were observed between the scores of the 2D-TSE and 3D-VRFA sequences, the 3D-VRFA allowed visualization of arteries in arbitrary orientations, as well as small plaque compositions such as ulcerations and calcifications not visualized on 2D-TSE. The RPL was highest on 2D-TSE, whereas the RPM was highest on 3D-VRFA. Conclusions: 3D-VRFA is a promising technique for the diagnosis of carotid plaques.

Key words： **Carotid plaque, Magnetic resonance imaging, Turbo spin-echo, Variable flip-angle**

Introduction

Of the various causes of stroke, carotid atherosclerosis is one of the leading causes of morbidity and mortality worldwide. The most common source of emboli in transient ischemic attacks and embolic stroke originates from atherosclerotic disease at the carotid bifurcation.[1),2)] The chemical constituents of the atherosclerotic plaque, as well as the plaque morphology and degree of stenosis, are extremely important in predicting the clinical outcome and in determining the management of the disease.[3)–7)]

Several investigators have reported the impact of magnetic resonance imaging, as well as Doppler sonography, to evaluate the chemical composition of carotid arteriosclerotic plaques. Vulnerable/soft plaques, which comprise lipid-rich necrotic cores and/or intraplaque hemorrhage can be assessed noninvasively by magnetic resonance plaque imaging. In particular, high signal intensity plaques on T1-weighted (T1W) images have been considered to correspond to vulnerable plaques which correlate with a higher level of ischemic events.[5),8)–10)]

Two-dimensional (2D), black-blood (BB) imaging utilizing the turbo spin-echo (TSE) with double inversion recovery (DIR) technique is commonly used to evaluate the composition of the carotid plaques in routine clinical examination. With this method, triggering by using ECG or peripheral pulse unit (PPU) is typically required to suppress the

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intraluminal flow signal, and to reduce artifacts related to the blood flow.[11),12)]

However, the 2D-TSE DIR technique has several limitations, such as restriction of imaging direction to the cross-sectional transaxial plane, with a compromise on the examination time-efficiency, and restriction of the contrast setting depending on the cardiac cycle of each patient.[13)–15)] In addition, 2D-TSE is subject to partial volume effects, owing to poor spatial resolution in the slice-selecting direction in assessing small plaque compositions.[16)]

To overcome these limitations of 2D imaging, several 3D imaging techniques have been employed for plaque imaging. Investigators have reported a carotid BB imaging technique using field-echo-based 3D sequences, such as 3D turbo field echo (TFE) or magnetization-prepared rapid gradient-echo (MPRAGE).[5),8),9),14)] However, usually these field-echo-based 3D-BB techniques also require ECG/PPU triggering for intraluminal signal suppression, which may become degraded due to either a complex flow or by difficulty in suppressing the flow within a longer arterial segment.[17)]

Recently, a variation of the black-blood 3D-TSE technique, which uses non-selective variable refocusing flip angle (VRFA) along the echo train to achieve a pseudosteady state for a low refocusing flip angle, was introduced. With this technique, a longer echo train can be applied while reducing the specific absorption ratio (SAR), image blurring, and degradation of image contrast.[18),19)] 3D-VRFA-TSE, combined with a lower refocus flip angle and a flow-sensitizing gradient (sensitized flow compensation), has been reported to efficiently reduce the intravascular signal and provide single-slab 3D-TSE BB imaging without using ECG/PPU- triggering.[20)] Hence, it is expected that the 3D-VRFA-TSE sequence may be useful in assessing carotid plaques.

The purpose of this study was to compare a non-triggered, T1-weighted 3D-VRFA-TSE sequence with a PPU-triggered 2D-TSE sequence and a PPU-triggered 3D-TFE sequence in image quality and contrast for carotid plaques.

Materials and Methods

Study Population

A total of fifteen consecutive patients (fourteen males and one female: age range= 67-83 years: mean age= 73 years) with unilateral carotid stenosis greater than fifty percent, which was found on routine time-of flight MR angiography (MRA) were included in this study.

Imaging Protocol

Bilateral carotid MR images were obtained on a 1.5T Philips Achieva whole-body scanner (Philips Medical Systems, Best, the Netherlands) using a SENSE head/neck coil with a quadrate head part with two neck elements. A chemical shift selective fat suppression of spectral presaturation with inversion recovery (SPIR) was applied to all carotid BB sequences. Axial 2D-TSE double-IR (DIR) T1W was acquired using PPU-triggering with the following parameters: TE/TI/echo train length/number of excitations= 7/263-399/7/2, matrix size of 320 x 320, a reconstruction matrix of 512 x 512, with a 200mm-field of view and 3mm section thickness. The TR was 1 cardiac cycle and ranged from 600 to 1000ms. The scan time ranged from 3 minutes 1 second to 4 minutes 24 seconds to obtain 4 slices.

An oblique-sagittal 3D-TFE DIR sequence with PPU-triggering was acquired centered at the unilateral carotid bifurcation with stenosis detected on MRA, with the following parameters: TR/TE/flip angle/ TI /number of excitations= 8/4/10/400/2, matrix size of 224 x 214 with reconstruction matrix of 512 x 512 with a 200mm field of view, 35 to 40 overcontiguous slices with the acquired section thickness of 1.2mm and reconstructed section thickness of 0.6mm. The scan time was 4 minutes 6 seconds to 4 minutes 51 seconds.

Finally, non-triggered, 3D-VRFA-TSE T1W was obtained in a coronal direction with the following parameters: TR/TE/echo train length /number of excitations= 450/16/20/2, matrix size of 225 x 224 with reconstruction matrix of 512 x 512, with a 200mm field of view. A refocus control of 60 degrees was selected to reduce the intraluminal signal. In addition, flow-sensitizing gradients (sensitized flow compensation) were employed for further suppression of the signal from slowly flowing blood.[20)] A total of 50 to 70 overcontiguous slices with an acquired section thickness of 1.2mm and reconstructed section thickness of 0.6mm were obtained with a scan time from 4 minutes 16 seconds to 5 minutes 58 seconds.

Image Analysis

The images obtained in each sequence were independently analyzed by three readers. Each reader was blinded to the results of other imaging sequences. Imaging quality was assessed by each reader based on overall image quality, motion/flow artifacts, and plaque-lumen differentiation, using a three-point scale; 3 = good, 2 = appropriate for diagnosis, and 1 = inadequate for diagnosis. Qualitative comparison was made using these scores as indices.

Major segments of the carotid plaque, occupying more than one-third of the plaque, were quantitatively assessed by signal intensity characterization. The signal intensities of the segments were measured by each reader with polygonal region of interests (ROI) drawn over the segments. The signal ratio of the carotid plaque to the arterial lumen (RPL), as well as that of the carotid plaque to the adjacent sternocleidomastoid or scalenus medius muscle (RPM) was then calculated for each sequence.

A repeated-measures analysis of variance with Bonferroni post hoc comparisons was used to compare image quality, RPLs and the RPMs between the BB sequences. The corresponding P values were Bonferroni corrected and thus were considered statistically significant for $P < .05$. All statistical analyses were performed by using the software program Dr. SPSS II for Windows, version 11.0.1 J (SPSS, Chicago, Ill).

Results

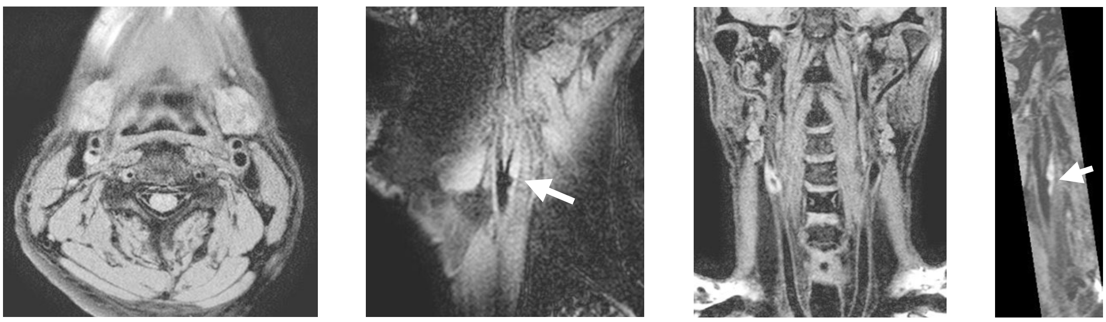
All fifteen patients successfully underwent the complete set of MR sequences. Representative images of each BB sequence are presented in Fig. 1. The qualitative assessment of the image quality of each sequence is summarized in Table 1. The score for 3D-TFE was significantly lower compared with VRFA-TSE ($p=0.009$). The 2D-TSE and 3D-VRFA-TSE images were acceptable in all fifteen subjects, whereas the 3D-TFE images were inadequate for diagnosis in four subjects. In these subjects, there was a pronounced flow artifact, particularly in the distal arterial lumen, and the plaque-lumen interface was indistinct on 3D-TFE (Fig. 2). Although a flow artifact was also observed in the distal lumen in three cases on both 3D-VRFA TSE and 2D-TSE, these sequences were capable of discriminating the plaque and lumen in all of the subjects (Fig. 2).

In contrast to the 2D-TSE, 3D-TFE and 3D-VRFA covered the entire extension of the plaque and enabled visualization of the plaque in arbitrary orientations, particularly in the long-axis views (Figs. 1 and 2). The details in the plaque shape and compositions, such as ulcerations (n=4) and calcifications (n=3) were better visualized on 3D-VRFA than on 2D-TSE (Fig. 1).

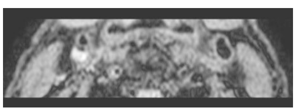
The quantitative assessment of the signal ratios acquired on 2D-TSE, 3D-TFE and 3D-VRFA sequences is summarized in Table 2. The RPL on 3D-VRFA was significantly higher than that on 3D-TFE ($p=0.013$) and lower than 2D-TSE ($p=0.048$). The RPL on 2D-TSE was also higher than on 3D-TFE ($p=0.008$). In addition, the RPM on 3D-VRFA was significantly higher than that on 2D-TSE ($p=0.001$) and 3D-TFE ($p<0.001$). The RPM on 3D-TFE was also lower than that on 2D-TSE ($p=0.03$).

Discussion

This study has demonstrated the efficacy of 3D-VRFA imaging for noninvasive evaluation of carotid plaques. Unlike 2D-TSE, 3D-VRFA allowed for visualization of carotid plaques in arbitrary orientations. In particular, the oblique sagittal view along the long axis of the carotid bifurcation was useful to demonstrate the entire distribution of the plaques (Figs. 1 and 2). In addition, the details about the plaque shape and composition were better visualized on 3D-VRFA than on 2D-TSE (Fig. 1). In contrast to the 3D sequences, 2D-TSE allowed acquisition of only four slices with a thick-

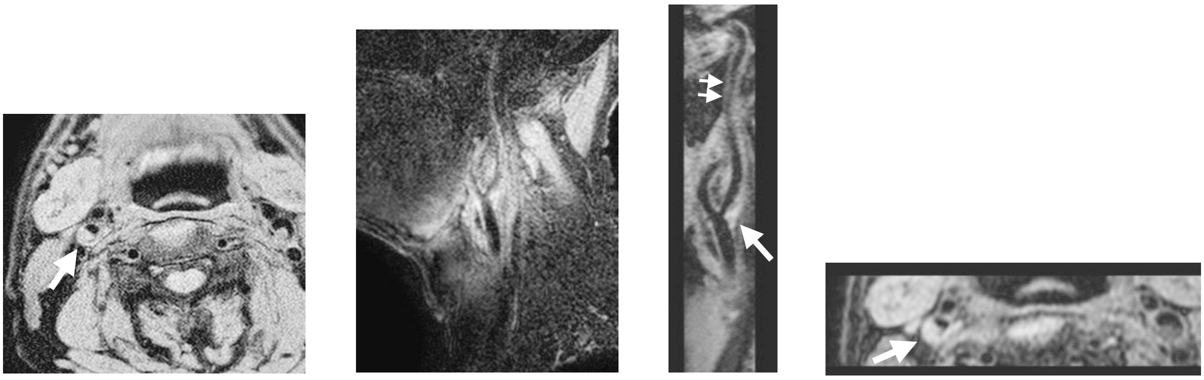


a) **b**) **c**) **d**)



e)

Fig. 1. An atheromatous plaque in a 67-year-old male.
A high signal intensity plaque at the right carotid bifurcation is shown on transaxial 2D-TSE (a), oblique sagittal 3D-TFE (b), coronal 3D-VRFA (c), and sagittal and transaxial reconstruction images of 3D-VRFA (d and e). The small ulceration is depicted only on 3D sequences (arrows in b and d).



a)　b)　c)　d)

Fig. 2. An atheromatous plaque in a 79-year-old male.
An atheromatous plaque (arrows) is visible on 2D-TSE (a), and on the sagittal and axial reconstruction image of 3D-VRFA (c and d), whereas the plaque-lumen interface is unclear on 3D-TFE (b). Although an intraluminal residual signal (double arrows) is observed in the distal portion of the internal carotid artery on 3D-VRFA (arrowhead), it does not affect the evaluation of the plaque (c).

Table 1. Qualitative Comparison of Image Quality Among Three Black Blood Sequences

	2D-TSE	3D-TFE	3D-VRFA
Image Quality	2.60+/−0.51	2.07+/−0.80	2.80+/−0.41

3D-TFE vs 3D-VRFA: $p<0.05$

Data are the mean values +/− standard deviations.

Table 2. Quantitative Comparison of RPL and RPM on Three BB Sequences

	2D-TSE	3D-TFE	3D-VRFA
RPL	21.33+/−15.7	7.16+/−3.10	11.24+/−4.05
	2D-TSE vs 3D-TFE: **	3D-TFE vs 3D-VRFA: *	2D-TSE vs 3D-VRFA: *
RPM	1.33+/−0.16	1.17+/−0.17	1.60+/−0.31
	2D-TSE vs 3D-TFE: *	3D-TFE vs 3D-VRFA: **	2D-TSE vs 3D-VRFA: **

Data are mean the values +/− standard deviations.
* $p<0.05$, ** $p<0.01$
RPL and RPM are the signal ratio of the carotid plaque to the arterial lumen, and that of the carotid plaque to the adjacent muscle, respectively.

ness of 3mm and an interslice gap of 4mm in a transaxial direction. Small plaque compositions may not be visualized due to low spatial resolution in the slice-select direction on 2D-TSE.[21)]

Although 3D-TFE with PPU- triggering also allowed image reconstruction in variable orientations, however, the suppression of the intraluminal signal was insufficient, and the images were compromised by plaque-mimicking artifacts in some cases. The residual signal on 3D-TFE reflects the difficulty in suppressing the signal from complex flow within the carotid bifurcation throughout the long-axis arterial segment, which is much longer than an axial slice on 2D-TSE.[17),22)]

In contrast, 3D-VRFA-TSE yielded acceptable suppression of the signal from flowing blood in all of the cases. Park and Kim proposed a T1-weighted 3D-TSE sequence with VRFA for efficiently reducing intravascular signal while retaining the signal from contrast-enhancing brain metastases. In addition to VRFA, adding the proposed flow-sensitizing gradients yielded further suppression of the signal from slowly flowing blood.[20)] Likewise, the present study indicated that 3D-TSE with VRFA and flow-sensitizing gradients is also useful in reducing the signal within the carotid bifurcations to assess atherosclerotic plaques.

The signal ratio of the plaque to the muscle (RPM) on 3D-VRFA was significantly higher than that on conventional 2D-TSE. The difference in the contrast between these sequences may have been caused by the differences in the repetition time (TR). Narumi et al. examined carotid plaques using a non-triggered, self-navigated radial-scan technique, and demonstrated considerable differences in the plaque signal among T1-weighted images with different TRs. In the hyperintensity plaques, a TR-dependent decrease of the plaque signal was evident, whereas the signal remained unchanged regardless of the TR in the isointensity plaques.[15] Hence, conventional triggered 2D T1W images with relatively long and intersubjectively different TRs may be inappropriate for assessing vulnerable carotid plaques. In the present study, we observed that a constant and relatively short TR (450 ms), which is independent of the cardiac cycle of the patients, may contribute to the highest signal ratio of the plaques obtained on 3D-VRFA. Hence, it is expected that 3D-VRFA will be useful to detect T1W-high signal carotid plaques.

Although VRFA-TSE provided clinically sufficient BB images, flow artifacts were observed in the distal lumen in three cases (Fig. 2). New blood-suppression techniques, such as motion-sensitized driven-equilibrium (MSDE) prior to TSE imaging may provide more efficient flow signal suppression.[23),24)]

There were several limitations to this study. One is the lack of pathological evidence of a plaque in all of our patients. We evaluated patients with carotid plaques which may comprise various constituents, including soft and/or hard components, and their signal intensity is therefore expected to vary on T1W images.[4)-10),13)-15)] Hence, the detectability of vulnerable/ soft plaques by using 3D-VRFA needs to be evaluated in future studies and correlated with pathological findings.

The second limitation is that we have not conducted systematic experiments to optimize the imaging parameters of the BB pulse sequences used in this study. The 2D-TSE and 3D-TFE in this study were performed according to the methods used in previous studies.[9),13),14)] However, 3D-VRFA is a relatively new technique and there are only a few reports regarding the imaging protocol using this sequence.[20),25)] Although Yoneyama et al[25)] recommended low refocusing flip angles between 30 and 50 degrees to efficiently decrease flow artifacts in contrast-enhanced brain imaging, we selected a slightly larger refocus flip angle (60 degrees) because a lower refocus flip angle tended to degrade the signal to noise ratio in our experience (unpublished data), and maintaining a higher spatial resolution is desirable in assessing small carotid plaques.

In conclusion, T1-weighted 3D VRFA-TSE is a promising method to assess carotid plaques in terms of imaging coverage, spatial resolution and lesion contrast. Further studies and pathological validation are needed to confirm the clinical utility of this pulse sequence.

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