European Journal of Radiology 81 (2012) e304–e309

Contents lists available at SciVerse ScienceDirect

European Journal of Radiology

journal homepage: www.elsevier.com/locate/ejrad

Characterization of carotid atherosclerosis with black-blood carotid plaque imaging using variable flip-angle 3D turbo spin-echo: Comparison with 2D turbo spin-echo sequences

Koichi Takano [a,*], Shinnichi Yamashita [a], Koichiro Takemoto [b], Tooru Inoue [b], Noriyuki Sakata [c], Yasuo Kuwabara [a], Kengo Yoshimitsu [a]

[a] Department of Radiology, Faculty of Medicine, Fukuoka University, 7-45-1 Nanakuma, Jonan-ku, Fukuoka-shi, Fukuoka 814-0180, Japan
[b] Department of Neurosurgery, Faculty of Medicine, Fukuoka University, 7-45-1 Nanakuma, Jonan-ku, Fukuoka-shi, Fukuoka 814-0180, Japan
[c] Department of Pathology, Faculty of Medicine, Fukuoka University, 7-45-1 Nanakuma, Jonan-ku, Fukuoka-shi, Fukuoka 814-0180, Japan

ARTICLE INFO

Article history:
Received 24 June 2011
Accepted 14 October 2011

Keywords:
Carotid plaque
Magnetic resonance imaging
Turbo spin-echo
Variable flip angle

ABSTRACT

Purpose: To compare the diagnostic performance of three-dimensional variable-flip-angle turbo spin-echo and two-dimensional turbo spin-echo sequences in carotid plaque imaging, with histological analysis as the standard of reference.

Materials and methods: Twenty-two patients scheduled for carotid endarterectomy underwent carotid plaque imaging including axial T1-weighted and T2-weighted two-dimensional turbo spin-echo, and coronal T1-weighted and T2-weighted three-dimensional variable-flip-angle turbo spin-echo sequences. The quality of images was visually graded using a three-point scale. The signal ratio of the arterial lumen to the plaque component, and that of the carotid plaque to the ipsilateral submandibular gland was calculated in each sequence. These ratios between two-dimensional and three-dimensional sequences were compared for each plaque component according to the histological category of the plaque.

Results: No significant difference was observed among the overall imaging quality scores of the two-dimensional and three-dimensional sequences, although three-dimensional sequences allowed visualization in arbitrary orientations, as well as depiction of small plaque components such as ulcerations and calcifications. The signal ratio of the plaque to the submandibular gland on T1-weighted three-dimensional sequence was significantly higher than that on two-dimensional sequence ($p < 0.01$), whereas no significant difference was found between two T2-weighted sequences.

The signal ratios of the plaque to the submandibular gland of histology-defined soft plaque components were significantly higher on T1-weighted three-dimensional sequence than on two-dimensional sequence ($p < 0.01$), whereas no significant differences were observed between two T1-weighted sequences for hard components.

Conclusions: Three-dimensional variable-flip-angle turbo spin-echo is a promising tool for the diagnosis of carotid plaques.

1. Introduction

Among the various causes of stroke, carotid atherosclerosis is one of the leading causes of morbidity and mortality worldwide. Moreover, the most common source of emboli in transient ischemic attacks and embolic stroke originates from atherosclerotic plaques at the carotid bifurcations [1,2].

The chemical constituents of the atherosclerotic plaque, as well as the plaque morphology and the degree of stenosis are extremely important factors to consider in predicting the clinical outcome and determining the management of carotid atherosclerosis [3–5].

Several investigators have reported the use of magnetic resonance imaging (MRI), as well as Doppler sonography to evaluate the chemical compositions of carotid atherosclerotic plaques. The presence of soft plaques, which consist of a lipid-rich necrotic core (LRNC) and/or intraplaque hemorrhage (IH), can be assessed noninvasively by magnetic resonance plaque imaging. Particularly,

* Corresponding author. Tel.: +81 092 801 1011; fax: +81 092 864 6652.
E-mail addresses: k-takano@fukuoka-u.ac.jp (K. Takano), yamashin@fukuoka-u.ac.jp (S. Yamashita), take9016@kuhp.kyoto-u.ac.jp (K. Takemoto), toinoue@fukuoka-u.ac.jp (T. Inoue), nysakata@fukuoka-u.ac.jp (N. Sakata), kuwabara@fukuoka-u.ac.jp (Y. Kuwabara), kengo@fukuoka-u.ac.jp (K. Yoshimitsu).

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doi:10.1016/j.ejrad.2011.10.012

the high signal intensity in carotid plaques on T1-weighted (T1W) images has been considered to correspond to soft plaques, which correlate to high level of ischemic events [3–6].

Two-dimensional (2D), black-blood (BB) imaging utilizing 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. In this method, triggering by using ECG or peripheral pulse unit (PPU) is typically required to suppress the intraluminal flow signal and reduce artifacts related to the blood flow [7,8].

However, 2D-TSE DIR technique has several limitations, such as restriction of imaging direction to the cross-sectional transaxial plane, thereby compromising the efficiency of the examination time, and restriction of the contrast setting depending on the cardiac cycle of each patient [9,10].

In addition, 2D-TSE is subject to partial volume effect, owing to poor spatial resolution in the slice-selecting direction in assessing small plaque compositions [11,12].

To overcome these limitations of 2D imaging, several 3D imaging techniques have been employed in plaque imaging. Some investigators have reported carotid BB imaging techniques using field-echo-based 3D sequences, such as 3D turbo field-echo (TFE) or magnetization-prepared rapid gradient-echo (MPRAGE) [3–5].

However, these field-echo-based 3D-BB techniques usually also require cardiac/pulse triggering for intraluminal signal suppression, which might be degraded by complex flow or by difficulty in suppressing the flow within a longer arterial segment [13].

Recently, a variation of the BB 3D-TSE technique, which uses non-selective variable refocusing flip angle (VRFA) alongside the echo train to achieve a pseudo steady state for a low refocusing flip angle was introduced. This technique allows the application of a longer echo train while reducing specific absorption ratio (SAR), image blurring, and degradation of image contrast [14,15]. Three-dimensional variable-flip-angle turbo spin-echo (3D-VRFA-TSE), combined with a lower refocusing flip angle, is reported to efficiently reduce intravascular signal and provide single-slab 3D-TSE BB imaging without using cardiac/pulse triggering [12,16].

Hence, it is expected that the 3D-VRFA-TSE sequence, which is capable of achieving variable contrast BB 3D-TSE, may be useful in assessing carotid plaques. Our previous study revealed that non-gated T1W 3D-VRFA was more efficient than peripheral pulse-gated T1W 3D-TFE DIR sequence in suppression of intraluminal signal. Overall image quality of the T1W 3D-VRFA was better than that of 3D-TFE and was comparable to that of the gated 2D-TSE DIR sequence [17].

The purpose of this study was to compare T1W and T2-weighted (T2W) non-gated 3D-VRFA-TSE sequences with pulse-gated 2D-TSE sequence in terms of their diagnostic performance in evaluating carotid plaques, using histological examination as the standard of reference.

2. Materials and methods

2.1.1. Study population

A total of 22 consecutive patients (21 men and 1 woman: age range, 47–84 years; mean age, 73 years) who underwent carotid wall BB MRI between September 2009 and August 2010, at most within 2 weeks before carotid endarterectomy (CEA), were included in this study.

The study protocol was approved by the institutional review board, and written informed consent was obtained from all the patients.

2.1.2. Imaging protocol

A bilateral carotid MRI was obtained using a 1.5 T Philips Achieva whole-body scanner (Philips Medical Systems, Best, the Netherlands) using a SENSE head/neck coil with a quadrature head part with 2 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 DIR T1W (TR/TE/TI/echo train length/number of excitations = 600–1000/7/263–399/7/2) and T2W (TR/TE/TI/echo train length/number of excitations = 1200–2000/80/490–640/21/3) images were acquired using a PPU-triggering. Other parameters included a matrix size of 320×320, a reconstruction matrix of 512×512, with a 200-mm field of view and 3-mm section thickness. Four transaxial slices were obtained with an inter-slice gap of 3 mm. The scan time ranged from 3 min 1 s to 4 min 24 s for T1W, and 3 min 13 s to 4 min 24 s for T2W.

The non-triggered 3D-VRFA-TSE T1W (TR/TE/echo train length/number of excitations = 450/16/20/2) and T2W (TR/TE/echo train length/number of excitations = 1800/105/40/1) were then obtained in a coronal direction. Other parameters included a matrix size of 225×224 with reconstruction matrix of 512×512, with a 200-mm field of view. For both T1W- and T2W-VRFA, a refocus flip angle (refocus control) of 60° was used. A flow-sensitizing gradient (sensitized flow compensation) was employed for suppression of the signal from slowly flowing blood [16].

Overall, 50–70 overcontiguous slices with an acquired section thickness of 1.2 mm and reconstructed section thickness of 0.6 mm were obtained with a scan time ranging from 4 min 16 s to 5 min 58 s for T1W, and 4 min 43 s to 6 min 36 s for T2W.

2.1.3. Image analysis

The imaging quality was assessed by two experienced neuroradiologists (K.T. and S.Y.) in consensus, using a three-point scale that contained the following factors: image coverage (3 = covers entire plaque, 2 = covers >50% of the plaque, and 1 = covers <50% of the plaque); flow artifact (3 = none, 2 = mild, and 1 = severe); morphological details (3 = good, 2 = acceptable, and 1 = inadequate); and overall quality (3 = good, 2 = appropriate for diagnosis, and 1 = inadequate for diagnosis).

The signal intensities of the intraplaque components were measured by one of the authors (K.T.) with polygonal region of interests (ROIs) drawn over the segments. Three pairs of corresponding ROIs were drawn per carotid plaque on 2D-TSE T1W and T2W images. On T1W- and T2W 3D-VRFA, ROIs corresponding to those on 2D-TSE were drawn on transaxial images reconstructed every 2 mm throughout the plaque. Thus, 264 regions were measured on 4 imaging sequences for 22 plaques. The signal intensities of the arterial lumen and those of the ipsilateral submandibular gland were also measured on each sequence.

The signal ratio of the arterial lumen to the carotid plaque component (RLP), as well as that of the plaque component to the adjacent submandibular gland (RPS) was then calculated for each ROI.

2.1.4. Histological evaluation

The plaques were dissected from the carotid bifurcation with endarterectomy and then fixed with 10% buffered formalin. The plaque samples were cut into 2 mm serial transverse slices through the length of the specimen. The samples were then decalcified and embedded in paraffin. Microscopic sections (3 μm) were cut from the paraffin-embedded tissue samples and stained with hematoxylin and eosin (H&E), Masson trichrome, and elastica-van Gieson