pISSN 2384-1095
eISSN 2384-1109

iMRI 2021;25:323-331

https://doi.org/10.13104/imri.2021.25.4.323

iMRI
Investigative Magnetic Resonance Imaging

Diagnostic Criteria of T1-Weighted Imaging for Detecting Intraplaque Hemorrhage of Vertebrobasilar Artery Based on Simultaneous Non-Contrast Angiography and Intraplaque Hemorrhage Imaging

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Original Article

Received: July 1, 2021
Revised: September 14, 2021
Accepted: October 1, 2021

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Purpose: To investigate the diagnostic criteria of T1-weighted imaging (T1W) and time-of-flight (TOF) imaging for detecting intraplaque hemorrhage (IPH) of a vertebrobasilar artery (VBA) compared with simultaneous non-contrast angiography and intraplaque hemorrhage (SNAP) imaging.

Materials and Methods: Eighty-seven patients with VBA atherosclerosis who underwent high resolution MR imaging for evaluation of VBA plaque were reviewed. The presence and location of VBA plaque and IPH on SNAP were determined. The signal intensity (SI) of the VBA plaque on T1W and TOF imaging was manually measured and the SI ratio against adjacent muscles was calculated. The receiver-operating characteristic (ROC) curve was used to compare the diagnostic accuracy for detecting VBA IPH.

Results: Of 87 patients, 67 had IPH and 20 had no IPH on SNAP. The SI ratio between VBA IPH and temporalis muscle on T1W was significantly higher than that in the no-IPH group (235.9 $\pm$ 16.8 vs. 120.0 $\pm$ 5.1, $P < 0.001$). The SI ratio between IPH and temporalis muscle on TOF was also significantly higher than that in the no-IPH group (236.8 $\pm$ 13.3 vs. 112.8 $\pm$ 7.4, $P < 0.001$). Diagnostic efficacies of SI ratios on TOF and TIW were excellent (AUC: 0.976 on TOF and 0.964 on T1W; cutoff value: 136.7% for TOF imaging and 135.1% for T1W imaging).

Conclusion: Compared with SNAP, cutoff levels of the SI ratio between VBA plaque and temporalis muscle on T1W and TOF imaging for detecting IPH were approximately 1.35 times.

Keywords: Intracranial artery; Atherosclerosis; Intraplaque hemorrhage; Magnetic resonance imaging

INTRODUCTION

The vertebrobasilar artery (VBA) is a common arterial system involved in ischemic stroke. Approximately 20% of ischemic strokes occur in the VBA, which involves the posterior circulation of the brain (1, 2). The VBA system supplies blood to the medulla, pons, midbrain, cerebellum, and occipital cortex. For this reason, VBA stroke can lead to multisystem dysfunction, significant disability, and even death. The mortality rate for VBA stroke is higher than 85% (3-6). Early detection of VBA stroke plays a crucial role in reducing complications and mortality rate of patients.

Atherosclerosis and subsequent plaque formation can result in arterial narrowing or occlusion, which is the most common cause of arterial stenosis. Especially, intraplaque hemorrhage (IPH) plays a critical role in the progression of atherosclerotic disease (7). It may serve as a measure of risk for ischemic stroke (8). Therefore, early detection and correct diagnosis for IPH within the carotid atherosclerosis have been widely studied and suggested in the neuroimaging field.

Of T1-weighted MR sequences, magnetization-prepared rapid acquisition with gradient-echo (MRRAGE) sequence and simultaneous non-contrast angiography and intraplaque hemorrhage (SNAP) sequence have been reported to have superior diagnostic capability for IPH detection of carotid atherosclerosis (9-11). However, these sequences need additional time for MR examination. Therefore, a signal intensity (SI) greater than 150% compared to adjacent muscle on routine T1-weighted MR sequences is generally used as the diagnosis criteria for IPH in carotid atherosclerosis. Some papers have used such criterion for detecting IPH in intracranial atherosclerosis without histological evidence (12-14). However, to our knowledge, the cutoff value of 150% of the T1 signal on adjacent muscle was arbitrary because of impossible histological research.

The purpose of this study was to establish cut off levels of SI ratios between VBA plaque and temporalis muscle on T1-weighted imaging (T1W) and time-of-flight (TOF) imaging based on SNAP imaging for early detection of IPH within VBA plaques.

MATERIALS AND METHODS

Patients

This study was approved by the local Institutional Review Board. Informed consent was obtained from all patients before imaging. Between December 2016 and December 2019, we consecutively selected patients with VBA stenosis using TOF MRA. During this period, all patients underwent initial brain MRI/MRA to detect any neurological symptoms or signs (such as headache, dizziness, giddiness, and vertigo) or stroke MR protocols to evaluate acute stroke. VBA stenosis status was documented. We performed high-resolution vessel wall imaging (HR-MRI) for evaluation of plaque in patients with VBA stenosis within two weeks after the initial MR study. The inclusion criterion was VAB plaque having a high SI on SNAP with VBA atherosclerosis and stenosis. Exclusion criteria were as follows: 1) plaque with massive calcification due to unclear visualization of high SI compared to dense calcified signal; 2) non-atherosclerotic vasculopathy such as dissection or moyamoya disease; and 3) insufficient MR imaging quality to evaluate contrast enhancement of the aneurysmal wall. We also included a control group of patients with VBA plaque who had no IPH.

MR Imaging Protocol

MRI was performed with a 3T MRI scanner (Achieva; Philips Medical Systems, Amsterdam, The Netherlands) with a 16-channel head coil. All patients initially underwent conventional brain MRI, which included three-dimensional (3D) TOF-MRA. TOF-MRA of the axial plane was obtained for each patient. Data were reconstructed using a dedicated online post-processing tool to determine blood vessel architecture. The HR-MRI protocol included five different scans: pre- and post-T1-weighted, T2-weighted, TOF axial, and SNAP. The black-blood (BB) technique with preregional 80-mm-thick saturation pulses to saturate incoming arterial flow was used for all scans.

The protocol was described previously (15, 16). We added SNAP sequence for evaluation of VBA IPH. BB T1W was acquired using a 2D turbo spin-echo sequence with the following imaging parameters: repetition time/echo time = 800/10 ms, field of view = 140 × 140 mm, matrix size = 140 × 150, slice thickness = 2.0 mm, echo train length = 10, and number of excitations = 2. Gadodiamide (0.1 mmol/kg body weight; Dotarem; Guerbet, Aulnay-sous-Bois, France) for contrast-enhanced BB T1W was injected as a bolus intravenously in all patients. Contrast-enhanced BB T1W was carried out at ~5 min after contrast injection. Imaging parameters for the TOF-MRA scan were as follows: repetition time/echo time = 18/3.8 ms, flip angle = 16°, field of view = 140 × 140 mm, matrix size = 312 × 165, slice thickness = 1.0 mm, echo train length = 1, and number

of excitations = 3. SNAP sequence was performed for evaluating optimal IPH as hyperintense. Image parameters were as follows: TR/TE/TI = 10/4.7/490 ms, FA = 11°, ETL = 98, FOV = 149 × 149 mm, and matrix = 187 × 216. The total scan time was 25 to 30 minutes. Patients remained in the MR machine for 35 to 45 minutes.

Clinical Data Assessment

Patients were classified as having either a symptomatic lesion or an asymptomatic lesion according to the presence of a recent ischemic stroke. Symptomatic stenosis was defined as a diffusion-restrictive lesion seen on DWI in the territory of the stenotic VBA with a corresponding acute neurologic deficit within 2 weeks before MR imaging. Clinical data, including basic demographics and risk factors for atherosclerosis, namely diabetes, alcohol, hypertension, hyperlipidemia, current smoking, atrial fibrillation, and history of coronary disease, were also recorded.

MR Imaging Analysis

All MR images were reviewed retrospectively by two neuroradiologists with 20 years and 11 years of experience, respectively, who were blinded to the clinical information of each patient. They assessed image quality by consensus using a 4-scale scoring system (1, poor; 2, adequate; 3, good; 4, excellent). Images with a score of 1 were excluded from the final analysis. Disagreements regarding image quality were resolved by consensus.

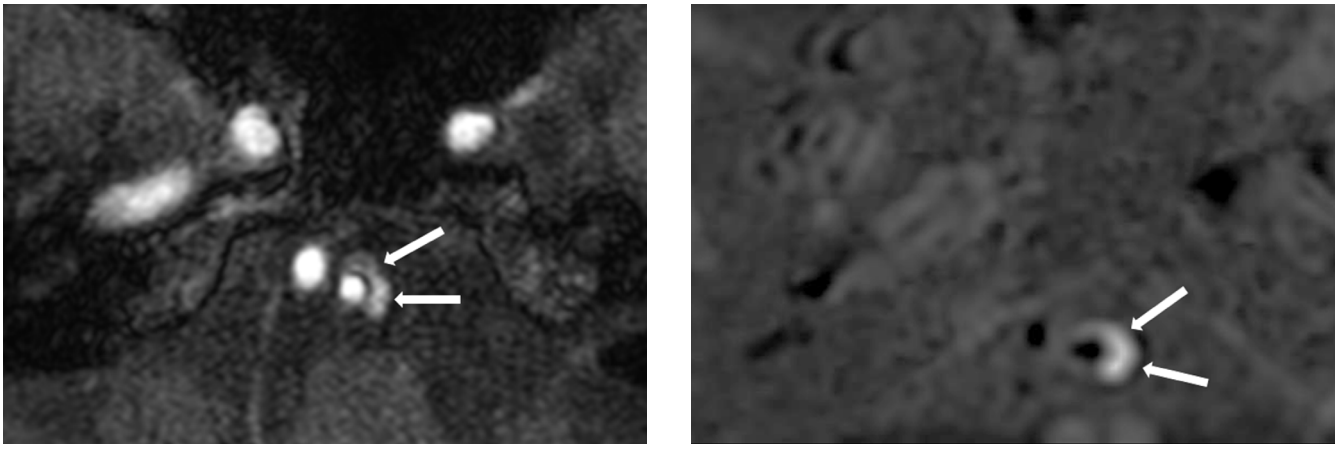
We searched for the presence of VBA plaques from both V4 segments to the BA among all samples using HR-MRI. Two neuroradiologists performed all these procedures. Plaque was defined as a thickening of the focal wall relative to image slices from beneath or above the focal wall as identified on T2W and T1W. An IPH of VBA plaques was defined as high-SI within plaques on SNAP as the reference standard. High SI according to previous criteria on magnetization-prepared rapid acquisition with gradient echo (MPRAGE) sequence was defined as an area with > 200% intensity of the signal of the temporalis muscle (17) (Fig. 1). VBA dissection was defined as false lumen with low SI on BB T2W and high SI on TOF MRA compared to IPH of VBA atherosclerosis (18, 19).

Initially, we calculated the SI of three points in the temporalis muscle and vessel lumen and calculated the mean SI. SI ratios between VBA plaques and temporalis on T1- weighted imaging and TOF source imaging were measured at the IPH area on SNAP (Fig. 1). We qualitatively assessed the presence or absence of IPH on T1W and TOF source imaging by consensus using a 4-scale scoring system (1, absence of IPH; 2, probably absence; 3, probably presence; 4, presence of IPH).

The percentage of stenosis was estimated on TOF-MRA using the formula of [(a-b)/a] × 100% (a = narrowed vessel diameter, b = proximal or distal normal vessel diameter) (20).

Statistical Analysis

Statistical analysis was performed using SPSS 23.0 for Windows (SPSS, IBM, Chicago, IL, USA) and MedCalc



a b

Fig. 1. IPH of the left vertebral artery. (a) Time-of-flight source imaging: halo sign positive (arrows). (b) SNAP: bright high signal intensity of IPH (arrows). IPH = intraplaque hemorrhage; SNAP = simultaneous non-contrast angiography and intraplaque hemorrhage.

software, version 16.4.2 (MedCalc, Ostend, Belgium). Continuous variables are expressed as medians and/or ranges. Categorical variables are expressed as counts and percentages. Continuous and categorical variables were compared among groups using the Mann-Whitney test and Fisher's exact test, respectively. Receiver-operating characteristic (ROC) curves of quantitative and qualitative analysis were assessed to evaluate the diagnostic efficacy for detecting VBA IPH on T1W and TOF source imaging. ROC curve analysis was performed to determine the sensitivity and specificity with a 95% confidence interval (CI) for IPH detection at cutoff values calculated by the Youden index. Statistical significance was defined at $P < 0.05$.

RESULTS

Patients

During the study period, 88 patients underwent HR-MRI for IPH evaluation of VBA plaques. Of these patients, 10 were excluded from this study due to poor imaging quality, 7 due to VBA dissection, and 4 due to massive calcification in VBA plaques. Sixty-seven patients (42 males; mean age, 73.5 years) with IPH of VBA plaques on MPRAGE and/or SNAP imaging were enrolled. Twenty patients (16 males; mean age, 66.4 years) without IPH of VBA plaques on HR-MRI or SNAP imaging were enrolled as a control group.

Assessment of Clinical Data between IPH and No-IPH Groups

Clinical characteristics of IPH and no-IPH groups are shown in Table 1. The mean age of patients with IPH was significantly older than that of patients in the no-IPH group (73.5 ± 1.1 vs. 66.4 ± 2.2 years, P = 0.003). When risk factors of atherosclerosis were compared, VBA plaques with IPH had the highest levels of cardiac problems (19.4% vs. 0%, P = 0.034), while VBA plaque without IPH had the highest ratio of smoking (60.0% vs. 31.3%, P = 0.02). Symptomatic plaque and degree of stenosis between the two groups were similar.

Signal Intensity Ratios of T1-Weighted and TOF Imaging

SI ratios of VBA plaques on T1-weighted and TOF imaging between IPH and no-IPH groups are shown in Table 2. The IPH group had significantly brighter SI on both imaging findings compared to the no-IPH group (T1 weighted imaging: 543.7 ± 35.2 vs. 291.8 ± 29.0, TOF imaging; 355.9 ± 21.8 vs. 199.6 ± 23.8, P < 0.001) (Fig. 2). SI ratios of VBA IPH between plaque and temporalis muscle on both imaging findings were significantly higher than those of the no-IPH group (T1 weighted imaging: 235.9 ± 16.8 vs. 120.0 ± 5.1, TOF imaging; 236.8 ± 13.3 vs. 112.8 ± 7.4, P < 0.001) (Fig. 3).

Comparison of ROC Analysis for IPH Detection

The ROC curve analysis of the SI ratio between both groups is shown in Table 3. The ROC curve analysis of the SI ratio revealed a higher diagnostic value for IPH detection on both imaging findings (TOF imaging: AUC = 0.904, 95%

Table 1. Clinical Characteristics of Vertebrobasilar IPH and No-IPH Groups

	Total (n = 87)	IPH group (n = 67)	No-IPH group (n = 20)	P
Age	71.9 ± 1.0	73.5 ± 1.1	66.4 ± 2.2	0.003
Male, n (%)	58 (66.7)	42 (62.7)	16 (80)	0.149
Hypertension, n (%)	71 (81.6)	56 (83.6)	15 (75.0)	0.511
Diabetes, n (%)	34 (39.1)	27 (40.3)	7 (35.0)	0.670
Hyperlipidemia, n (%)	17 (19.5)	13 (19.4)	4 (20.0)	1.000
Smoking, n (%)	33 (37.9)	21 (31.3)	12 (60.0)	0.02
Previous stroke, n (%)	26 (29.9)	23 (34.3)	3 (15.0)	0.097
Atrial fibrillation, n (%)	3 (3.4)	3 (4.5)	0	1.000
Coronary heart disease, n (%)	13 (14.9)	13 (19.4)	0	0.034
Alcohol, n (%)	31 (35.6)	21 (31.3)	10 (50.0)	0.126
Symptomatic, n (%)	26 (29.9)	19 (28.4)	7 (35.0)	0.569
Stenosis	53.2 ± 5.6	55.0 ± 7.0	47.3 ± 5.7	0.731

IPH = intraplaque hemorrhage

Table 2. Single Intensity Ratio of Vertebrobasilar Plaques on T1-Weighted and TOF Imaging

	IPH group (n = 67)	No-IPH group (n = 20)	P
T1-weighted imaging			
SI of plaque	543.7 ± 35.2	291.8 ± 29.0	< 0.001
SI ratio: plaque/temporalis	235.9 ± 16.8	120.0 ± 5.1	< 0.001
TOF source imaging			
SI of plaque	355.9 ± 21.8	199.6 ± 23.8	< 0.001
SI ratio: plaque/temporalis	207.2 ± 11.	112.8 ± 7.4	< 0.001

IPH = intraplaque hemorrhage; SI = signal intensity

Table 3. ROC Curve Analysis of Signal Intensity Ratios for Both Groups

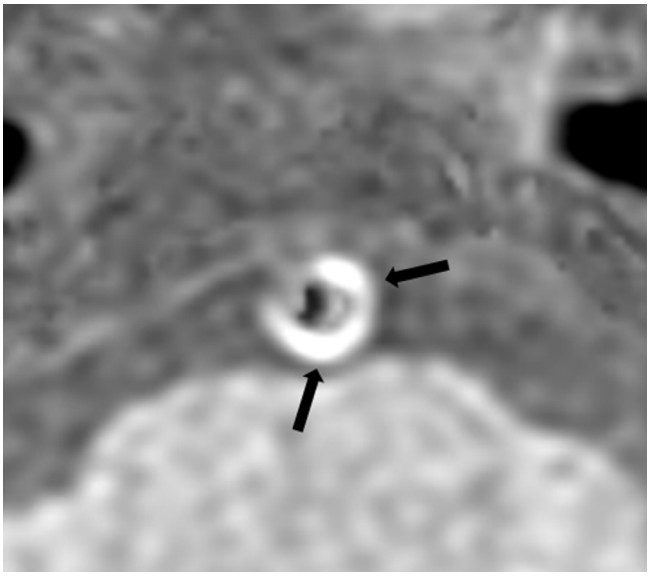
	TOF: SI ratio: Plaque/temporalis	T1: SI ratio: Plaque/temporalis
AUC	0.904	0.897
95% CI	0.833 - 0.976	0.830 - 0.964
P	< 0.001	< 0.001
Sensitivity	0.9	0.85
Specificity	0.896	0.881
Cut-off	136.7	135.1

AUC = area under curve; CI = confidence interval; ROC = receiver-operating characteristic; SI = signal intensity; TOF = time-of-flight

CI = 0.833-0.976, P < 0.001; T1-weighted imaging: AUC = 0.897, 95% CI = 0.830-0.964, P < 0.001) (Fig. 4). Using ROC analysis, we determined the best cutoff value was 136.7% for TOF imaging and 135.1% for T1W, with which the sensitivity and specificity for detecting VBA IPH were the highest.

DISCUSSION

This study demonstrates a comparison of SI ratios between the IPH and no-IPH group in patients with VBA



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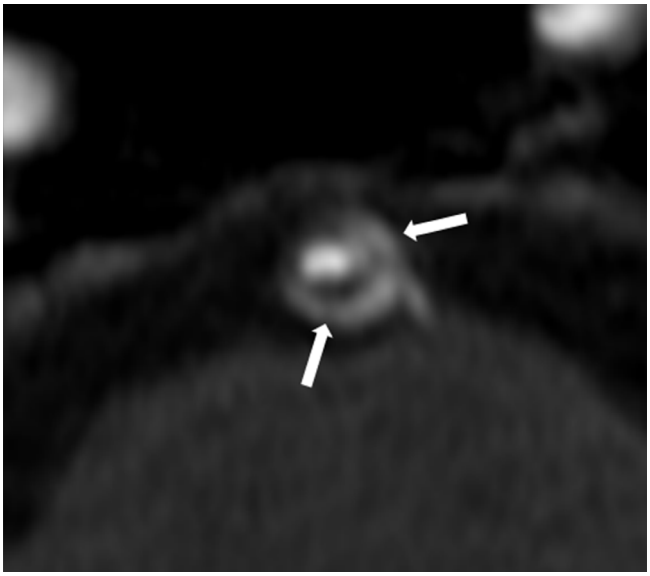

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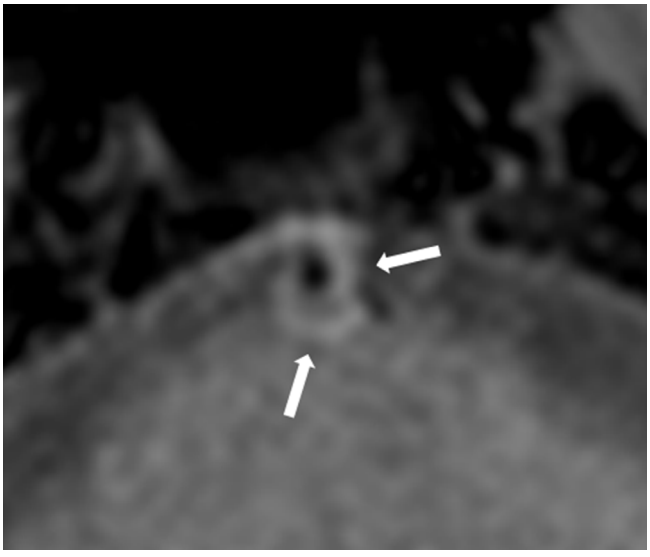

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Fig. 2. A 74-year-old man with stenosis of BA. IPH of the proximal BA. (a) SNAP imaging showing bright high signal intensity of the proximal BA (arrows). (b) TOF MR source imaging showing a positive halo sign (arrows). The signal intensity ratio of BA IPH between plaque and temporalis muscle was 2.5 times. (c) T1-weighted imaging showing a bright high signal intensity of the plaque (arrows). The signal intensity ratio of BA IPH between plaque and temporalis muscle was 1.4 times. BA = basilar artery; IPH = intraplaque hemorrhage; SNAP = simultaneous non-contrast angiography and intraplaque hemorrhage; TOF = time-of-flight

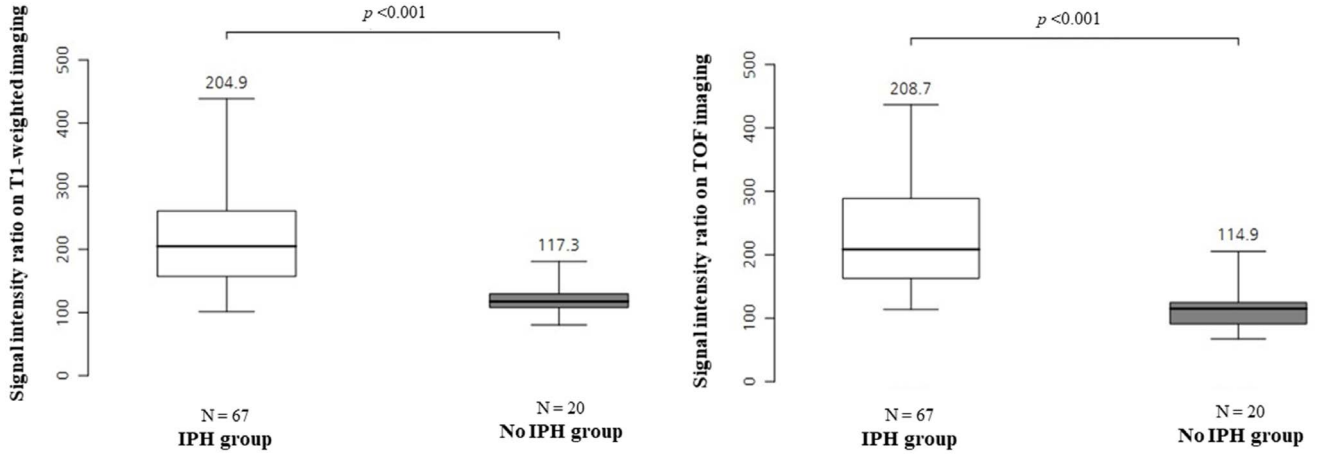

Fig. 3. Signal intensity ratio between vertebrobasilar plaque and muscle of IPH and no-IPH groups. (a) T1-weighted imaging. (b) TOF imaging. IPH = intraplaque hemorrhage; TOF = time of flight.

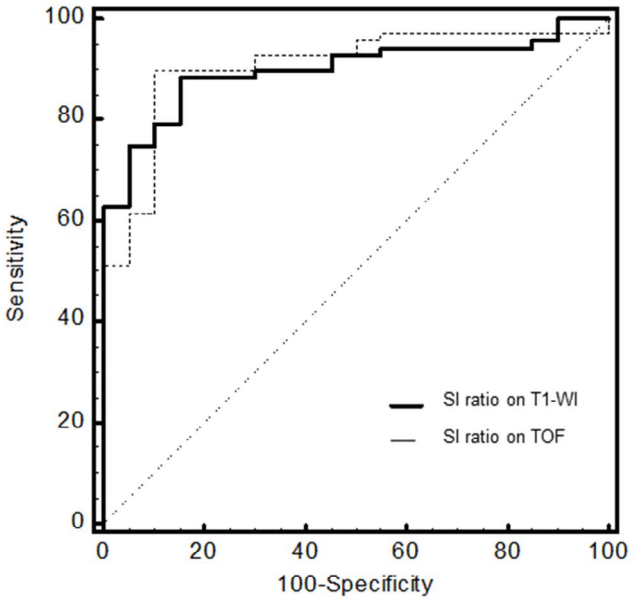

Fig. 4. Receiver operator characteristic curves of signal intensity ratio between the IPH group and the no-IPH group on T1-weighted imaging and TOF imaging. IPH = intraplaque hemorrhage; TOF = time of flight.

plaques on T1W imaging and TOF imaging. In previous studies, carotid IPH was manually characterized as high SI by visual examination or using an arbitrary threshold of 1.5 compared to the SI of adjacent muscle on T1W imaging or TOF imaging (11, 21-24). We find that the cutoff level of the SI ratio between VBA plaque and temporalis muscle on T1W and TOF imaging for detection of IPH is approximately 1.35 times.

Recent studies have revealed evidence that current management guidelines focusing on degree of stenosis might need to be revised. Identification of plaque characteristics including IPH or necrotic core could be consider the indicator for future stroke risk (12, 25). Wang et al. (13) have performed a multivariate regression analysis and found that not IPH, but plaque enhancement (OR: 7.193; 95% CI: 1.880 to 27.517; P = 0.004) and smoking (OR: 4.402; 95% CI: 1.218 to 15.909; P = 0.024) are independent risk factors of posterior circulation stroke in patients with BA stenosis > 50%. In contrast, Shi et al. (26) have performed a multivariate regression analysis on identification of high-risk plaque features in intracranial atherosclerosis and found that IPH (OR: 17.803, P = 0.008) is a strong independent predictor of stroke symptoms with two other risk factors: minimal luminal area (OR: 1.515, P = 0.008) and enhancement ratio (OR: 71.979, P < 0.001). Zhu et al. (12) have performed a study on the clinical significance of IPH in low and high-grade BA stenosis on HR-MRI and found that IPH is the best overall marker of symptomatic plaque with an odds ratio of 27.5. This study supported the use of IPH in BA atherosclerotic plaque as a better indicator of symptomatic plaque than stenosis or plaque burden alone (12).

Previous IPH studies have mostly been performed on carotid artery plaques. IPH in carotid artery plaque is commonly detected by T1 weighted MR sequences

in clinical practice. This is because methemoglobin, a degradation product of hemoglobin, can cause T1 shortening and eventually lead to high SI on T1-weighted MR imaging (25). Ota et al. (11) reported that among T1-weighted sequences, MPRAGE sequences demonstrated better diagnostic capability for detecting and quantifying IPH than fast spin-echo and TOF imaging using histology as the standard of reference. Liu et al. (9) also reported that on MPRAGE with a threshold of 1.6, the adjacent muscle intensity had a good performance for IPH detection and achieved high correlation (r = 0.83-0.93) for IPH area quantification. According to Li et al. (10), SNAP could detect carotid IPH with a smaller size, showing higher sensitivity in detecting hemorrhage than MPRAGE. It could detect 70% more IPH than MPRAGE. Furthermore, Wang et al. (27) have proposed the potential of SNAP as a first-line screening tool for high-risk intracranial atherosclerosis disease evaluation. In our study, we used SNAP as reference standard and aimed to find SI ratios between VBA IPH and temporalis muscle on TOF and T1 commonly used in a clinical setting.

A previous intracranial plaque study done by Yu et al. (25) has focused on BA IPH using MPRAGE and its prevalence. They defined high SI as an area with 150% intensity of the signal of the adjacent muscle. However, to our knowledge, the cutoff value of 150% was arbitrary. There was no evidence on how this cutoff of 150% was chosen to be the SI cutoff value. Yu et al. (25) used MPRAGE images as the only reference standard. MPRAGE images in a previous carotid histologic study could have higher accuracy in assessing patients with IPH than T1W or TOF imaging (11). On the other hand, previous studies used T1W for detecting BA IPH (12-14). IPH was defined as a SI greater than 150% of the T1 signal of adjacent muscle in these studies (25). We thought that MPRAGE and T1W might have different criteria regarding the SI of adjacent muscle for detection of BA IPH because T1W showed lower sensitivity for detection of carotid IPH in a pathologic study (11). In our study, SNAP imaging was used as a reference standard for detection of VBA IPH, where VBA IPH was defined as a SI greater than 200% of the signal of adjacent muscle. The IPH group had significantly higher SI on T1W and TOF imaging than the no-IPH group. SI ratios of VBA IPH between plaque and temporalis muscle on both imaging findings were significantly higher than those of the VBA non-IPH group. Also, in our study, the optimized intensity threshold for VBA IPH was 136.7% for TOF imaging and 135.1% for T1W. The diagnostic value for IPH detection of a high SI on both imaging findings revealed higher performance in ROC analysis. These findings demonstrate that the diagnostic criterion for intracranial IPH detection (> 150% SI of adjacent muscle) used in previous studies is reasonable (12, 13, 25).

This study has several limitations. First, this study was done retrospectively in a single center with a relatively small number of patients. Second, no histologic validation was done on the presence, absence, or size of IPH identified on MRI images. A pathologic correlation between HR-MRI and intracranial atherosclerosis has been reported in only one case study (28). The definition of VBA IPH can be used in a histological study of carotid HR-MRI.

In conclusion, the VBA IPH group had a significantly higher SI on both T1W and TOF imaging than the no-IPH group. SI ratios of VBA IPH between plaque and temporalis muscle on both imaging findings were significantly higher than those of the VBA non-IPH group. Compared with SNAP, cutoff levels of the SI ratio between VBA plaque and temporalis muscle on T1W and TOF imaging for detection of IPH were approximately 1.35 times. Generally, a SI ratio of 1.5 times for detection of VBA IPH is acceptable.

Acknowledgments

Competing interests: The authors declare that they have no conflicts of interest.

Ethical approval: All procedures performed in this study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee, the 1964 Helsinki Declaration and its later amendments, and comparable ethical standards.

Informed consent: The requirement for patient informed consent was waived due to the retrospective nature of this study by reviewing patient records and images.

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