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Reproducibility and differentiation of cervical arteriopathies using in vivo high-resolution black-blood MRI at 3 T

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Abstract
Introduction The aims of the present study are to evaluate the potential of high-resolution black-blood MRI (hr-bb-cMRI) to differentiate common cervical arteriopathies and to evaluate interobserver reproducibility.
Methods Forty-three consecutive patients with distinct cervical arteriopathies were examined with cervical hr-bb-cMRI at 3.0 Te with fat-saturated pre- and post-contrast T1w, T2w, and TOF images using dedicated carotid surface coils at our institution. Twenty-three patients had atherosclerotic disease, causing significant stenosis in 12 patients while 11 patients had moderate stenosis. Eight patients presented with cervical vasculitis, and five patients had arterial dissection. Furthermore, seven control subjects with no evidence of carotid disease were included. Two experienced readers blinded to all clinical information reviewed all MR images and classified both carotid and vertebral arteries as affected either by atherosclerosis, dissection, vasculitis, or no disease. Finally, a consensus reading was performed.
Results On a per-vessel level, test performance parameters (sensitivity, specificity, positive predictive value, negative predictive value) were 95, 97.7, 92.9, and 98.5 % for atherosclerotic disease; 91, 100, 100, and 98.7 % for vasculitis; and 100, 100, 100, and 100 % for dissection, respectively. On a per-patient level, performance parameters were 95.7, 85.7, 97.2, and 85.7 % for the diagnosis of atherosclerosis and 100, 100, 100, and 100 % for the diagnosis of dissection and of vasculitis, respectively. Accuracy rates were all above 95 % for all entities. There was a high agreement between observers both in a per-vessel ($\kappa = 0.83$) and in a per-patient analysis ($\kappa = 0.82$).
Conclusion This study demonstrates that hr-bb-cMRI is able to non-invasively differentiate between the most common cervical arteriopathies with an excellent interreader reproducibility.

Keywords MRI · Atherosclerosis · Dissection · Vasculitis · Accuracy

Background

Magnetic resonance imaging (MRI) is well known as a powerful tool for the non-invasive evaluation of the cervical arteries [1]. Using dedicated carotid artery surface coil high-resolution black-blood cervical MRI (hr-bb-cMRI) sequences offers a higher intrinsic contrast and spatial resolution compared to other clinically available non-invasive imaging modalities.

Over the last years, hr-bb-cMRI has been established as a diagnostic tool for the most common cervical arterial diseases. It has been demonstrated that in comparison with histopathology, hr-bb-cMRI can reliably differentiate various components of atherosclerotic plaques [2–4]. Several prospective studies have confirmed that the plaque composition as assessed by MRI has predictive value for future cerebrovascular events [5–7]. In addition, hr-bb-MRI is also well known for its ability to visualize intramural hematomas facilitating

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the diagnosis of acute and chronic arterial wall dissection and has a high diagnostic accuracy in patients with clinically suspected cervical dissection [8, 9]. Furthermore, it has been shown that inflammatory processes of the arterial wall as in different forms of vasculitis can be detected and characterized by hr-bb-cMRI [10–12].

Diagnostic accuracy of hr-bb-cMRI has been demonstrated for most of the mentioned pathologic entities in comparison with different reference standards [8]; however, uncertainty remains whether the high diagnostic accuracy reported can be upheld with hr-bb-cMRI as the first-line diagnostic modality in a realistic clinical setting comprising a diverse patient cohort with various arterial pathologies.

To the best of our knowledge, no study evaluated the potential of hr-bb-cMRI in differentiating between the aforementioned most common arteriopathies, using hr-bb-cMRI as the first-line imaging modality. Therefore, this study included a cohort of consecutive patients who were referred for hr-bb-cMRI of the cervical arteries for any suspected arterial pathology. Two experienced readers, who were blinded to all clinical or laboratory information, evaluated patients independently, and results of the blinded reading were then compared to the results obtained by the gold standard, which was determined by an expert panel with the use of all patient data. The aims of this study were to evaluate the potential of hr-bb-cMRI to establish the final diagnosis and to evaluate interobserver reproducibility in patients with different cervical arteriopathies.

Materials and methods

Patient recruitment

The local institutional review board of our institution approved this study. Overall, 43 patients who were scheduled to undergo elective cervical hr-bb-cMRI between January and August 2010 were consecutively included in this study. Twenty-three patients were referred for a detailed workup of atherosclerotic disease, ten patients were referred for clinically suspected carotid artery vasculitis, and ten patients were referred for the workup of suspected carotid or vertebral artery dissection on the basis of Doppler ultrasound. No other patients with non-carotid disease were scanned with this protocol during the study period. Due to institutional policies, patients with impaired renal function (glomerular filtration rate <30 ml/min), history of allergic reaction to gadolinium-containing contrast agents, pacemakers, or a history of severe claustrophobia were excluded. Informed written consent was obtained from each patient. Cardiovascular risk factors and laboratory values were recorded routinely for all patients.

MRI data acquisition

All scans were performed on a 3-T MRI scanner (Magnetom Verio, Siemens Healthcare, Erlangen, Germany) using a 12-channel head coil and a four-channel dedicated surface coil for the carotid arteries (Machnet, Eelde, Netherlands). After acquisition of scout images, the routine multi-sequence protocol included a 3D-gradient-echo time-of-flight (TOF) angiography [repetition time (TR) = 21 ms, echo time (TE) = 3.96 ms], a fat- and blood-suppressed 2D-T1 Turbo Spin Echo (TSE) sequence [TR = 800 ms, TE = 12 ms], and a fat- and blood-suppressed 2D-T2 TSE sequence [TR = 3000 ms, TE = 65 ms]. Best in-plane resolution was 0.5×0.5 mm^2 after Fourier transformation with a field of view of 160×120 mm^2 in all patients. Slice thickness of TOF images was 1 mm; slice thickness of T1- and T2-weighted series was 2 mm in all patients. For blood suppression, we used double inversion recovery in T1; in PD and T2, we used inflow-outflow blood separation. In patients with suspected atherosclerotic disease, the T1- and T2-weighted series consisted of contiguous slices, while in all other patients, T1- and T2-weighted series had variable slice gaps of 2–4 mm. Number of images was 15–30 for T1-weighted and T2-weighted series and approximately 100 for TOF series. Coverage included at least the carotid bifurcation as well as the origin of the basilar artery.

Parallel imaging with a PAT factor of 2 was applied for all sequences using the generalized autocalibrating partially parallel acquisition algorithm (GRAPPA). Approximately 5 min, after the intravenous administration of 0.1 mmol/kg gadolinium-DTPA-BMA (gadobutrol, Bayer Schering, Leverkusen, Germany), post-contrast T1-weighted images were acquired using identical settings.

Complimenting imaging studies

According to institutional policies, patients underwent several complementing imaging studies: prior to carotid MRI, all patients had undergone a dedicated color Doppler ultrasound examination of the carotid arteries. All patients, in whom vasculitis was the main diagnosis, had a clinically indicated whole-body 18F-fludeoxyglucose (FDG)-PET-CT scan to document disease activity and identify other potentially affected vascular territories. Patients with arterial dissection were followed clinically and underwent imaging follow-up after 3 months to evaluate changes in vessel wall hematoma. For all patients who underwent carotid endarterectomy over the study period, the histopathological report describing the specimen was retrieved.

Establishment of a reference diagnosis

All scans were performed in the context of clinical routine, and a routine radiological report was provided to the referring physicians. These routine reports were not part of this study. For this study, an expert panel consisting of two radiologists and one neurologist with extensive experience in black-blood carotid artery MR imaging convened 6 months after the inclusion period had ended and discussed all 43 cases in detail to establish a reference diagnosis for all patients. The panel had access to all patient data on record (including all clinical, imaging, and laboratory data) and the clinical course of the patient. On this basis, panelists assigned one of the following diagnoses on a per-vessel level for the four major cervical arteries (common/internal carotid arteries and vertebral arteries) in all patients: (I) mild or severe atherosclerotic disease, (II) vasculitis, (III) arterial dissection, or (IV) no evidence of disease. Based on all accessible information and the clinical course, panelists then agreed on the pertinent (i.e., most relevant) diagnosis for every patient, assigning every patient to one of the following groups: (1) atherosclerotic disease, (2) vasculitis, (3) arterial dissection, and (4) no relevant disease in any of the arterial vessels. The control group consisted of the patients of group (4) in which imaging and clinical work-up found no evidence for carotid disease of any kind.

Image data post processing

Since, in atherosclerotic patients, T1-weighted and T2-weighted series were contiguous while, in the other patients series, had a slice gap of 2–4 mm, potential bias could be introduced by unblinding of readers during analysis. To avoid this problem, one of the expert panel radiologists modified the series for the atherosclerosis patients by selecting only every other image from the pre- and post-contrast T1-weighted and T2-weighted series—which were renamed as pre-T1-w_{mod}, post-T1-w_{mod}, and T2-w_{mod}. Care was taken to choose identical slice positions for all series in each patient. These modified series had an artificially created slice gap. To take the reduced number of images in the pre-T1-w_{mod}, post-T1-w_{mod}, and T2-w_{mod} series of the atherosclerosis group into account, the T1-weighted and T2-weighted series of the other groups (vasculitis, dissection, or control group) were reduced in the number of images accordingly (to approx. 9–11 images). After this reduction in the total number of images, series were analogously renamed as pre-T1-w_{mod}, post-T1-w_{mod}, and T2-w_{mod}. All series were centered on the slice position of the carotid bifurcation. If carotid bifurcations were on different slice positions, the center between both was taken as the reference position. Care was taken to maintain this center even when the numbers of images were reduced. Finally, all DICOM images were pseudonomyzed, transferred to an external workstation, and displayed without any information about slice thickness or original slice gaps for the purpose of this study.

Image analysis and imaging criteria

For image analysis, cases were presented in random order. Two experienced radiologists who were not part of the expert panel and blinded toward all clinical data and the final diagnosis independently analyzed all series. Readers were blinded to the prevalence of each disease in the analyzed cohort according to the results of the expert panel. Readers first evaluated image quality on a three-point scale for all patients (1: excellent image quality; 2: moderate image quality, diagnostic interpretation feasible; 3: insufficient image quality). Subsequently, both readers assigned one of the following diagnoses on a per-patient and on a per-vessel level: (I) mild or severe atherosclerotic disease, (II) arterial dissection, (III) vasculitis, or (IV) no evidence of disease. After independent readings were documented, readers discussed all cases in which they had stated different opinions and formed a consensus opinion. An overview of the typical MRI appearance of the distinct cervical arteriopathies is given in Table 1.

Statistical analysis

The D'Agostino-Pearson test was used to test if ratio-scale variables followed normal distribution, in which case, they were reported as mean ± standard deviation. All variables not following normal distribution are reported as median with interquartile range. To address agreement between readers for categorical variables, κ-statistics were used. To describe the test performance of hr-bb-cMRI for the diagnosis of the various arterial pathologies, 4×4 confusion matrices were used and sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) for each of the three classes of pathology (i.e., atherosclerotic disease, arterial dissection, and vasculitis) derived. To test for differences in means, the Student's t test was applied if a variable followed normal distribution; otherwise, means were compared using non-parametric tests. For all tests, p values of 0.05 or less were considered statistically significant. Data were analyzed using MedCalc (Version 9.3.0.0, MedCalc Software, Mariakerke, Belgium) and SPSS (21.0, IBM, Armonk, USA).

Results

Patient population and diagnostic reference standard

Between January and August 2010, 43 consecutive patients were referred for hr-bb-cMRI scan of the carotid arteries and were included in this study. Median scan time was 32 min (range 18–46 min). Of 23 patients referred with a suspicion

Table 1 Overview over the most important parameters for differential diagnosis of cervical arteriopathies

	Atherosclerosis	Vasculitis	Dissection
Morphology	Eccentric, focal wall thickening	Concentric wall thickening, long vessel segment	Vessel wall hematoma
Perivascular contrast uptake	–	+++	+
Perivascular edema	–	+++	+
Stenosis	Variable	Variable	Initially often >70 % or occlusion
Typical MR features	Lipid-rich/necrotic core without contrast uptake	Three-layered appearance of the vessel wall ("arterial bull's eye sign")	Hyperintense vessel wall on fs T1w, often crescent shaped

fs fat saturated, *MR* magnetic resonance

of atherosclerotic disease (group 1), 12 showed severe disease with luminal narrowing of over 50 %, while the other 11 patients had only mild or moderate stenosis (<50 %). In the group with severe atherosclerotic disease, the diagnosis was confirmed by histopathological analysis of the resected endarterectomy specimen in ten patients (83 %, 10/12) while the remaining two patients did not undergo carotid endarterectomy, but diagnosis was confirmed with ultrasound. An example of a patient with atherosclerotic cervical disease is shown in Fig. 1.

Ten patients were referred for the workup of suspected arterial dissection on the basis of clinical symptoms and a Doppler ultrasound exam. In these patients, the suspected diagnosis was confirmed in five patients (50 %, 5/10, group 3), all of which underwent follow-up MRI after 3 months. An example of a patient with bilateral dissection of both vertebral arteries is shown in Fig. 2.

Of ten patients presenting with a suspicion for vasculitis, eight (80 %, 8/10) showed clear signs of vasculitis by MRI, which was confirmed by an 18F-FDG-PET-CT examination (group 2). Figure 3 shows MRI images of a patient with cervical vasculitis.

Finally, seven patients (two and five referred for suspected vasculitis or dissection, respectively) did not exhibit features of either disease in any of the cervical vessels (group 4).

On a per-vessel level, 100 vessels (58 %, 100/172) showed no evidence of disease, 41 vessels (24 %, 41/172) exhibited either moderate or severe atherosclerotic disease, 22 vessels (13 %, 22/172) showed vasculitis, and in 9 vessels (5 %, 9/172), an arterial dissection was found. Table 2 compares patient demographics and risk factors.

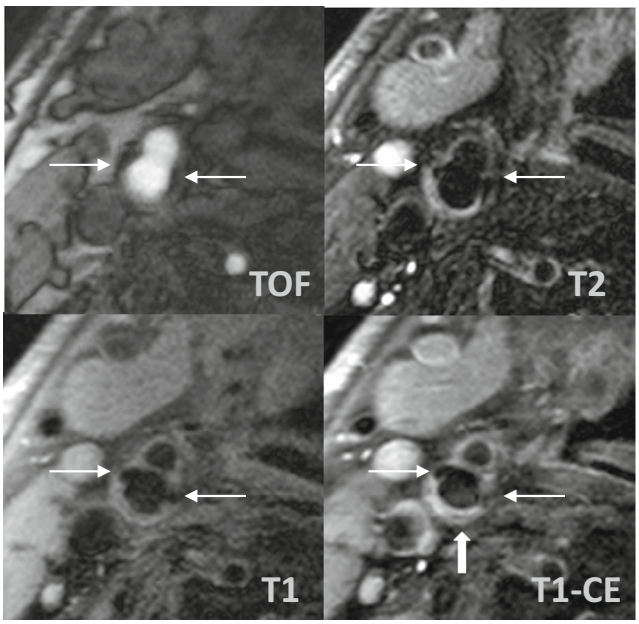

Fig. 1 Cervical hr-bb-cMRI images of an 82-year-old male patient. The *thin arrows* point on calcifications in the right-sided carotid bifurcation in each image. The *thick arrow* points on a lipid/necrotic core in the T1-CE image. The findings are consistent with severe atherosclerotic changes

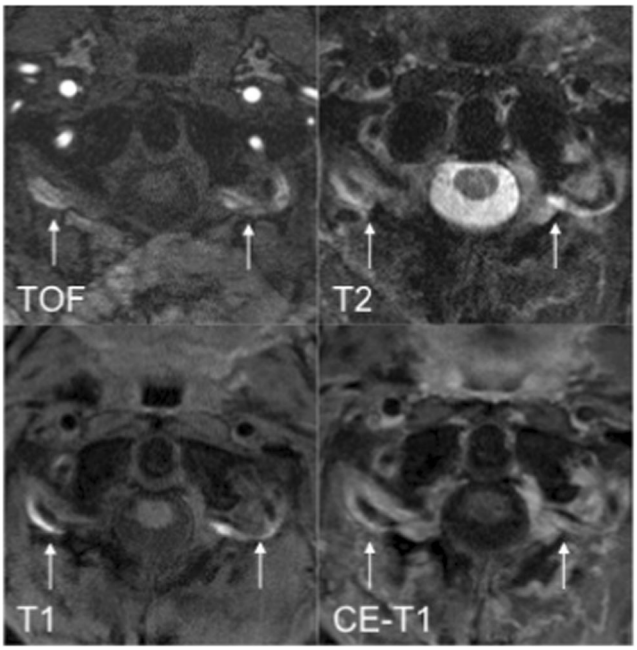

Fig. 2 Cervical hr-bb-cMRI images of a 61-year-old male patient. The *arrows* point to a hyperintense area on TOF, T1w, and T2w images in the V3 segments of the left and right vertebral arteries, consistent with vessel wall hematoma. The patient was diagnosed with cervical artery dissection

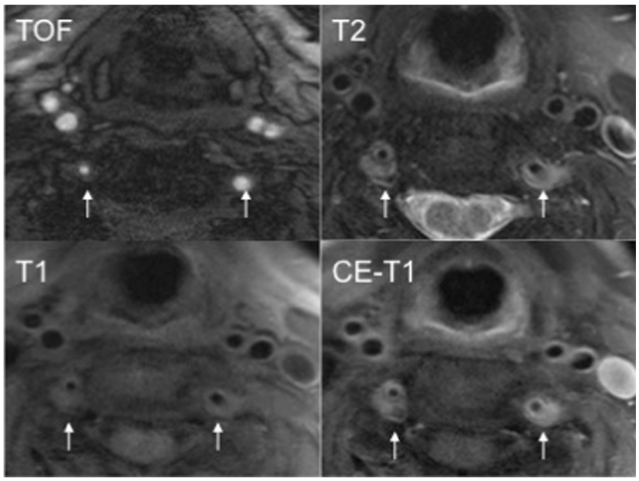

Fig. 3 hr-bb-cMRI cervical images of a 72-year-old female patient. The *arrows* point to the left and right vertebral arteries, which show concentric wall thickening, perivascular edema, and contrast uptake, consistent with vasculitis

Image quality rating

Reader 1 attributed excellent image quality in 29 cases (67 %, 29/43) and moderate image quality in 14 cases (33 %, 14/43), while reader 2 attributed excellent and moderate image quality in 28 (65 %, 28/43) and 15 cases (35 %, 15/43), respectively. There was a high agreement between readers in assessment of image quality ($\kappa = 0.64$). In no case, image quality was considered insufficient for diagnostic evaluation. In patients with atherosclerotic disease, vasculitis, and dissection and patients of the control group, excellent image quality was reported in 70 % (16/23), 75 % (6/8), 80 % (4/5), and 43 % (3/7). Differences in proportions were not significant (chi-square test, $p = 0.47$).

Interobserver agreement

Both readers analyzed the four major cervical arteries in all 43 patients. For the specification of disease, interobserver agreement was excellent both on a per-patient level ($\kappa = 0.82$) and on a per-vessel level ($\kappa = 0.83$). Therefore, values from the consensus interpretation were used for the calculation of test performance measures.

Test performance on a per-vessel level

Table 3 summarizes diagnostic test parameters on a per-vessel level. Overall, 20 out of 22 vessels with vasculitis, 9 out of 9 vessels with dissection, and 39 out of 41 vessels with atherosclerotic changes were correctly identified. In 97 out of 100 vessels, readers correctly stated that there was no evidence of vascular disease. In four vessels, readers missed vascular pathology, namely two arteries with mild atherosclerotic disease, and two vessels with vasculitis. On the other hand, in three normal vessels, readers falsely described mild atherosclerotic disease.

For the diagnosis of dissection, this resulted in sensitivity, specificity, PPR, and NPR of 100 % on a per-vessel level and an accuracy rate of 100 %. For the diagnosis of vasculitis, test performance measures were 90.9, 100, 100, and 98.7 % and the accuracy rate was 98.8 %. For the diagnosis of atherosclerotic disease, measures were 95.1, 97.7, 92.9, and 98.5 % and the accuracy rate 97.1 %. When analyzing test performance for the diagnosis of any disease, sensitivity, specificity, and positive and negative predictive values were 94.4, 97.0, 95.8, and 96.0 % and the accuracy rate 95.9 %.

Test performance on a per-patient level

On a per-patient level, readers falsely classified one patient with mild atherosclerotic disease as disease-free. Conversely, one patient without any sign of vascular disease was falsely classified as mildly atherosclerotic. All cases of vasculitis and dissection were correctly identified. The two cases of vasculitis falsely classified as normal on a per-vessel-level did not transform into false negatives on a per-patient level, since both patients also had vasculitis in other cervical arteries, which was correctly identified.

On a per-patient level, sensitivity, specificity, PPV, and NPV for the diagnosis of atherosclerotic disease, test performance measures, were 95.7, 100, 100, and 95.0 % and the

Table 2 Patient demographics and risk factors: *n* (%) or mean ± SD

	All	Atherosclerosis	Vasculitis	Dissection	No disease
n	43	23	8	5	7
Age (years)	62.4 ± 15.7	70.2 ± 7.1	58.8 ± 20.2	40.6 ± 14.1	56.7 ± 15.8
Male	23 (53 %)	16 (70 %)	0 (0 %)	2 (40 %)	5 (71 %)
BMI (kg/m^2)	24.8 ± 3.16	25.8 ± 2.4	22.5 ± 3.6	22.7 ± 2.8	25.5 ± 3.9
Smoking	23 (53 %)	13 (57 %)	1 (13 %)	4 (80 %)	5 (71 %)
Diabetes	9 (21 %)	6 (26 %)	2 (25 %)	0 (0 %)	1 (14 %)
Hypertension	25 (58 %)	16 (70 %)	4 (50 %)	2 (40 %)	3 (43 %)

BMI body mass index

Table 3 Summary of test performance parameters on a per-vessel level

	Atherosclerosis (%)	Vasculitis (%)	Dissection (%)	Any disease (%)
Sensitivity	95.1	90.9	100	94.4
Specificity	97.7	100	100	97.0
PPV	92.9	100	100	95.8
NPV	98.5	98.7	100	96.0

PPV positive predictive value, *NPV* negative predictive value

accuracy rate was 97.6 %. For the diagnosis dissection and for the diagnosis of vasculitis, parameters and accuracy were all 100 %. For the diagnosis of any disease, test performance measures were 97.2, 85.7, 97.2, and 85.7 % and the accuracy rate 95.4 %. Table 4 summarizes test performance measures on a per-patient level.

Discussion

In this study, we analyzed 43 consecutive patients who were referred for hr-bb-cMRI for the workup of cervical arterial disease of various causes. An expert panel, which had access to all available clinical and imaging information, the clinical course, and all laboratory results, determined a consensus diagnosis for every patient, which was used as the gold standard. MRI series were anonymized and presented to two independent readers who proposed a diagnosis both on a per-vessel and per-patient level. Overall, the accuracy rates were all above 95 % on a per-patient and on a per-vessel level for all disease entities, demonstrating that MRI is a powerful tool to differentiate between different cervical arteriopathies, as a first-line imaging tool.

No patient had to be excluded due to insufficient quality, showing that MRI can reliably be used for vessel wall imaging and differentiation of pathologies. In addition, for the specification of disease, our results show an excellent interobserver agreement both on a per-patient level (Cohen's $\kappa = 0.82$) and on a per-vessel level (Cohen's $\kappa = 0.83$), which further demonstrates that the proposed imaging criteria can be used successfully by different readers. Recently, Sun et al. reported a good to excellent interscan reproducibility of carotid MRI in patients with atherosclerotic disease, even in a multi-center setting with 3-T scanners of different vendors [13]. Consistent with this study, Bley et al. also reported a high interobserver agreement of cervical MRI in 64 patients with cervical giant cell vasculitis, with a Cohen's κ of 0.68 [14]. Finally, Naggara et al. reported excellent interobserver agreement in high-resolution MRI for the diagnosis of vertebral dissection ($\kappa = 0.88$) even at 1.5 T [15]. We confirm the findings of these previous studies which demonstrated a high interobserver agreement for presence/absence of one specific disease. However, our findings go beyond the positive findings of these manuscripts, showing not only that MRI alone is able to evaluate whether a specific disease is present, but that it is also able to differentiate between different cervical arteriopathies in most cases, being used as a first-line diagnostic modality. Of note, we were able to establish the correct diagnosis by MRI without any clinical information. Our study showed that this technique also yields very high NPVs for all arteriopathies, demonstrating that this technique is also suited to exclude the presence of cervical artery disease. On a per-patient basis, only one patient with mild atherosclerotic disease was falsely classified as disease free and one patient without any sign of vascular disease was falsely classified as suffering from mildly atherosclerotic disease. It is debatable whether small amounts of atherosclerotic plaques are significant for decisions on treatment strategies in a realistic clinical setting, especially in an older patient cohort where a high prevalence of mild atherosclerotic burden has been described [16].

In this study, the image protocol only covered the distal part of the common carotid artery. To cover the proximal common carotid artery is not standard due to the possibility of breathing artifacts and insufficient fat suppression. Our results show that this approach is sufficient for establishing the diagnosis.

While other diagnostic criteria such as clinical history, presenting complaint, or lab values might contribute to the final

Table 4 Summary of test performance parameters on a per-patient level

	Atherosclerosis (%)	Vasculitis (%)	Dissection (%)	Any disease (%)
Sensitivity	95.7	100	100	97.2
Specificity	100	100	100	85.7
PPV	100	100	100	97.2
NPV	95.0	100	100	85.7

PPV positive predictive value, *NPV* negative predictive value

diagnosis, the workup of cervical arteriopathies will routinely include imaging at some point. Several other imaging modalities have been used for the assessment of cervical artery diseases. CT angiography is a non-invasive imaging modality providing excellent information on vessel lumen and degree of stenosis. However, it is an examination with radiation exposure and the assessment of the vessel wall is limited in comparison to hh-bb-MRI, especially in the presence of vessel wall calcifications [17]. In particular, CTA is unable to detect plaque hemorrhage, a well-described feature of the vulnerable atherosclerotic plaque [6], and has difficulties to detect vessel wall hematomas in arterial dissection [18]. Although CTA is able to visualize the concentric wall thickening typically seen in vasculitis, it is unable to evaluate the inflammatory activity and has thus difficulties to differentiate between atherosclerotic disease and vasculitis. Ultrasound, including color-coded Duplex examinations, is a non-invasive modality without radiation exposure and no need of intravenous contrast agents. Limitations are the high dependency on the experience of the performing physician and that it is not possible to examine vessels that are behind bony structures; this makes it difficult or impossible to evaluate the distal parts of the internal carotid arteries and vertebral arteries. PET-CT with the use of radioactive labeled tracers is able to provide anatomical and functional parameters of arterial diseases. Although the radiation exposure of the examination is relative high, its low spatial resolution only allows for the assessment of larger vessels and specificity is comparably low especially when differentiating between chronic vasculitis and inflammation associated with atherosclerotic disease often seen in older patients [19].

Findings of this study strongly suggest that hr-bb-cMRI can be relied upon in the triage and diagnosis of patients presenting with unclear cervical arteriopathy or with recent cerebral ischemia and a suspicion for a vascular origin in the cervical region. Furthermore, this technique might be most helpful in the workup of patients presenting with ambiguous results from prior imaging studies or laboratory tests. In addition, the imaging review criteria established in our study might also be useful to differentiate between distinct intracranial arteriopathies in which other imaging tests more often are unable to establish a definite diagnosis.

Our retrospective, single-center study has several limitations. First, the patient cohort was quite inhomogeneous regarding age, gender, and risk factors and there was not a single other test applied as a gold standard. However, our patient cohort was recruited from patients continuously referred to undergo a cervical MRI and we consider these patients to be rather representative for the cohort in which this test could be considered. Furthermore, the inhomogeneity of the reference standard applied simply stems from the fact that currently, the imaging modalities used for detailed workup of cervical arteriopathies are based strongly on clinical suspicion. Until now, no imaging test exists which can reliably distinguish between the most common cervical arterial diseases.

Conclusions

In this study, we report a high interobserver reproducibility and a high diagnostic accuracy of hr-bb-cMRI for the workup of cervical arteriopathies both on a per-patient and per-vessel level. Both, positive and negative predictive values were over 95 % for all cervical arteriopathies on a per-patient analysis, suggesting that this technique might serve as a reference standard and might be used earlier in the clinical work-up patients with various suspected cervical arterial diseases. This might lead to a possible lower use of examinations with radiation exposure and a more rapid establishment of diagnosis followed by an effective treatment. Additional clinical studies are necessary to confirm that this high diagnostic accuracy holds true in a prospective study environment.

Compliance with ethical standards We declare that all human and animal studies have been approved by the Ethics Committee Ludwig-Maximilians-University Munich, Germany, and have therefore been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its later amendments. We declare that all patients gave informed consent prior to inclusion in this study.

Conflict of interest We declare that we have no conflict of interest.

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