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High Field Atherosclerotic Plaque MRI

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Abstract

Manifestations of atherosclerotic plaque in different arterial beds range from perfusion deficits to overt ischemia such as stroke and myocardial infarction. Atherosclerotic plaque composition is known to be associated with its propensity to rupture and cause vascular events. MRI of atherosclerotic plaque using clinical 1.5T scanners can detect plaque composition. Plaque MRI at higher field strengths offers both opportunities and challenges to improving the high spatial-resolution and contrast required for this type of imaging. This article summarizes the technological requirements required for high field plaque MRI and its application in detecting plaque components.

Keywords

Carotid plaque imaging; high field MRI; Atherosclerotic plaque composition

Introduction

Atherosclerotic plaque imaging is a branch of cardiovascular imaging whose main goal is to identify vulnerable plaque that poses increased risk of causing cardiovascular events. Plaque imaging has been extensively validated at 1.5T and has proven its utility in several natural history studies, treatment efficacy studies and multicenter clinical trials. Since its inception, plaque imaging techniques have also improved significantly. But the main imaging goals remain: to achieve high resolution images that are able to identify key plaque components such as lipid rich necrotic core, intraplaque hemorrhage, calcium, to measure plaque burden, and to detect defects of the luminal surface, such as disruption and fibrous cap conditions. Some of these imaging goals can be further improved by scanning at higher field strengths. This chapter addresses the opportunities, challenges, and current status of high field atherosclerotic plaque imaging.

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High-field plaque MRI

Plaque MRI requires a high SNR for acquisition for a number of reasons: 1) due to the small size of its imaging target, atherosclerotic plaque MRI needs to be acquired at high spatial resolution to faithfully characterize the morphology of the plaque; 2) to visualize the plaque on vessel wall, the bright luminal signal needs to be suppressed; 3) to accomplish large coverage scans in a clinical feasible time also demands a higher signal-to-noise ratio (SNR) to avoid compromised image quality.

Three areas of technological improvements can improve the SNR and contrast between vessel wall, lumen and the outer wall: scanner field strength, surface RF coils and vessel wall imaging sequences. Each of these areas is addressed below along with their respective challenges arising from high field imaging. Following this, advances in our knowledge of the atherosclerotic disease process using these new technologies are described. Throughout this chapter, 3T is considered as high field; 7T and above is considered ultra-high field.

High field MR scanners

Compared to lower field strengths, higher field strength promises higher overall SNR. Theoretical analysis predicts that the SNR of the MRI system will increase by 100% should the main magnetic field be doubled (e.g. from 1.5T to 3T). This increased SNR is the primary motivation for moving plaque MRI to high fields. Although the actual SNR improvement *in vivo* can vary for different applications^{1–4}, this overall improvement makes high field MRI a more preferable imaging platform for plaque imaging compared to 1.5T. The SNR gain can be traded for shortened imaging time, higher spatial resolution or a combination of the two depending on the imaging needs. Nevertheless, increased magnetic field strengths also represents new challenges, such as prolonged T1 relaxation time², increased field inhomogeneity, susceptibility, etc⁴.

Whole body MR scanners at 1.5T and 3T are now well established for vessel wall imaging. 3T provides an improved contrast-to-noise ratio of 1.4–2.4 times compared to 1.5T black-blood MRI^{5, 6}. Wide bore magnets are also desirable, since large patients are generally prone to atherosclerosis.

Fat suppression is necessary in vessel wall imaging to delineate the outer wall. Thus, field inhomogeneity can be challenging at higher field strengths for achieving good fat suppression. Good first-order shimming routines are often adequate for vessel wall imaging. In a few cases higher order shimming may be necessary. Newer MR systems are equipped with RF shimming capabilities and may prove useful for vessel wall MRI.

RF Coils

Body coil transmission is used for vessel wall imaging and is useful for uniform excitation and the large coverage needed for special blood suppression techniques. However, body coil reception does not provide high enough SNR for visualizing the vessel wall. Surface coils pick up signal from a relatively small area, but with increased sensitivity. Since the carotid arteries are relatively superficial, they can be imaged with surface coils to increase SNR. Surface coils with four, six and eight coil elements have been developed for use at 3T. Dedicated four element phased array coils enable high-resolution imaging at 1.5T⁷ and 3T⁸. Increasing the number of coil elements provides larger coverage. An eight element carotid coil not only provided a 1.7 fold SNR increase over a 4 element design but also provided increased coverage along the length of the carotid artery. Currently, carotid phased array coils with four, six and eight coil elements are available commercially on the major scanner platforms. Figure 1 shows the design of the eight element coil and its commercial

equivalent. Usually each coil element is read out through a separate RF channel. The noise picked up by the receive chain can be further reduced by digitizing the signal from the coil elements. Newer MR systems digitize the received signal directly at the coil thereby reducing noise picked up in each of the channels. Such systems can further improve the performance of these coils but require additional components on the coil to digitize the received signal. Improvements in both coil design and the RF receive chain allow plaque imaging with higher SNR and therefore enable higher spatial resolution to be attained. Such improvements will benefit vessel wall imaging in vascular beds such as coronary and intracranial vasculature where very high spatial resolution (<0.5mm in-plane) is required.

3D Black blood imaging sequences

Compared to its 2D counterparts, three-dimensional (3D) imaging sequences present a number of advantages for atherosclerotic plaque imaging. Benefiting from the extra phase encoding direction, 3D imaging sequence provides significant SNR enhancement as the imaging volume expands in the third dimension. This extra SNR advantage can be utilized to achieve isotropic resolution, as previous studies have shown that isotropic voxels can potentially reduce registration and segmentation errors⁹, as well as provide more reproducible quantitative measurements¹⁰ for vessel wall imaging. Despite these benefits, achieving high resolution 3D isotropic resolution *in vivo* is challenging. Depending on the field strength, achieving isotropic resolutions may require long scan times. As a result, many of the 3D implementations^{11, 12} on 1.5T have adopted anisotropic voxel size to accommodate clinical needs.

The improved SNR offered by high magnetic field strength provides a potential solution to this issue. Recently a 3D turbo spin echo with variable-flip-angle refocusing RF pulses (SPACE) technique was utilized to achieve high resolution isotropic ($0.72 \times 0.72 \times 0.72 \text{ mm}^3$) large coverage ($380 \times 374 \times 100 \text{ mm}^3$) peripheral artery imaging at 3T¹³. The whole volume can be acquired in 11.32min. A similarly configured 2D sequence, on the other hand, would need 20min to cover the same volume at a much lower slice direction resolution of 3mm.

Motion-sensitized driven equilibrium (MSDE)¹⁴ is a new imaging technique that can effectively suppress blood signal by dephasing moving spins in the blood. When combined with proper acquisition schemes, high temporal efficiency can be achieved. In only 2 minutes, the entire carotid artery tree can be imaged using a 3D MSDE Prepared Rapid Gradient Echo (3D-MERGE) sequence¹⁵ with high spatial resolution ($0.7 \times 0.7 \times 0.7 \text{ mm}^3$) and large coverage (250mm Foot-Head direction) (Fig.2). More importantly, recent research reveals that the 3D-MERGE sequence can not only provide plaque burden measurement, but can also be used to detect high risk plaque components if the parameters are properly optimized. Two separate studies have separately demonstrated the usefulness of 3D-MERGE to detecting lipid-rich necrotic core (LRNC)¹⁶ and intraplaque hemorrhage (IPH)¹⁷. These findings suggest that the optimization toward higher temporal efficiency plaque imaging does not essentially rule out its potential for simultaneous high risk plaque component detection.

Challenges and opportunities of high-field plaque MRI

Increased field inhomogeneity

The magnetic field inhomogeneity describes the level of field fluctuation in the image field of view. Two types of field inhomogeneities are present: the inhomogeneity of the main magnetic field (B₀ inhomogeneity); and the inhomogeneity of the transmission radiofrequency (RF) field (B₁ inhomogeneity). In high field MR systems, both fields are more susceptible to variations than at lower field strengths, especially for complicated

anatomical regions like the neck, which is a common target of plaque imaging. It is therefore more important to design new sequences to compensate for these inhomogeneities.

The MSDE black-blood imaging technique can provide robust blood suppression even in challenging anatomical regions¹⁴. It relies on the dephasing among moving particles to achieve black blood effect. Since it does not put any direct requirement on flow velocity like other BB techniques do, MSDE can suppress blood more effectively in regions of complex blood flow.

A practical problem with use of MSDE at high field is its sensitivity to B1 inhomogeneity. As shown in Fig. 3, when the B1 value drifts away from the nominal value (i.e. relative B1 drifts away from 1), significant signal drop can be observed on the MSDE sequence. At high fields SNR can vary across the field of view due to this B1 sensitivity.

To address this issue, an improved MSDE (iMSDE) sequence was proposed¹⁸. In the iMSDE sequence, the original 90-180-90 RF chain was replaced by the MLEV-4 pulse train (Fig. 4), which is known to be more robust to B1 inhomogeneity. Almost no noticeable signal drop could be observed on the iMSDE pulses on Fig. 3 even when significant inhomogeneity is present (towards the peripheral of the image).

By further incorporating an improved gradient design to compensate for eddy currents, the iMSDE sequence significantly improved image quality when applied to carotid artery plaque imaging applications (Fig. 5). The vessel boundaries on the MSDE image are indistinct due to the lower SNR, whereas the artery can be clearly delineated on the iMSDE image.

Long T1 effect

Prolonged T1 relaxation time is another well-known effect observed in high field MR imaging. As reported before¹⁹, significantly higher T1 relaxation times of different tissue were measured at 3T than at 1.5T. This increased T1 relaxation should be factored into sequence pulse sequence parameter optimization to achieve the desired contrast at high fields²⁰.

Longer T1 also helps to improve the efficiency of tissue saturation in MR images since it will take a longer time for the tissue to recover. Time of flight (TOF) technique is a commonly used technique that can generate time-efficient MR angiography data on major arteries without the administration of contrast agents²¹. TOF images visualize flowing blood signals by saturating the static tissue with repetitive RF pulses. On higher magnetic field strengths, static tissues tend to be saturated more effectively, leaving the background signal more uniformly suppressed⁴, compared to the more prominent signal variation on 1.5T images²². This efficient background saturation provides higher luminal contrast and better lumen boundary delineation on 3T scanners, making them a more favorable imaging platform for TOF angiography.

In addition to T1 lengthening, T1 value separation among tissues has also been found to increase¹⁹, allowing tissues to be more easily separated at a higher magnetic strengths. In atherosclerotic plaque imaging, differentiating tissue components based on their respective T1/T2 values is an important approach in detecting high-risk plaque components. Compared to the T2 values, the prolonged T1 relaxation time provides a unique way to better detect high risk components on T1 weighted images. One example is the detection of intraplaque hemorrhage (IPH) tissue, which usually presents a high signal on T1 weighted images. The increased T1 weighting on 3T systems makes it more reliable to detect IPH in vivo. Compared to the multicontrast approach of combining a number of T1w sequences for IPH

identification on 1.5 T²², it is possible to use a single T1-weighted sequence to achieve the same goal at 3T^{23–25}.

At 3T, Magnetization Prepared Rapid Acquisition Gradient Echo (MP-RAGE) sequence has been shown to provide higher sensitivity and specificity in IPH detection when compared to the traditional approaches²⁶. A recently proposed Slab-selective Phase-sensitive Inversion Recovery (SPI) sequence²⁵ provides even higher tissue contrast between IPH and vessel wall, as well as between vessel wall and lumen, compared to MP-RAGE. With its improved IPH contrast, the SPI sequence has the potential to further improve IPH detection accuracy in atherosclerosis patients.

Increased susceptibility

Susceptibility effect describes the degree of magnetization of an object in response to the external magnetic field. On MR images, a stronger susceptibility effect usually causes a stronger local magnetic field disturbance, leading to a more pronounced signal void in the vicinity. In high field MRI, stronger susceptibility artifacts are expected when compared to lower field strengths⁴. This effect has been found to make plaque components such as calcification more easily identifiable.

A benefit of the increased susceptibility on 3T is the use of susceptibility weighted imaging (SWI) to separate lumen and wall signal, thus achieving vessel wall imaging without suppressing blood signal²⁷. Since no flow velocity requirement is posed by this technique, the SWI image can theoretically achieve satisfactory lumen/wall separation in even challenging circumstances, making it a potential alternative for plaque size measurements.

Specific Absorption Rate (SAR)

Although higher field strength provides a number of benefits for atherosclerotic plaque imaging, it has also been known to cause faster energy accumulation in the human body, reaching the specific absorption rate (SAR) limit more quickly. The major impact on imaging protocol design due to SAR increase is reduced time efficiency: a higher energy deposition during a certain amount of time forces a delay of the next RF pulse – to lower the time averaged energy deposition – thus making the overall time efficiency drop significantly.

A potential solution for the issue is the utilization of parallel transmission²⁸, which, instead of using only 1 RF transmission source, uses two or more sources to achieve more homogenous energy deposition across the FOV. This technique is able to shorten spatially selective RF pulses in two or three dimensions, therefore minimizing the overall SAR value²⁸.

Invivo 3T plaque MRI

Criteria for identification of plaque components at 1.5T^{29–31} have been validated against histology. These criteria are generally applicable at 3T with some differences due to higher field strength characteristics described earlier. Here we discuss in detail, studies that focused on differences between 1.5T and 3T plaque imaging and how MRI of each of the major plaque components is benefited at 3T.

Comparison to 1.5T

3T MR scanners are widely available. Advantages of 3T over 1.5T have been described for MR imaging in several clinical applications³². An SNR improvement of 2X is expected at 3T over 1.5T. Several investigations have reported improvements close to this theoretically

expected SNR increase. Cury et al reported an increase of 1.8, 1.7 and 1.6 times on PDw, T2w and T1w vessel wall imaging³³. Similarly Yarnykh et al found 1.7, 1.8 and 1.5 times improvement on the same contrast weightings⁵. Other studies^{6, 34} found greater than 2X improvement but with slightly different sequence parameters and phased array coil configurations at the two different field strengths. Notably blood suppression was equally effective at both field strengths leading to increased contrast-to-noise ratio and therefore better delineation of the carotid vessel wall at 3T. The delineation of the outer wall may also be improved at 3T due to greater effectiveness of spectral fat saturation methods at higher field strengths. Cury et al reported better fat suppression at 3T leading to better vessel wall visualization, likely due to increased separation of fat and water peaks at 3T and thereby improved performance of spectral fat saturation³³. Together these studies demonstrate the potential benefits of higher field strength for vessel wall imaging. The improved SNR can be translated into faster scanning by reducing the number of averages required. The increased SNR at 3T allows reducing the number of averages from two⁵ (Fig 6). Alternately the resolution can be improved at the expense of SNR. Currently a combination of these approaches is preferred so that in-plane resolution of 0.5mm is routinely possible at 3T with short scan times.

Once MR images are available, they must be processed and measured for quantitative plaque burden assessment. Reproducibility of plaque burden assessment at 3T was similar to 1.5T. Quantitative measurement of plaque burden showed a coefficient of variation (CV) of 4.2% for wall volume and 3.02% for percent wall volume at 3T³⁵. These were comparable to CVs of 5.8% for wall volume and 3.2% for percent wall volume at 1.5T using similar MRI protocols and measurement methods³⁶. The SNR improvement over 1.5T does not necessarily translate into improved reproducibility likely due to measurement errors secondary to patient positioning⁹ as well as different imaging parameters between field strengths.

Methods of plaque composition measurement developed at 1.5T are also applicable at 3T with some differences. Underhill et al showed that there was good agreement between the two field strengths for calcification ($k=0.72$), lipid-rich necrotic core ($k=0.73$)³⁷. The agreement for hemorrhage was slightly lesser ($k=0.66$) with more hemorrhage being detected at 1.5T than 3T (14.7% vs 7.8%). This is attributable to the lengthening of T1 relaxation at high fields thereby reducing the signal from hemorrhage when using similar imaging parameters between the two field strengths (Fig 7). Increased susceptibility at 3T may also be a contributing factor to reduced sensitivity for hemorrhage at 3T. Due to the increased susceptibility, calcifications measured larger at 3T (Fig 7). To overcome these problems new sequences have been developed at 3T. MP-RAGE or SPI sequences are added for highly sensitive detection of hemorrhage^{38, 39}. Ultrashort echo time (UTE) sequences are being explored for accurate quantification of calcification^{40, 41}. Automated methods of plaque composition measurement developed for 1.5T have also been shown to be applicable at 3T (Fig 8). Intraclass correlation coefficient (ICC) for area measurements of lipid core, hemorrhage, fibrous tissue and calcification ranged from 0.89 to 0.98⁴².

Assessment of disease

Advanced atherosclerotic plaque is composed of several plaque components such as a lipid-rich necrotic core (LRNC) with overlying fibrous cap (FC), intraplaque hemorrhage (IPH), calcification (CA) and loose matrix (LM) interspersed among fibrous tissue framework. These major components of the plaque can be identified by MRI. The qualitative and quantitative measurement of these plaque components have been extensively validated and reported at 1.5T^{30, 43, 44}. In this section we focus on studies that have benefited from the technical improvements or higher SNR at 3T.

Intraplaque hemorrhage

The association between IPH of carotid atherosclerotic plaque and ischemic brain symptoms has been identified by many studies^{45–48}. IPH is visible on T1 weighted images as a hyperintense signal due to short T1 relaxation time of methemoglobin, a breakdown product of hemoglobin. While methemoglobin could be identified using TOF at 1.5T, it could not be reliably identified at 3T using TOF⁴⁹ (Fig 6). In a comparison study between 1.5T and 3T field strengths³⁷ using TOF, 32/218 sections showed IPH at 1.5T while only 17/218 sections showed IPH at 3T. No IPH that was not detected at 1.5T was detected at 3T. In addition the size of IPH measured lesser at 3T although the difference was not statistically significant. Use of a highly T1 weighted scan such as MP-RAGE^{38, 50} at 3T can improve the sensitivity and specificity for IPH²⁶ (Fig 9). When small IPH (<2.81 mm²; 3 pixel diameter) or calcified IPH was excluded, sensitivity and specificity were 80%, 97% for MPRAGE; 70%, 92%, for T1w fast spin-echo; and 56%, 96% TOF with histology as gold standard²⁶. The sensitivity further increased for larger IPH. Improvements of the MPRAGE technique with suppression of luminal signal (Slab-selective Phase sensitive Inversion recovery²⁵ or SPI), can further improve the sensitivity of MP-RAGE for IPH detection. Such inversion recovery techniques perform better at 3T for short T1 species with increased SNR due to the higher field strength. An alternative method is use of pre-contrast mask image in contrast-enhanced MRA studies to identify IPH⁵¹. Since this sequence is also highly T1 weighted, IPH can be identified as a hyperintense signal. However sensitivity may be reduced due to lack of fat suppression with the pre-contrast mask technique.

IPH has been shown to accelerate plaque growth and is associated with cerebrovascular events and post-surgical brain infarcts. Patients with IPH had an increase in percent change in wall volume (6.8% vs –0.15%) and LRNC volume (28.4% vs –5.2%) over 18 months compared to controls with similar levels of plaque at baseline⁵². They were also more likely to have new IPH (43% vs 0%). In a follow-up study, baseline IPH was strongly associated with subsequent symptoms over 3 years (hazard ratio 5.2)⁴⁸. While these 1.5T studies used TOF and T1w spin echo images to identify IPH, studies at 3T using MP-RAGE for IPH detection have reported similar findings. A hazard ratio of 9.8 was reported for MP-RAGE detectable IPH baseline over a follow-up period of 28 months⁴⁶. In an asymptomatic group of 91 subjects with 16–79% stenosis by ultrasound, 6 events occurred (HR 3.6) with all occurring on the side with IPH⁴⁷.

Lipid-rich necrotic core

Identification of LRNC at 3T is similar to 1.5T. Good agreement (Cohen's kappa= 0.71) was found for identification of LRNC between the two field strengths³⁷. There was no difference in LRNC volume measurements between the two field strengths. At 3T, sequences such as 3D-MERGE can also contribute to the identification of LRNC¹⁷. Higher SNR at 3T allows use of diffusion weighted imaging (DWI) for identification of LRNC⁵³. While these new 3T techniques are still under development, spin-echo based black blood MRI has been used to follow small changes in LRNC over time. Zhao et al serially imaged subjects with coronary artery disease or carotid disease were treated with atorvastatin in the CPC (Carotid Plaque Composition) study at 1 year intervals for 3 years⁵⁴. Percent LRNC area reduced from 8.4% to 5.2% over 3 years. Over the observation period, percent LRNC reduced from 14.2 % to 7.4% when slices with normal wall were excluded with 3.2%, 3.0% and 0.91% reduction rates in the first, second and third years, respectively⁵⁵. The corresponding Percent Wall Volume also decreased by 3.8% over 3-years with 0.3%, 3.6% and 0.1% reduction rates in the first, second and third years, respectively.

Other plaque components

Calcifications at 3T could be identified to the same extent as 1.5T (Cohen's kappa 0.72) but the size measurements were increased due to higher susceptibility at 3T³⁷. Therefore spin-echo sequences are preferable over gradient echo sequences for calcium measurement at 3T. Newer UTE techniques may improve size measurement of calcium at higher field strengths⁴¹. Fibrous cap identification and measurement may be improved at 3T due to higher SNR and improved coil designs but is yet to be demonstrated. Loose matrix tissues can be identified with similar sensitivity and specificity on both field strengths but their contribution to plaque vulnerability is currently unknown.

Ultra-high Field Imaging

Along with the gradual adoption of 3T systems as the mainstay of plaque imaging, MR systems with ultra-high field strength, such as 7T or even higher, are now available. To take the advantage of the even higher SNR offered by such systems, a number of studies have been conducted to explore the feasibility of plaque imaging on these ultra-high field systems.

A crucial step in conducting plaque imaging on high field scanners is development of proper transmit-receive coils since 7T scanners are not equipped with transmission body coils. As reported by different groups, both 8-channel⁵⁶ and 16-channel⁵⁷ bilateral carotid coils have been developed for 7T systems with excellent delineation of the carotid artery. The 16-channel coil is also equipped with a 6-channel transmit coil array to achieve more homogenous and energy efficient B1 transmission⁵⁷. As a result, the energy intense TSE sequence has also been successfully implemented on the 7T system for high resolution carotid artery wall imaging.

Another challenge of 7T imaging is the availability of a dedicated black blood imaging technique. Although a number of BB techniques have been developed for 1.5T/3T systems, they cannot be used at 7T because they all require a global transmission coil for blood nulling. When the body transmission coil is unavailable, as is the case on most 7T systems, blood suppression will be nullified by the strong in-flow effect. To overcome this limitation, a Local excitation Black Blood Imaging (LOBBI) sequence was proposed⁵⁸. The essence of this sequence is to suppress blood signal by destroying its phase coherence similar to MSDE but after blood is excited by the excitation RF pulse. By doing so, the time gap between blood suppression and data acquisition is greatly shortened, thus minimizing the in-flow effect. As shown in a flow phantom experiment (Fig. 10), LOBBI is the only technique can suppress blood signal successfully with a local transmission coil.

Besides the development in novel coil and pulse sequences, the high SNR at 7T has found application in new target vessels not commonly imaged at lower field strengths. A recent work using a 7T scanner demonstrated the feasibility of intracranial artery vessel wall MRI in vivo⁵⁹. Excellent delineation of the circle-of-willis vessel wall imaging was achieved at an isotropic 0.8mm resolution. This isotropic resolution allows for the free reformation of the targeted vessels, which is necessary for tortuous targets like intracranial arteries.

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Summary

Although the main focus of atherosclerotic plaque MR imaging at present has been the carotid artery due to ease of imaging and availability of endarterectomy specimens for validation, many of the techniques presented in this chapter have already been translated to other vascular beds like peripheral arteries and/or intracranial arteries at 3T. Ongoing efforts are aimed at translating similar techniques into coronary artery wall imaging. Like other cardiac MR applications, clinical application of coronary wall imaging at 3T requires further technical developments to overcome the challenges of the increased magnetic field inhomogeneities and the large motion of coronary arteries with the cardiac cycle.

In summary, the increased SNR at high-fields benefits atherosclerotic plaque imaging despite increased undesired issues like increased field inhomogeneities. Particularly, 3D isotropic imaging of atherosclerotic plaque only becomes clinically feasible with the extra SNR brought by high-field MR scanners. The higher SNR, reduced scan time, increased through plane resolution and new scan techniques promise faster translation of plaque imaging to the clinics and new applications such as coronary vessel wall imaging in the near future.

Key Points

- Increased SNR at 3T has allowed new 3D isotropic sequences with large coverage to be developed with improved slice resolution compared to 1.5T
- Criteria for identification of plaque components at 1.5T are also applicable at 3T with minor differences for intraplaque hemorrhage and calcification.
- Signal from intraplaque hemorrhage is reduced on TOF compared to 1.5T due to longer T1 relaxation times at 3T. Dedicated sequences such as MP-RAGE can improve both sensitivity and specificity for hemorrhage detection.
- Calcifications are larger at 3T due to increased susceptibility effects.
- High field plaque imaging is possible in multiple arterial beds such as carotids, peripheral arteries and aorta. Intracranial vessel wall imaging is also improved at 3T. Challenges such as motion, field inhomogeneities, susceptibility and SAR are yet to be overcome for routine coronary plaque MRI.

Diagnostic Checklist

The following morphological features represent important information which can be obtained through high field atherosclerotic plaque imaging:

- Atherosclerotic Plaque Size
- Intraplaque Hemorrhage (IPH)
- Lipid-Rich Necrotic-Core (LRNC) size
- Luminal Stenosis/ulcer
- Calcification

Fig 1. Eight element carotid phased array coil for use at 3T: (a) shows the four elements on one side. (b) High resolution (0.27 mm² in-plane resolution T1w MRI with excellent delineation of the thin carotid walls. (c) Commercial version of the eight element coil with integrated head rest. Adapted with permission from (8).

Fig. 2. 3D isotropic high resolution ($0.7 \times 0.7 \times 0.7 \text{ mm}^3$) carotid artery image acquired with 3D-MERGE sequence. Arrow on axial reformat shows a small piece of calcification. Vessel wall boundaries are clearly visible on all reformats. Reprinted with permission from (15).

Fig. 3. Comparison of simulated signals as functions of relative B1 inhomogeneity between MSDE and iMSDE sequences. The iMSDE sequence provides consistently higher signal intensity compared to the MSDE sequence, and the signal improvement becomes more pronounced when rB1 value drifts further away from unit. Adapted with permission from (18).

Fig. 4. Pulse sequence diagram of MSDE (a) and the iMSDE (b) preparations. The adoption of the MLEV-4 pulse in the iMSDE sequence significantly reduced the sequence's sensitivity to the B1 inhomogeneity. Adapted with permission from (18)

Fig. 5. Significantly improved carotid artery vessel wall delineation on the iMSDE image (right) compared to that on the MSDE image (left). Adapted with permission from (18).

Fig 6.

Axial carotid MRI sequences obtained at 1.5T and 3T using the same sequence parameters. Note the improved SNR at 3T with NEX=1 with improved vessel wall delineation (arrow) and appearance of small structures as nerve roots (arrowheads). With NEX=2 at 1.5T some of the SNR loss can be offset but comes at expense of increased scan time. Adapted with permission from reference (2).

Fig 7.

Serial matched sections of the same subject scanned at 1.5 and 3T. Note that calcifications (double arrows) appear larger at 3T (columns a-c). A smaller calcification in the internal carotid (column d) is more easily detected at 3T due to higher SNR. Intraplaque hemorrhage (arrowhead, column A) is visible at 1.5T but not seen at 3T using TOF. Reprinted with permission from (4).

Fig 8. Carotid boundaries were manually drawn for the same subject scanned at 1.5T and 3T. The last column shows plaque components automatically identified and contoured by the MEPPS algorithm (ref) within the carotid boundaries. (LRNC – yellow, loose matrix – purple, IPH – red). Adapted with permission from (42).

Fig 9.

IPH in a moderately calcified plaque on three T1 weighted sequences: TOF, T1 weighted fast spinecho and MP-RAGE: IPH is hyperintense on all three sequences but most prominent by MP-RAGE which also corresponds to actual extent of IPH on histology (arrow). Adapted with permission from (26).

Fig. 10.

Pulse sequence diagram of the LOcal excitation Black Blood Imaging (LOBBI) sequence (left panel) and a comparison of flow suppression capabilities among different BB techniques (right panel). Right panel shows baseline image (a), DIR (b), MSDE (c) and LOBBI (d) images. Flow on only the LOBBI image is successfully suppressed.

Table

Table with recommended MR sequences and protocols

Recommended protocol for high-field plaque MRI					
Parameters	Scan type				
	1	2	3	4	5
3D MERGE					
Sequence	TFE	TSE	FFE	PSIR	TSE
Image mode	3D	2D	3D	3D	2D
Scan plane	Coronal	Axial	Axial	Axial	Axial
TR (ms)	10	4000	20	13	800
TE (ms)	4.8	50	4	3	10
Flip Angle (°)	6	N.A.	20	15	N.A.
FOV (cm)	25×16×3.5	14×14	14×14×3.2	14×14×3.2	14×14
Resolution (mm)	0.7×0.7×0.7	0.55×0.55	0.55×0.55×2	0.55×0.55×2	0.55×0.55
Slice thnk (mm)	N.A.	2	N.A.	N.A.	2
Blood suppression	MSDE	MDIR/MSDE	Sat-band for venous flow	N.A.	QIR/MSDE
Fat suppression	Yes	Yes	No	Yes	Yes

Please refer to the text for detailed description of each sequence