In Vivo T2-mapping and Segmentation of Carotid Artery Plaque Components using Magnetic Resonance Imaging at 1.5T

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Abstract

Atherosclerosis is regarded as a lifestyle disease, where artery lumen is reduced due to deposition of calcium and fatty materials such as cholesterol and triglyceride. These plaques can become unstable and rupture, resulting in life threatening cardiovascular events. Multicontrast cardiovascular magnetic resonance (CMR) has been used on 1.5T and 3T scanners to identify carotid plaques and study their morphology in vivo, however it does not provide quantitative information. Carotid arteries of healthy volunteers and patients with known atherosclerosis were imaged on a 1.5T Siemens Aera MRI scanner. Standard imaging protocol consisted of a TOF sequence to localize the carotid bifurcation, followed by the acquisition of T1-, T2- and PD-weighted images to assess the plaque qualitatively. Finally, T2 relaxation time mapping was performed through the plaque center using a Multiple-Spin-Echo sequence. Custom software was written in MATLAB to generate T2 maps and discriminate different plaque types, confirmed by multicontrast CMR. This study showed that T2 mapping of atherosclerotic plaque is possible on a 1.5T scanner. Measurements demonstrated the ability to discriminate plaque components on T2 maps, which are in good agreement with conventional multicontrast CMR.

1. Introduction

Acute ischemic strokes are commonly associated with unstable carotid atherosclerotic plaques that can be detected using various modalities. Typically contrast angiography is the golden standard in evaluation of the severity of atherosclerotic carotid stenosis. Unfortunately this method provides only information about the change in luminal wall profile, giving no insight into the plaque composition; therefore no morphological information can be gathered using this method [1]. The possibility to conduct intravascular ultrasonography (IVUS) enabled physicians and scientist to look further into the plaque composition and quickly has become the standard reference method for imaging normal and atherosclerotic coronary and peripheral vessel wall morphology [2].

In contrast to the above-described methods, magnetic resonance angiography (MRA) has been looked into as a viable non-invasive alternative. The three-dimensional time-of-flight (TOF) MRA method is available on all modern clinical MR systems and has proven to be accurate in assessing degree of stenosis [3]. Using multicontrast cardiovascular magnetic resonance (CMR), the morphology and composition of atherosclerotic plaques can be characterized and classified [4]. The idea behind multicontrast CMR is that following a series of co-registered images, acquired with different sequence parameter setting (reflecting relaxation time and proton density weighting), plaque components can be discriminated using their relative signal intensities. Using so-called T1- T2- and PD-weighted images, identification of major plaque components such as lipid-rich necrotic core (LNRC), calcification, intraplaque hemorrhage (IPH) and fibrous tissue is possible, and has been previously validated by histology [5,6]. Table 1 describes how the discrimination of plaque components is carried out using multicontrast CMR.

Table 1. Plaque components perception on images acquired using multicontrast CMR approach.

Plaque component	T2w	T1w	PDw	TOF
Hemorrhage	+/-	++	+/-	++
Lipid core	+/--	--	++	+/-
Necrosis	+++	--	++	--
Fibrous tissue	+/-	+/-	++	-
Calcification	--	--	--	--

Tissue contrast is relative to muscle; with FAT SAT.

Multicontrast CMR for carotid plaque assessment is unfortunately a non-quantitative method and usually requires time-consuming interpretation. What is more, due to inherent differences between imaging sequences, the MR scanner hardware (even within the same manufacturer/model), it is difficult to compare results from *in-vivo* studies [4], as relative contrast between

tissues might change quite significantly.

Relaxation time mapping has been proposed as an alternative method of plaque characterization that would enable true quantitative information about the plaque components in addition to the physicians' qualitative assessment. An important advantage is that mapping provides direct information about the tissue properties, allowing standardization of this method between various manufacturers. Furthermore, quantitative mapping has the potential to provide fast and repeatable information, including automatic segmentation and classification of plaques according to the CMR-modified AHA scheme [5]. The concept of relaxation time mapping in cardiac studies has been a hot topic with regard to T1 mapping of the heart, where this method enables assessment of tissue viability without administering gadolinium-based contrast agents [7] or T2* mapping, where it provides validated quantitative information about iron overload in thalassemia patients [8]. Relaxation time mapping with regards to the heart is difficult due to its movement and time constraints, while the same idea applied to carotid artery plaques encounters the problem of high-resolution requirement due to the size of imaged structures. One recently published paper by Biasiolli et al. [9] has tackled *in-vivo* T2 mapping of the carotid plaque using a 3 T MRI system. These high field systems have become increasingly available in diagnostic centers, but still many cardiologists prefer the older 1.5 T MRI systems. Although these provide typically lower signal to noise ratio (SNR), lower magnetic field provide better contrast between tissues of similar relaxation time characteristics. Studies have been conducted that show the differences in image quality of 1.5 vs. 3 T systems with regards to carotid plaque imaging [10]. As it was expected, the SNR, contrast to noise ratio (CNR), general image quality, scan times and spatial resolution have all benefited from the higher field. However, the general conclusion of this study was that both 1.5 T and 3 T scanners could be used in clinical studies concerning plaque morphology.

The purpose of this study was to investigate the possibility of performing *in-vivo* quantitative T2 measurements and segmentation of the carotid plaque components in atherosclerotic patients at 1.5 T.

2. Materials and methods

Carotid arteries of a healthy volunteer and patients with indications of atherosclerosis were imaged on a 1.5T Siemens Aera scanner (Siemens Healthcare). All subjects gave informed written consent. The healthy volunteer served for optimization of all sequences with regards to time, SNR and resolution. A standard phased-array head-neck Siemens RF coil was used for imaging. The multicontrast CMR protocol commenced with a non-contrast 3D TOF sequence, used to localize the carotid bifurcation and occlusion site. Based on the TOF images, a series of cross-sectional slices covering the plaque and perpendicular to the carotid arteries flow were acquired using a fast spin echo (FSE) sequence with parameters (multicontrast protocol parameters are listed in Table 2) enabling T1-, T2- and PD- weighting. Multicontrast images were acquired using Double-Inversion-Recovery (DIR, TI=330ms) and cardiac gating in the end diastole to prevent pulsatile artifacts. Additionally chemical shift fat saturation (FAT SAT) was used to suppress the signal from subcutaneous and perivascular fat.

Table 2. Sequence parameters used in this study.

	T1w	T2w	PDw	3DTOF
Readout seq.	FSE	FSE	FSE	GRE
TR [ms]	1R-R	3R-R	3R-R	23
TE [ms]	11	48	12	4.57
ETL [ms]	11	19	8	n.a.
Flip angle [deg]	180	180	180	20
Averages	1	1	1	1
FOV [cm]	133x80	210x280	210x280	200x151
Matrix	212x128	336x448	336x448	314x640
In plane resol.	0.6x0.6	0.6x0.6	0.6x0.6	0.3x0.3
No slices	12	12	6	156
Slice thick [mm]	2	2	2	1
Flow sup.	DIR	Inflow	Inflow	Veins
Scan time [min]	4:33	5:32	6:36	6:03

Finally, single slices centered through the plaque were acquired using a built in Multiple-Spin-Echo sequence, branded by Siemens as Spin-Echo-Multi-Contrast (SE_MC). This sequence is based on the Carr-Purcell-Meiboom-Gill (CPMG) sequence in which a 90 deg excitation pulse is followed by a train of 180 deg refocusing pulses to generate multiple spin echoes at every TR, where every echo is phase-encoded to the same k-space line in different k-space planes, resulting in a set of images with different TE times. Multi-SE parameters were TE = 14, 28, 42, 56, 70, 84, 98, 112 ms, TR = 2 R-R intervals, field of view (FOV) = 160 × 120 mm^2 and matrix size = 256 x 192. In plane resolution was 0.625 mm square. Total acquisition time for single average was 4:02 min. Slice thickness (2 mm) and pixel bandwidth (130 Hz/pix) were the same for Multi-SE and FSE. The echo train used in Multi-SE sequence was defined assuming an expected $T_2 \sim 50$ ms for normal carotid wall, which corresponds to a transverse magnetization half-time $T_2 * \ln(2) \sim 35$ ms. The last TE used was

approximately equal to 3 half-life times. Partial Fourier imaging was used to collect 5/8 of k-space (160 phase-encoding steps) and reduce the acquisition time of single-slice Multi-SE to circa 320 R-R intervals. The quality of Multi-SE and multicontrast images was assessed after each scan by an experienced reviewer (T. M.-J.), who decided when carotid wall and plaque were not clearly visible.

Image intensity of every respective voxel in the Multi—SE image series corresponds to the mono-exponential magnetization T2 relaxation curve. A region of interest (ROI) was drawn on the first image in the series so to encompass the vessels and surrounding muscle tissue. The signal intensity (SI) of the first echo will not fit in the exponential decay curve, being purely a primary echo, while others are stimulated, therefore it was not used for fitting purposes. For every ROI voxel the T2 decay curve $SI = \beta \cdot e^{-TE/T2}$ was therefore fitted to 7 SIs collected at different TEs (β includes the effect of proton density, T1 weighting, coil sensitivity, signal amplification and other factors). The regression model used for T2 calculations consisted of a nonlinear monoexponential fit carried out by the Levenberg-Marquardt algorithm, initialized by an expected value of T2=50 ms and β=250. To ensure significant results, data points at long TEs, where the plaque was hard to differentiate from the background (defined with SNR<2), were discarded; 95% confidence intervals for the exponential curve (Figure 1) and for the fit parameters were estimated. Finally, only voxels with significant T2 and β estimates (R^2>0.90) were accepted for generating T2 maps used for segmentation, while disregarded voxels have been filled by interpolation of the T2 values of the nearest neighbors.

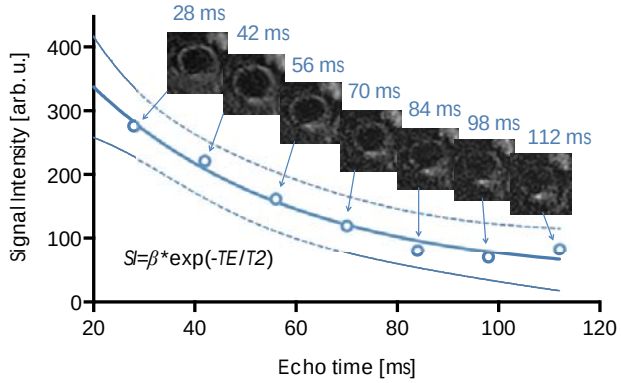

Figure 1. Signal intensity decay with changing echo time.

Inner and outer vessel wall have been manually drawn on the Multi-SE series images. Voxels were manually selected from all the T2 maps to represent a specific tissue using multicontrast CMR as a guide, i.e. they were chosen inside a plaque component identified on multicontrast CMR. In order to help match the corresponding plaque features, multicontrast images were co-registered, so that inner and outer vessel boundaries detected on T1W images could then be superimposed on PDW and T2W images. Mean ± SD of the T2 values of voxels classified as LRNC, fibrous tissue and recent IPH were calculated. The algorithms were implemented in MATLAB.

3. Results

Patients with suspected atherosclerotic plaques in the carotid arteries underwent a multicontrast CMR with additional T2 mapping sequence imaging protocol using a 1.5 T Siemens Aera MR system. The used image post-processing enabled the generation and segmentation of carotid plaques T2 maps.

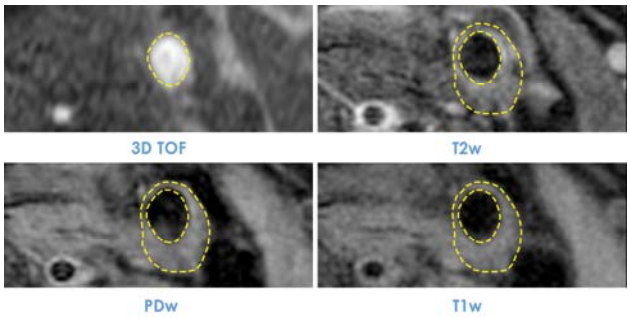

Figure 2. Multicontrast images of one of the carotid arteries as seen on TOF, T2w, T1w and PDw images.

Segmentation was carried out using k-means clusters, assuming 3 classes of tissues. Using this method, mean ± SD of the T2 values of voxels classified as LRNC (black), fibrous tissue (grey) and recent IPH (white) were calculated to be 24(8), 48(12) and 80(30) ms, respectively.

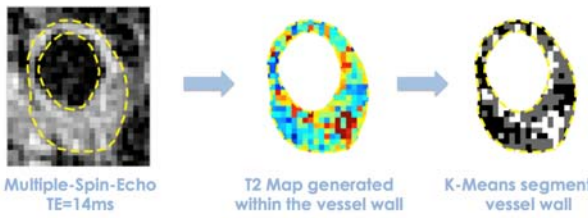

Figure 3. Scheme of the mapping and segmentation procedure used in this work. The first image in the echo train, was used to depict inner and outer walls of the arteries, followed by calculation of the T2 maps and consequently the segmentation into tissue types.

4. Summary

These quantitative results have been generally in good correlation with the standard qualitative assessment based on multicontrast images, proving that relaxation time

mapping of the carotid plaques is possible at the 1.5 T field strength. It must be emphasized that it is always necessary to look at the goodness of fit measures, before including calculated T_2 values into further analysis. This is especially true, when working at 1.5 T, where the images acquired with longer TE have significantly deteriorated quality to the point the vessel walls are indistinguishable from the surrounding noise. Furthermore, due to weaker magnetic field it is best if more signal averages are used, in order to raise the SNR values of the images.

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