3D T_1 and T_2 mapping of the carotid vessel wall using variable α and variable TE iMSDE black-blood imaging

Bram F Coolen[1], Henk Smit[2], Dirk HJ Poot[2,3], Gyula Kotek[2], Stefan Klein[2], and Aart J Nederveen[1]

[1]*Department of Radiology, Academic Medical Center Amsterdam, Amsterdam, Netherlands,* [2]*Biomedical Imaging Group Rotterdam, Erasmus MC Rotterdam, Netherlands,* [3]*Imaging science and Technology, Delft University of Technology, Delft, Netherlands*

Introduction Recent studies on MR imaging of carotid atherosclerosis have shown strong correlations between plaque composition and subsequent cerebrovascular events [1]. The assessment of plaque composition, including lipid core, calcifications, fibrous tissue and hemorrhage is currently performed using multi-contrast weighted imaging, in which each component has a unique combination of hyper- and hypo-intense signal on T_1w, T_2w and proton density weighted images. However, due to its qualitative nature, the reproducibility of this method will be strongly affected by several factors, such as coil positioning, sequence parameters and observer dependent variability. Alternatively, quantitative MR imaging is capable of directly measuring the structural tissue parameters (T_1, T_2) and has been shown to have high reproducibility in various applications [2]. This therefore serves as an attractive method for use in longitudinal studies or when comparing results between different research sites. Additionally, this would provide the possibility to define threshold values for automatic segmentation purposes. Unfortunately, no protocol for combined T_1 and T_2 measurements of the vessel wall has been presented so far, due to the need for blood suppression imaging and high spatial resolution. **Aim:** we present a protocol for T_1 and T_2 mapping of the carotid vessel wall with full 3D coverage and high isotropic resolution (0.7 mm). The protocol was evaluated using phantom experiments and simulations. Feasibility of the approach was demonstrated in a healthy volunteer.

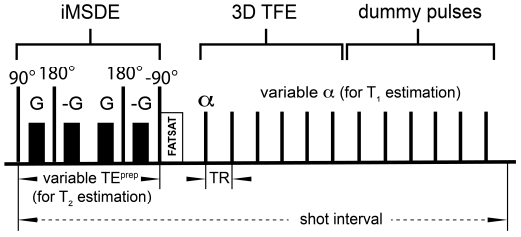

Fig. 1: Sequence for 3D black-blood carotid T_1 and T_2 mapping. After each TFE read-out, steady-state conditions are restored by a series of dummy pulses. T_1 is estimated from scans with different flip angle α, while T_2 is estimated from scans with different TE^{prep}. Parameter values are mentioned in the 'Method' section.

Methods *Sequence* – Fig. 1 shows the proposed sequence for carotid 3D T_1 and T_2 measurements, which is an extension of a previously reported method for black-blood carotid 3D T_1 mapping [3]. The overall sequence is based on a 3D iMSDE prepared black-blood segmented k-space TFE sequence [4]. This uses motion-sensitized gradients around non-selective 180° -pulses to create intravoxel dephasing of flowing tissue. An important feature of the sequence is the addition of dummy pulses after signal acquisition to restore the steady-state signal perturbed by the iMSDE preparation. This allows for variable flip angle T_1 analysis. Because the iMSDE preparation has inherent T_2-weighting, a variable TE^{prep} scheme at a fixed flip angle can be used for T_2 estimation, also meaning that one high flip angle scan is shared for both T_1 and T_2 estimation. In the current protocol, a total of four scans were used to calculate both T_1 and T_2-maps using the parameters in Table 1. Note that the number of dummy pulses needed to reach steady-state conditions is dependent on the flip angle and is allowed to vary between scans. Other sequence parameters were: TR/TE = 10/3.65 ms, TFE factor = 32; venc = 4 cm/s, FOV = 156×156×25 mm (coronal view), resolution = 0.7×0.7×0.7 mm. Total imaging time of all four scans was 15 min. *Phantom/Simulation experiments* – Phantoms were prepared based on Carrageenan gels, for which T_1 and T_2 could be changed by adding $GdCl_3$ and agarose, respectively [5]. These were used to compare T_1 and T_2 estimations of the proposed method with those obtained from gold standard sequences. Using the phantom T_1 and T_2 values, Bloch equations were used to simulate possible errors in T_1 and T_2 quantification. *In vivo measurements* – A healthy volunteer (40y) was measured in a Philips 3T Ingenia MR scanner using a dedicated 8-channel carotid coil (Shanghai Chenguang Medical Technologies, Shanghai, China). All scans were registered to scan 2 using custom registration software based on published methods [6]. *Analysis* – T_1 mapping was performed by fitting the variable flip angle data (scan 1-2) to the linearized form of the Ernst equation [2], while T_2 mapping was performed by fitting a mono-exponential decay function of the form $M_0e^{-TEprep/T2}+B$ to the variable TE^{prep} data (scans 2-4).

scan	α [°]	TE^{prep} [ms]	N^{pulses} [-]
1	4	11.5	180
2	15	11.5	80
3	15	26	80
4	15	45	80

Table 1: Sequence parameters. T_1 and T_2 mapping is performed using scans 1-2 and 2-4, respectively. N^{pulses} is the sum of TFE and dummy pulses.

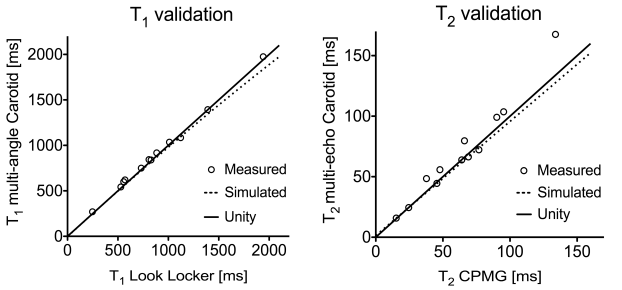

Fig. 2: Phantom and simulation results. Comparison of T_1 and T_2 values obtained with the proposed carotid artery specific method and gold standard reference methods.

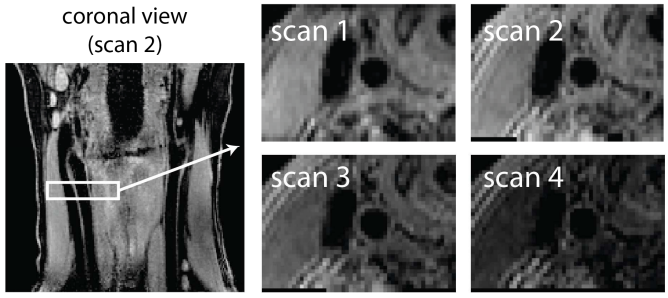

Fig. 3: *in vivo* anatomical data. (left) Coronal view shows full 3D coverage of the carotid artery. (right) Axial views from a reference region for each T_1w and T_2w scan. Note the clear decrease in signal for subsequent T_2w scans (2-4).

Results and Discussion Fig. 2 shows very good agreement between T_1 and T_2 values obtained with the carotid specific sequence and gold standard methods, while simulations also indicate that good estimations are expected in the entire physiological range. Although T_2 is slightly higher compared to CPMG measurements, it is actually known from literature that the latter may underestimate high T_2 values [7]. *In vivo* anatomical images for all protocol scans and corresponding T_1 and T_2 maps are shown in Fig. 3&4, respectively. Blood suppression was very efficient, resulting in good delineation of the vessel wall. This is also apparent in the quantitative maps, suggesting good registration of the separate anatomical scans. T_1 values (mean ± sd) for vessel wall and muscle tissue were 980 ± 311 and 1412 ± 172, respectively, while corresponding T_2 values (mean ± sd) were 43 ± 22 and 33 ± 6. This is in line with published values. More specifically. carotid artery values agree well with those obtained from either ex vivo measurements [8] or 2D *in vivo* T_2 mapping [9]. With regard to the high standard deviation of carotid T_2 values, we believe this will improve by increasing SNR through compressed sensing approaches or improved coil design. Moreover, when imaging patients with thicker vessel walls and carotid plaques, partial volume effects will naturally be less prominent.

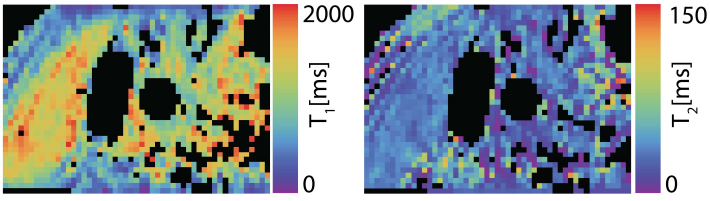

Fig. 4: *In vivo* carotid T_1 and T_2 maps corresponding to the images in Fig. 3.

Conclusion We presented a novel protocol using an adapted iMSDE black-blood sequence, capable of performing 3D T_1 and T_2 measurements in the carotid artery. In future research, we will evaluate the reproducibility of the method and investigate its performance for atherosclerotic plaque characterization.

[1] Takaya et al. Stroke 2006 [2] Deoni et al. Neuroimage 2008 [3] [3] Coolen et al. Proc. ISMRM 2013 [4] Wang et al. J Magn Reson Imaging 2010 [5] Ikemoto et al. Med Phys 2011 [6] van 't Klooster et al. Med Phys 2013 [7] Coolen et al. Magn Reson Med 2013 [8] Degnan et al. Magn Reson Imaging 2012 [9] Biasiolli et al. J Cardiovac Magn R 2013