# 3D carotid wall $T_1$ quantification using variable flip angle 3D Merge with steady-state recovery

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**Introduction** In atherosclerosis MR imaging, methods to assess vessel wall plaque burden and more specifically plaque vulnerability have been studied extensively [1-5]. Importantly, it has been shown that plaque composition is a key factor in determining the risk for future cardiovascular events [4]. Using multi-contrast MR protocols (T1w, T2w, PDw), plaque components, such as lipid core, hemorrhage and calcifications can be distinguished by their different contrast weightings. However, this is mostly a qualitative analysis, which in terms of reproducibility may suffer from differences in sequence parameters, variations in coil sensitivity and inter/intra-observer variation. Quantitative imaging, such as $T_1$ relaxometry, may overcome these issues and could serve as an important tool in longitudinal studies. Unfortunately, no current $T_1$ mapping method has been applied to the carotid wall *in vivo*, mostly due to incompatibility with black-blood suppression, which is crucial for delineation of the vessel wall. **Aim** We propose a variable flip angle 3D black-blood imaging protocol allowing $T_1$ mapping of the carotid artery. Simulations, phantom studies and *in vivo* measurement were performed to test the feasibility of this approach.

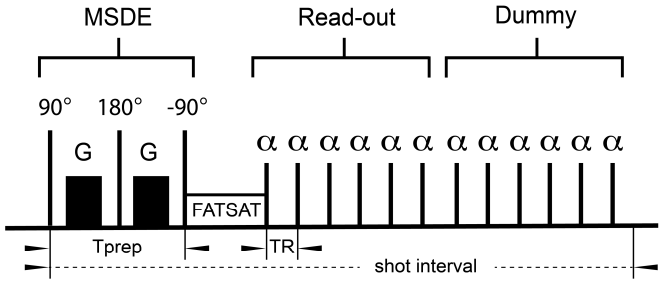


**Figure 1:** Sequence for 3D carotid $T_1$ mapping. Black-blood is created by a MSDE preparation using motion-sensitized gradients. Dummy pulses following read-out restore steady-state conditions for variable flip angle (α) $T_1$ analysis. Parameter values are mentioned in the 'Method' section.

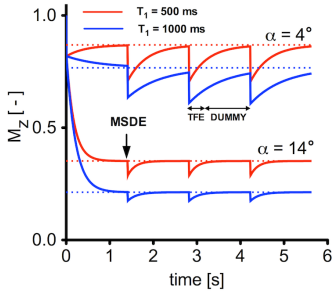


**Figure 2:** Simulated $M_z$ magnetization-time curves (solid) for different α and $T_1$ ($T_2$ = 50 ms [8]) and their theoretical steady-state values (dotted). nTFE / nDummy = 30/145.

**Methods** *Sequence* - In Figure 1, the proposed sequence for carotid 3D variable flip angle T1 measurements is shown, which is based on a 3D MERGE black-blood segmented k-space TFE sequence with fat suppression [5]. A limited number of TFE pulses (nTFE = 30) is used to minimize $T_1$ modulation, followed by a number of dummy pulses (nDummy) to maintain steady-state conditions required for $T_1$ quantification. *Simulations* - Figure 2 illustrates the theoretical $M_z$ magnetization behavior of the sequence obtained through Bloch equations with different flip angles and $T_1$ values. Apart from blood suppression, the MSDE module unfortunately also causes $T_2$ weighting of the signal, which disturbs steady-state conditions significantly. Simulations show that the number of dummy pulses needed to restore steady-state is lower for higher flip angles. Therefore, to minimize imaging time, two flip angles of α = 4° and α = 14° with a different ratio of nTFE/nDummy were used: 30/145 and 30/45, respectively. Other parameters were as follows: TR/TE = 8/3.6 ms, Tprep = 10 ms, venc = 5 cm/s, FOV = 144×144×27 mm (coronal), Pixel size = 2.0×0.6×0.6 mm, total imaging time (both angles) = 8 min. *Phantom measurements* – The Eurospin phantom (Diagnostic Sonar, Ltd) was used to compare $T_1$ estimations of the proposed method with a gold standard Look Locker IR sequence. *In vivo measurements* – A healthy volunteer was measured in a Philips 3T Ingenia scanner using flexible coils on both sides of the neck. Images with different flip angles were registered, after which $T_1$ mapping was performed by fitting the variable flip angle data to the linearized form of the Ernst equation [6].

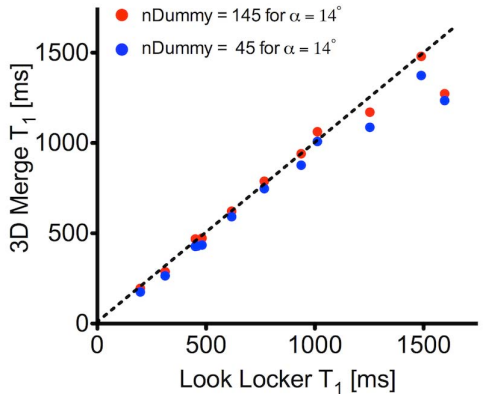


**Figure 3:** Phantom measurements. Comparison of $T_1$ estimations between the proposed 3D Merge–based method and a gold standard Look-Locker IR sequence. A slight underestimation of $T_1$ occurs at high $T_1$ values.

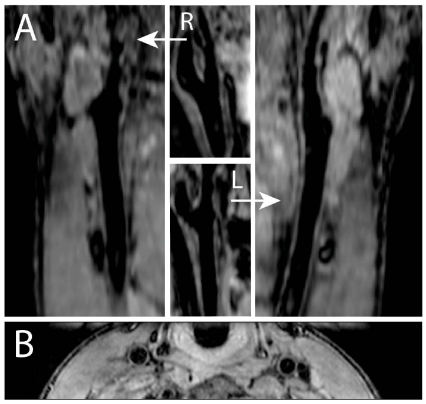


**Figure 4:** *In vivo* black-blood coronal (A) and transversal (B) views of the carotid artery reformatted from a 3D dataset. The right (R) and left (L) carotid bifurcations in (A) are magnified.

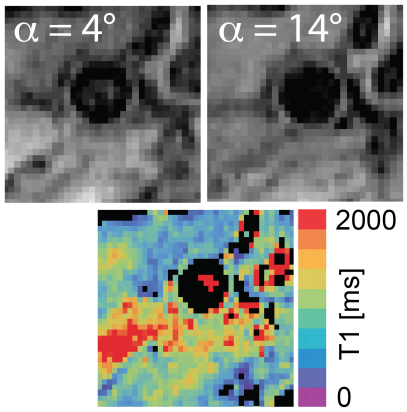


**Figure 5:** Example of variable flip angle data (top) and a resulting carotid artery $T_1$ map (bottom), corresponding to the right carotid artery in Figure 4.

**Results and Discussion** Figure 3 shows phantom results illustrating the accuracy of $T_1$. Perfect agreement with gold standard Look Locker IR measurements was obtained for $T_1$ values up to 1000 ms. For higher $T_1$ values, a slight underestimation occurred due to incomplete steady-state recovery, in accordance with simulations (not shown). As expected a decrease in Ndummy for α = 14° had little effect on $T_1$ estimations. *In vivo* measurements are shown in Figures 4 and 5. Although 'Tprep' of the MSDE module was short, a high degree of blood saturation was obtained with accurate delineation of the carotid wall (Fig. 4B). $T_1$ maps calculated from variable flip angle data (Fig. 5) showed little blurring compared to the anatomical images, justifying pixel-wise $T_1$ estimation. Carotid wall $T_1$ values were 869±224 ms, whereas $T_1$ in a muscle reference ROI (see Fig. 4B) was 1091±136 ms. The latter is somewhat lower compared with literature values, although this was expected when considering findings from phantom experiments. Increases in SNR from advanced carotid coil designs and the use of acceleration techniques will allow for a more favorable nTFE/nDummy pulse ratio, thus further improving $T_1$ estimation.

**Conclusion** We presented to our knowledge the first method capable of performing 3D $T_1$ measurements in the carotid artery. We foresee many applications for atherosclerotic plaque characterization and quantification of various plaque components.

**References** [1] Fayad et al. *Circ Res* 2001 [2] Cai et al. *Circulation* 2002 [3] Chu et al. *Stroke* 2004 [4] Hellings et al. *Circulation* 2010
[5] Balu et al. *Magn Reson Med* 2011 [6] Coolen et al. *NMR Biomed* 2010 [7] Stanisz et al. *Magn Reson Med* 2005 [8] Biasiolli et al. *J Magn Reson Imaging* 2011