Fast Relaxation Time Mapping in Human Carotid Artery Wall Using Black Blood DANTE 2D Turbo Spin Echo

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Introduction: Quantitative evaluation of $T_1$ and $T_2$ is very useful in clinical detection and classification of atherosclerotic plaques in imaging of human carotid artery wall. Because of the small size of arteries and the local field inhomogeneity, caused by the complex composition of plaque and susceptibility differences between blood and vessel wall, a fast and robust black blood (BB) imaging technique is required to deliver high resolution $T_1$ and $T_2$ maps on pixel-by-pixel basis. Candidates for fast $T_1$ and $T_2$ mapping are the DESPOT1 and DESPOT2 imaging techniques. However, these techniques cannot be used for $T_1$ and $T_2$ mapping of human carotid arteries due to their inherent blood signal enhancement. In addition, sensitivity to field inhomogeneity and magnetization transfer effects further compromise the use of DESPOT2 in $T_2$ mapping. DANTE (Delays Alternating with Notation for Tailored Excitation) pulse trains are a rapid series of low flip angle RF pulses interspersed with gradients. It has previously been demonstrated that during application of DANTE as preparation pulses for 2D turbo spin echo (TSE) imaging, the longitudinal magnetization of flowing spins is largely attenuated in contrast to static tissue, whose longitudinal magnetization is mostly preserved.

In this work, we first derived a highly simplified linear equation $M\dot{=}M_0\{1-1/2(T_1/T_2)^2\}$ from the longitudinal Bloch equation at steady state case in the presence of DANTE pulses. This equation was then verified to be applicable in the case that the DANTE pulse train is interspersed with readout modules. Finally, preliminary in-vivo BB experiments for $T_1$ and $T_2$ mapping demonstrate that DANTE-TSE has the potential to be applied as a fast (3 measurements in 10 minutes with 39 slice coverage), high resolution (0.6×0.6×2mm) and robust (insensitive to susceptibility in both preparation and readout module) imaging tool for relaxation time mapping of human carotid artery walls.

Theory: First the simplest case is considered in Fig. 1a where a single infinite long DANTE pulse train with gradient $G$, interspersed between RF pulses, is applied. The gradient $G$ must be larger than $2\pi/\gamma r_\Delta t$ to avoid banding artefacts (i.e. to render them subpixel or sub-slice thickness). In the equations shown in Fig. 1a, $\gamma$ is the gyromagnetic ratio, $r_\Delta t$ is duration between DANTE pulses, $\alpha$ is the DANTE flip angle and $\Delta t$ the pixel size or the slice thickness. $M_{SS}$ is the longitudinal signal at steady state when the number of pulses, $N_p$, is a large number. Under the condition of $G/2\pi r_\Delta t > \alpha$, the DANTE pulse train is considered to be small compared with the tissue $T_1$ and $T_2$, the integration of the equation can be solved and simplified into a linear equation $M_{SS} = M_0\{1-1/2(T_1/T_2)^2\}$. The more practical case, where the DANTE pulse train is interspersed with readout modules, is considered in Fig. 1b. It was found that when $T_\text{R}$, the readout module duration (typically <100ms), is small compared with the tissue $T_1$, the equation derived in Fig. 1a may be still valid.

Methods: A Siemens 3T Verio along with a 4-channel neck coil was used for experiments. A healthy volunteer (male, 24-35 years) underwent DANTE prepared TSE. Minimally, three measurements are required to yield both $T_1$ and $T_2$ maps. Measurements 1 and 2, implemented with DANTE $\alpha=$4$^\circ$, 8$^\circ$, and 10$^\circ$, respectively, and a TSE echo time of 19ms. These two measurements can generate a $T_1/T_2$ ratio map. Measurement 3 was undertaken with TE=60ms and a DANTE $\alpha=$4$^\circ$. Pixel-based calculation of images from Measurements 1 and 3 yield a $T_2$ map. From these data a $T_1$ map can also be calculated. To verify the derived linear equation in-vivo, additional measurements were implemented with DANTE $\alpha=0^\circ, 2^\circ, 6^\circ$ along with a readout TSE TE=19ms. For all images a matrix of 256×256×39 was used with FOV 150mm, yielding 0.6×0.6×2mm resolution. Each measurement took 3 minutes (turbo factor=7, bandwidth/Px=391Hz, $T_E$=70ms, DANTE $N_p=32$, $r_\Delta t=1$ms, and a gradient $G_z=18$mT/m, $ipat=2$, NEX=2).

Results: Bloch equation simulations according Fig. 1b, were implemented under the assumed parameters shown in Fig. 2 as an initial verification of linear equation. The solid lines in Fig. 2a show the longitudinal signal of static tissue with different DANTE $\alpha$. The blood signal is shown as dashed lines demonstrating that when $\alpha=4^\circ$ the blood signal may be ignored. Extracted static tissue signal from these Bloch simulations is shown in Fig. 2b (blue circles). For comparison, the red crosses in Fig. 2b are calculated from the linear equation with varying $\alpha$. This shows good agreement between Bloch simulation and the prediction of the simplified equation. For in-vivo assessment, $T_1$ and $T_2$ maps of the carotid artery wall are shown in Fig. 3a and 3b, respectively. They are created from the three image measurements described in Methods. In order to demonstrate the linear relationship of true tissue signal versus $\alpha$ signal from the muscle ROIs shown in Fig. 3 (red circles) was extracted from measurements with $\alpha=0, 2, 4, 6, 8^\circ$ all with TSE TE=19ms. The fitting results in Fig. 4 show that the $T_2/T_1$ ratio of muscle is 31. Given that the $T_2$ in the ROI is determined to be 40 ms, this implies a $T_1$ of 1240 ms. Independent single-slice inversion recovery $T_1$ measurements determined $T_1$ at the same location as 1108ms, which agrees reasonably with our fitting results.