Theory-based single-point T₁ mapping for quantitative analysis of first-pass cardiac perfusion MRI: a validation study

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Introduction: Quantitative analysis of first-pass contrast-enhanced cardiac perfusion MRI requires a conversion of the T₁-weighted signal-time curve to contrast agent (Gd-DTPA) concentration-time curve. For this purpose, a theory-based single-point T₁ measurement method has been proposed and validated in phantoms at 1.5T [1-2]. The specific choice of the k-space ordering of the TurboFLASH readout can modulate the effect of B₁ variation, particularly at 3T, on the accuracy of the T₁ measurement [3]. In this work, we i) investigated the sensitivity to B₁ variation of the single-point T₁ mapping method, depending on its k-space acquisition order (linear or centric) and ii) validated in vivo the single-point T₁ mapping method in the left ventricle (LV) of the cavity and myocardium during contrast enhancement.

Methods: A saturation-recovery TurboFLASH sequence was implemented on a 3T whole-body MR scanner (Siemens; Tim Trio). Images were acquired with the following parameters: FOV = 320mm × 262mm, slice thickness = 8mm, matrix = 144 × 94, TE/TR = 1.24/2.4 ms, flip angle = 10°. TSENSE with acceleration factor 2, and effective saturation pulse [4]. The saturation-recovery time delay (TD) was 10/50 ms and total image acquisition time = 136/176 ms for the linear and centric k-space trajectories, respectively. The effective longitudinal magnetization at the center of k-space was calculated as a function of T₁, using the Bloch equation, as previously described [1]. A proton density-weighted image was acquired in the first heartbeat, with flip angle = 5° and without the saturation pulse, in order to normalize the image signal. A theoretical relationship was thus obtained between the normalized signal and T₁. TDs were chosen so that linear and centric sequences had a similar signal-T₁ theoretical relationship. Note that for the pulse sequence parameters used in this study, the normalized signal for T₁>1000ms is less than 5% of equilibrium magnetization, indicating that the signal-to-noise ratio (SNR) at pre-contrast is inadequate for the single-point T₁ method. Therefore, pre-contrast T₁ measurements were performed using a multi-point T₁ mapping sequence to ensure accurate T₁ measurement. Reference T₁ measurements were performed at nominal B₁ calibration with a multi-point saturation recovery TurboFLASH sequence with variable TD and a centric k-space trajectory. A least square linear regression was used to fit the 10 points on the saturation recovery curve. First, to investigate the effect of B₁ variation, 6 dilutions of Gd-DTPA (Magnevist) in water (T₁ [48–1100] ms) were imaged for each k-space trajectory (linear or centric) with the excitation flip angle ranging from 40 to 120% of nominal 10°. Second, the accuracy of the single-point T₁ measurements using the optimal centric k-space trajectory, as determined by the phantom experiment, was assessed in vivo in 4 healthy volunteers (35±12 years old). A basal short-axis plane of the heart was imaged at 9 time points with the single-point and reference multi-point acquisitions: pre-contrast, 5, 10, 15, and 20 min post first injection (0.1mmol/kg) of Gd-DTPA, and 5, 10, 15, and 20 min post a second injection of Gd-DTPA. Reference T₁s were fitted from 7 data points: no saturation and TDs from 100-600 ms (100ms steps).Contours for the myocardium and left ventricular (LV) cavity were drawn manually (Fig.2.A). Measured T₁s were converted to Gd-DTPA-concentrations ([Gd]) with the following equation: [Gd] = (1/T₁-1/T₁\text{baseline}) / kGd, assuming fast water exchange condition [5] and T₁ relaxivity (kGd) of 3.8L/mmol/s [6-7], and T₁\text{baseline} measurement with the multi-point fit to ensure its accuracy.

Results: Compared with a linear k-space trajectory, a centric k-space trajectory was found to be less sensitive to clinically relevant B₁ variation at 3T in phantoms (Fig.1). Consequently, the centric k-space trajectory was validated in vivo. A good linear correlation was found between the reference and single-point T₁ measurements in the LV cavity and wall (Fig.2.B, R=0.97, p<0.001), as well as between the corresponding Gd-DTPA concentrations ([Gd]) (Fig.2.C, R=0.98, p<0.001). Bland-Altman analyses showed an increasing error in the single-point measurements for longer T₁ values, likely due to the correspondingly lower SNR. The underestimation observed for long T₁ is also likely related to apparent signal increase due to Rician noise bias.

Conclusion: We have validated the single-point T₁ mapping sequence against the multi-point T₁ mapping sequence in vivo. Compared with a linear k-space trajectory, a centric k-space trajectory has the advantage that it requires a longer TD to achieve adequate SNR, and it yields slight edge enhancement, due to high-pass filtering effects in the k-space. Comparative advantages of the centric k-space trajectory are that it is relatively insensitive to B₁ inhomogeneities, inflow effects, and refocusing of residual transversal magnetization from imperfect radio-frequency spoiling. Therefore, the modeling of the signal is simpler for the centric k-space ordering than for the linear k-space ordering. The single-point T₁ mapping pulse sequence with centric k-space trajectory is thus promising for quantitative analysis of first-pass cardiac perfusion MRI.


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