Ultradense sampling of FID and SE signals using an interleaved multiple gradient echo sequence for improved T2* mapping

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Introduction
T_2* mapping is employed for quantification purposes in many research fields including functional MRI (BOLD effect)[1,2], bone densitometry[3,4], SPIO-labeled cellular imaging[5,6] and imaging of therapeutic agents, e.g., holmium-loaded microspheres (HoMS) in local radiation therapy[7,8]. Typically, T_2* relaxometry is performed by sampling of the MR signal with multiple gradient echoes. In this study we present an interleaved multiple gradient-echo (IMGE) sequence which allows for ultradense sampling of either a FID or a SE. The proposed method will be shown to provide a complete characterization of signal decay curves per pixel as well as the accurate determination of a wide range of T_2* values down to the sub-millisecond range. In particular this sub-millisecond range becomes relevant considering the increasing interest in high field MR and T_2* agents (SPIO's), which yield very short T_2* values.

Methods- *Imaging:* Sampling of FID and SE signals was done using an EPI readout with removed phase encoding blips. The echo spacing (ES) between consecutive gradient echoes was set to 1.08 ms. Ultradense sampling of FID and SE signals was achieved by shifting of the complete gradient readout train and acquisition window over N consecutive sub-millisecond intervals[6,9] (Fig. 1). This resulted in N+1 images separated by an effective echo spacing (ES*) of the interleaved sequence of ES*=ES/N, where N denotes the number of intervals. An effective ES* of 0.12 ms was achieved by taking N=9. Other imaging parameters: gradient readout train=15; FOV=176x176 mm^2; matrix= 128^2; slice thickness=10mm. For sampling of the FID: TR/TE/α/Tacq = 20 ms/ 9,6 ms/ 25º/ 47 s. For sampling of the SE: TR/TE/α/Tacq = 100 ms/ 25 ms/ 90º/ 2:46 min. *Phantom experiments:* Two agarose (2%) gel phantoms containing dilution series with HoMS concentrations ranging from 0 to 7 mg/ml were created to provide distinctly different and widely ranged R_2* values (r_2*$_{[HoMS]}$ = 86.8 ±3.5 s^{-1}.mg^{-1}.g)[8]. The baseline relaxation rate (R_2*) of phantom A was determined by the agarose gel matrix resulting in an R_2*=28 s^{-1}. By adding MnCl2.4H2O to the gel matrix the baseline relaxation rate of phantom B increased to 469 s^{-1}. Phantom A was used to sample both FID and SE, phantom B to sample FID signals only. *Data analysis:* Data analysis was performed using Matlab. Data points with signal intensity higher than the mean offset plus twice the standard deviation of the noise were included in the analysis. To verify the validity of a mono-exponential fitting model the FID and SE signal intensities were presented on a logarithmic scale (Fig. 2c and d).

Results and Discussion- Ultradense sampling of FID and SE signals yielded detailed signal decay curves (Fig. 2a and 2b) for a wide range of R_2* values. These curves were used to study signal decay characteristics. The offsets seen in both the FID and SE signals in Fig. 2 originate from Rayleigh distributed noise and are accentuated even more by averaging over the ROI. The peak of the SE signal (Fig.2b and d) is lowered, presenting non-monoexponential signal behavior, which might be caused by diffusion effects or macroscopic gradients. This signal behavior makes the SE signal less suitable for quantification based on a simple signal model. Fig. 2c shows that the FID signal decays mono-exponentially which is therefore used for T2* mapping. The calculated R_2* map of the phantom is shown in Fig.3. The determined R_2* values of both dilution series are shown in Fig 4. The range of calculated R_2* values was 28-1085 s^{-1} and the HoMS relaxivities were r_2*= 90.0±1.5 s^{-1}.mg^{-1}.g and r_2*= 88.1±0.7 s^{-1}.mg^{-1}.g, which is in good correspondence with the literature[8].

Conclusion- The modified interleaved multiple gradient-echo sequence presented in this work allows for accurate determination of a wide range of T2* values (<1-35ms) by ultradense sampling of the FID with an arbitrary sampling density. The densely sampled FID and SE signals allow very detailed assessment of signal decay characteristics and frequency distributions as well as validation of experiments with numerical simulations of magnetic field distortions caused by (super-)paramagnetic particles such as (U)SPIO's and HoMS.

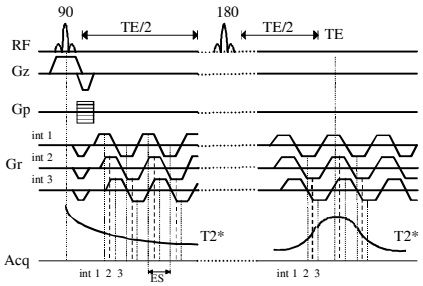

Figure 1. The IMGE sequence, shown for both FID and SE sampling.

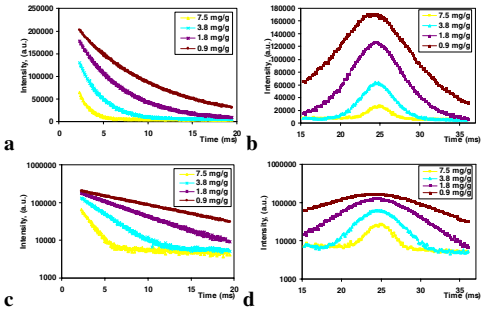

Figure 2. Ultradensely sampled FID (**a**) and SE (**b**), acquired using the proposed IMGE sequence. On a logarithmic scale the FID (**c**) shows monoexponential behavior above the noise. The SE (**d**) shows non-monoexponential behavior.

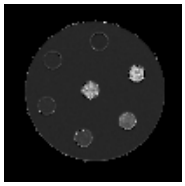

Figure 3. R2* map of gel phantom B containing the HoMS dilution series with MnCl2 added.

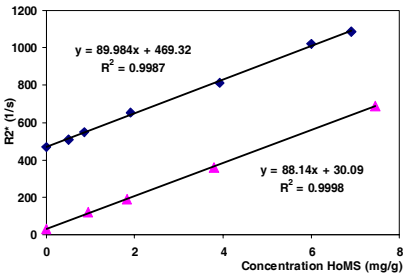

Figure 4. R2* values of HoMS dilution series with (squares) and without (triangles) MnCl2 added.

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