Interleaved Slice Excitation for Echo-Shifted Acquisition of Orthogonal Proton Resonance Frequency Temperature Images

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Introduction

In thermal therapy techniques such as laser-induced interstitial thermotherapy (LITT), precise monitoring of the induced temperature changes is mandatory for a safe and effective treatment. Thermal therapies highly benefit from MR guidance, as MR imaging enables excellent target identification and additionally allows for completely non-invasive temperature measurements. The most widely used method for temperature mapping employs the shift of the proton resonance frequency (PRF) with temperature [1]. To measure these frequency changes, gradient echo techniques are used to acquire phase images [2] for continuous treatment monitoring. As the temperature induced frequency change is very small (temperature sensitivity, α = 0.01 ppm/K), long echo times are required (10-30 ms), which limits the repetition time (20-50 ms). However, long TRs lead to long acquisition times especially for conventional gradient echo pulse sequences (FLASH), so that complete spatial target coverage with multi-slice imaging becomes challenging.

When long echo times are used in conventional gradient echo sequences, the available time between RF excitation and data readout is only partly filled with the encoding gradients. Recently, a novel slice-interleaved imaging sequence has been presented [3], which enables highly time-efficient consecutive excitations and readouts of parallel slices. In this work, this imaging strategy was modified to achieve a time-efficient interleaved acquisition of two orthogonal slices in order to provide control over the heated region in all three spatial directions.

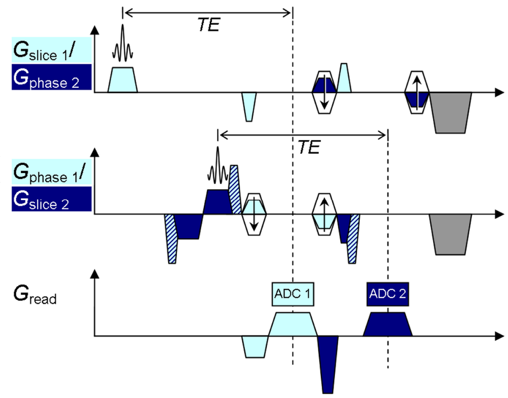

Fig 1: Timing diagram of the interleaved excitation and readout technique for acquisition of 2 orthogonal slices. The gradients are adjusted to realize the same TE for both slices.

Materials and Methods

The interleaved excitation and readout technique for time-efficient acquisition of two orthogonal slices was implemented on a clinical 1.5 T whole body MR scanner (Siemens Symphony, Erlangen, Germany). The timing diagram of the MR pulse sequence (Fig. 1) shows the similarity to echo-shifted techniques [3-5]. Both imaging slices use the same readout direction G_{read} whereas the directions of slice-selection and phase encoding gradients are interchanged (shown here in light and dark blue). The zeroth momentum of $G_{slice\ 2}$ is balanced to avoid erroneous dephasing effects of the MR signal during readout of the first echo (ADC 1). Unwanted signal contributions during readout of the second echo (ADC 2) are minimized by spoiling $G_{slice\ 1}$. Furthermore, additional crusher gradients (shaded in Fig. 1) are applied along the slice selection direction of slice 2, to avoid unintended rephasing of $G_{slice\ 2}$ by subsequent application of $G_{phase\ 1}$. Spoiler gradients are finally used to suppress unwanted stimulated echoes.

The pulse sequence was initially tested in a LITT experiment with *ex vivo* porcine liver. A 2.5×2.5×5 cm^3 piece of liver was placed in between two plastic containers filled with phantom liquid (Gd-DTPA/H_2O: 1/800) to ensure mechanical stability during the experiment. A water-cooled LITT applicator (Δt_{laser} = 80 s, P_{laser} = 20 W; Nd:YAG, λ = 1064 nm, Dornier, Germany) was penetrated to the center of the tissue sample. The two slices, axial and coronal, were centered on the diffuser tip of the laser fiber. Temperature images were acquired prior, during and after laser irradiation (TR/TE = 20/10 ms, BW = 510 Hz/Px, FA = 15°, FOV =200×200 mm^2, thick: 5 mm, matrix: 128×128, TA_{tot} = 2.6 s). Temperature maps were calculated from complex phase difference images and corrected for baseline drifts and potential temporal phase wraps.

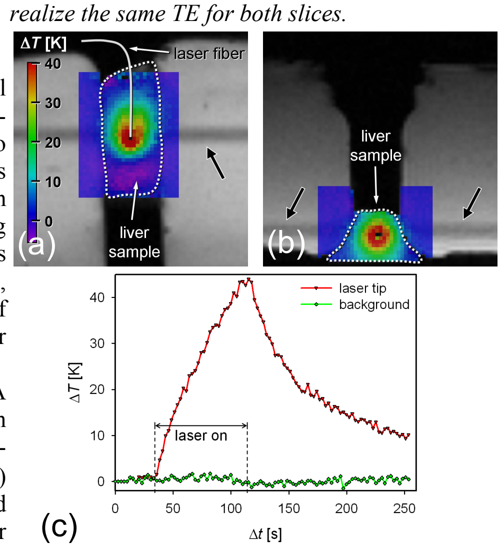

Fig. 2: Coronal (a) and axial (b) temperature maps. Temperature time curve (c) indicates temperature increase up to about 45 K close to the tip of the laser fiber.

Results and Discussion

With the specified TE of 10 ms, the interleaved excitation and readout technique allowed for a minimal TR of about 15 ms (spoiling time: 1 ms). Compared to a sequential excitation and readout with a conventional gradient echo sequence (TR_{min} ≈ 12 ms), the temporal resolution was improved by approximately 38%. No image artifacts due to unwanted signal contributions from the orthogonal slice were found. A narrow band of signal void (reduction by 35%, black arrows in Fig. 2a,b) could be seen in the overlap region of both slices which is due to RF saturation effects. Temperature measurements in the overlap region were not affected by this saturation effect as the SNR was still sufficiently high (SNR ≥ 18). In Fig. 2, two orthogonal temperature images are shown indicating a maximal temperature increase of about 45 K after 80 s of laser irradiation which is consistent with previous FLASH MR temperature experiments. A temperature accuracy of about ±1.0 K was estimated from the non-heated background region, which is comparable to existing temperature measurement techniques [6].

In comparison to existing fast gradient echo sequences for PRF-based thermometry such as segmented EPI techniques, the achieved temporal resolution is still lower (TA/2 slices = 2.6 s), which might be improved by optimization of the gradient timing. The full potential of this interleaved excitation and readout technique might be exploited after combination with EPI sampling strategies. Future work will also address the integration of flow compensation and motion correction for temperature monitoring in moving organs. Nevertheless, these results already demonstrate that a time-efficient interleaved acquisition of two orthogonal temperature images is feasible. Furthermore, this imaging strategy enables simultaneous temperature monitoring in all three spatial directions.

References

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