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Research article

Clinical application of Half Fourier Acquisition Single Shot Turbo Spin Echo (HASTE) imaging accelerated by simultaneous multi-slice acquisition

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ABSTRACT

Purpose: As a single-shot sequence with a long train of refocusing pulses, Half-Fourier Acquisition Single-Shot Turbo-Spin-Echo (HASTE) suffers from high power deposition limiting use at high resolutions and high field strengths, particularly if combined with acceleration techniques such as simultaneous multi-slice (SMS) imaging. Using a combination of multiband (MB)-excitation and PINS-refocusing pulses will effectively accelerate the acquisition time while staying within the SAR limitations. In particular, uncooperative and young patients will profit from the speed of the MB-PINS HASTE sequence, as clinical diagnosis can be possible without sedation.

*Materials and Methods*MB-excitation and PINS-refocusing pulses were incorporated into a HASTE-sequence with blipped CAIPIRINHA and TRAPS including an internal FLASH reference scan for online reconstruction. Whole brain MB-PINS HASTE data were acquired on a Siemens 3T-Prisma system from 10 individuals and compared to a clinical HASTE protocol.

*Results*The proposed MB-PINS HASTE protocol accelerates the acquisition by about a factor 2 compared to the clinical HASTE. The diagnostic image quality proved to be comparable for both sequences for the evaluation of the overall aspect of the brain, the detection of white matter changes and areas of tissue loss, and for the evaluation of the CSF spaces although artifacts were more frequently encountered with MB-PINS HASTE.

*Conclusions*MB-PINS HASTE enables acquisition of slice accelerated highly T2-weighted images and provides good diagnostic image quality while reducing acquisition time.

1. Introduction

Half-Fourier acquisition single-shot turbo spin-echo (HASTE) is the single-shot form of the widely used rapid acquisition with relaxation enhancement (RARE [1]) technique, also called fast spin-echo (FSE) or turbo spin-echo (TSE). It is nowadays routinely used in clinical practice because of its short acquisition time combined with diagnostic T2 contrast image quality [2]. HASTE makes exclusive use of spin echoes [3] which reverse the effect of T2‘ relaxation and eliminate the inhomogeneity effects of the static magnetic field. Due to the high number of 180° refocusing pulses used in the extended echo train, HASTE sequences have high radio-frequency (RF) power depositions. This is especially problematic at high spatial resolutions (requiring many refocusing pulses) and high field strength (where the power deposition per pulse is higher).

Several methods have been developed to reduce the power deposition in conventional TSE/HASTE sequences. A straightforward solution is to reduce the flip angle of the 180° refocusing pulses [4]. To improve the signal at low refocusing angles and regain sensitivity, the refocusing pulse angles can be tailored to approach a suitable equilibrium [5]. Taking the steady state nature of TSE into account [6], one obtains the greatest signal if the magnetization is continuously in a pseudostatic steady state [7]. In long echo trains, high signal intensity can be obtained for the k-space center lines and low signal intensity for the outer parts of k-space by using this approach, which is called transition between pseudo steady states (TRAPS) [7].

Recently, Norris et al. [8] have shown that it is possible to reduce the power deposition in TSE to a level where it becomes applicable at 7T. They investigated the orthogonal approach of simultaneous multi-

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slice (SMS) imaging, also called multiband imaging (MB), using power independent of number of slices (PINS) pulses for excitation and refocusing [9]. Besides TSE, PINS pulses have also been successfully applied to high spatial resolution resting state fMRI using SE-EPI at 7T [10] and high resolution DWI [11].

SMS imaging was first proposed by Larkman [13] in 2001 and provides the possibility to accelerate acquisition in the slice direction by exciting and acquiring N slices simultaneously without the penalty of a sqrt(N)-reduction in signal to noise ratio. [14,15]. For a recent review on SMS imaging see Barth et al. [26].

A restriction in SMS-imaging which needs to be considered for the protocol setup is that the total number of acquired slices needs to be a multiple of the MB-factor. Since the power deposition and amplitude of the MB pulses depends linearly on the number of simultaneously excited slices, MB RF pulses become rather demanding especially when high MB-factors are used. Due to the long echo-train used in HASTE imaging, the major power deposition in a HASTE acquisition is deposited by the many refocusing pulses. It is therefore not critical to adjust or optimize the excitation pulse in terms of power deposition, as its contribution is negligible.

PINS pulses rely on periodic excitation to circumvent the increased power deposition of the traditional approach. This way, the number of simultaneously excited slices is only limited by the dimensions of the RF coils or the size of the body. In fact, the higher the number of simultaneously excited slices, the higher is the reduction in power deposition. Recently, a combination of MB and PINS pulses has also been introduced called MultiPINS [17]. In this context, it is further advisable to also apply blipped CAIPIRINHA to be able to reduce the distance between simultaneously excited slices at constant G-noise [16]. This method shifts individual slices within the FOV by a defined shift factor FOV/x improving image quality and allowing closer gaps between adjacent slices by effectively benefiting from the coil sensitivity variations in both the slice and phase encoding direction to reconstruct simultaneously excited slices.

Gagoski et al. [12] introduced in a TSE acquisition a combination of MultiPINS and an improved k-space sampling method (called Wave-CAIPI) which allows the image reconstruction to benefit from the spatial variations of the receiving coil sensitivities in all three directions even when accelerating in one single direction. It should be noted that the latter was only demonstrated in standard segmented TSE acquisition unlike the HASTE sequence.

Because of the short acquisition time, T2 HASTE is commonly used in neuroimaging of uncooperative patients, unsedated children (usually below 6 years of age), or for dynamic image acquisitions. The overall aspect of the brain and the CSF spaces can be adequately evaluated for the diagnosis and follow-up of hydrocephalus [18], and gross pathology such as large space occupying lesions or areas of tissue loss [19]. In comparison to a T2 TSE sequence, small lesions and small areas of tissue signal intensity changes may, however, be overlooked with a T2-HASTE sequence [20]. T2 HASTE can also be applied for imaging other parts of the body, such as the spine, abdomen (imaging moving organs such as bowel) or fetal imaging [21,22].

In this work, we present an ultrafast whole brain high resolution HASTE acquisition with standard MB excitation and PINS refocusing pulses combined with blipped CAIPIRINHA and TRAPS which speeds up the acquisition compared to a standard clinical HASTE protocol.

2. Materials and methods

2.1. Design of sequence

A standard Siemens HASTE sequence was modified by us in the following way: MB excitation pulses and PINS refocusing pulses were incorporated as features. The MB pulses consist of complex-summed [15] individually modulated RF pulses. The MB excitation pulse duration was prolonged to 3.5 ms compared to 2.0 ms for the standard Siemens HASTE in order to obtain an adequate slice profile which was simulated in MATLAB (The MathWorks Inc., Natick, MA, 2000) using a Bloch equation tool. The prolongation of the pulse additionally allows for a slight reduction in power deposition. The PINS refocusing pulses had a slightly prolonged duration of 2.3 ms, instead of 2.0 ms in the original HASTE sequence to allow some extra time for the slew rate demanding PINS gradient blips and still accommodate 11 PINS-sub-pulses. In prior simulations using IDL (Harris Geospatial Solutions, Boulder Colorado), the 11 sub-pulses were optimized by adjusting the individual flip angles to obtain the best possible slice profile for a given ratio of “slice spacing/slice thickness = N”. The optimization was done in an iterative way varying the RF-subpulse amplitude while maintaining the symmetry of the pulse to account for the nonlinearity of the Bloch equations. The least squares difference was minimized between a target function having a value of 1 within the slice and 0 outside for transverse magnetization in the optimization of excitation pulses, and −1 within the slice and 1 outside for longitudinal magnetization in the optimization of inversion/refocusing pulses. The simulation showed that the use of 11 sub-pulses set a maximum value of 11 for the value of N: thinner slices were not possible. The bandwidth (BW) of the PINS pulses depends on N and is given by: It is therefore desirable to keep N as small as possible, but even when pushing it to its limits in terms of reconstruction feasibility, PINS remain low BW RF pulses.

$$BW_{PINS} = \frac{1}{duration} \times no\ of\ sub\ pulses \times \frac{slice\ \ thickness}{slice\ \ spacing}. \quad (1)$$

To avoid off-resonance artifacts, the BW of the MB excitation pulse was matched to the BW of the PINS pulses. In any case, the slice profile of the PINS should not influence the actual slice profile to a great extent since the actual slice profile will be mainly defined by the MB excitation RF pulse.

In order to fulfill the CPMG condition, the phase ramps of the individual pulses which were summed to make the MB pulse were set to give zero phase at the center of the pulse, and the phase ramp applied to the individual PINS sub-pulses was implemented had zero phase for the central sub-pulse. Applying a 90° phase difference between the centers of excitation and refocusing pulses ensured fulfilment of the CPMG condition.

We further combined the gradient moments necessary for the application of the blipped CAIPIRINHA technique with the spoiler gradients around the refocusing RF pulses to ensure the shortest possible echo spacing.

Unlike segmented TSE acquisitions [9], HASTE acquisitions, as a single-shot acquisition, have a long echo-train. Therefore, it is necessary to use in-plane parallel imaging techniques such as GRAPPA [23] into the protocol to shorten the echo-train length (ETL). The low BW pulses lead to a significant chemical shift displacement error for the fat signal which in combination with parallel imaging leads to parallel imaging artifacts caused by the physical separation of the fat and water slices, which makes fat saturation essential in SMS protocols [24].

To decrease the power deposited along the echo-train, we also implemented the TRAPS option for the PINS design [8]. This way only the center of k-space +3 lines would experience the full 180° flip angles followed by a ramp of 6–10 echoes. All other refocusing pulses had the indicated target TRAPS flip angle.

The entire sequence diagram is shown in Fig. 1.

In SMS imaging, it is advisable to acquire an odd number of slices in interleaved series mode to avoid adjacent slices being excited immediately one after another. The application of PINS refocusing pulses can lead to a degraded slice profile which can affect and saturate neighboring slices. An interleaved slice order, an increased slice gap and a slightly prolonged TR all help in avoiding saturation effects.

For the protocol setup, it is additionally necessary to consider the reconstruction feasibility of the aliased slices. To be able to cleanly disentangle the simultaneously acquired slices, the slice spacing cannot be arbitrarily small, but usually remains around 27–30 mm for brain