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Increasing robustness of radial GRASE acquisition for SAR-reduced brain imaging

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Abstract

Purpose: *To improve a radial multi-slice 2D gradient- and spin-echo (GRASE) sequence and provide an appropriate image reconstruction technique for SAR-reduced high-resolution neuroimaging.*

Methods: *Additional readout gradients per radio-frequency (RF) refocusing allow for a reduced number of RF pulses. In this way, a specific absorption rate (SAR) reduction is achieved and the application at high-field systems becomes more feasible. A phase insensitive image reconstruction is proposed to reduce signal dropout artifacts originating from opposite readout polarities. In addition, the image reconstruction allows for the calculation of images with varying contrast from one measurement.*

Results: *Results obtained at 3 T and 7 T demonstrate a SAR-reduction of at least 66% for a single-slice experiment with radial GRASE. The reduced SAR is used for an increased spatial coverage without increasing the measurement time. Experiments at 3 T and 7 T showed that the visual image quality is comparable to standard TSE and GRASE sequences with the same measurement parameters. Using higher EPI factors and the presented image reconstruction, artifact-free images with a significant SAR-reduction can be achieved.*

Conclusion: *Radial GRASE enables SAR-reduced acquisitions of high-resolution brain images with different contrasts from one measurement and is a promising sequence for high-field neuroimaging.*

Keywords: SAR, High-resolution, Radial imaging, TSE

Introduction

In recent years, high-field MRI examinations at $B_0 \geq 3\,\mathrm{T}$ have become increasingly common and are of great interest for clinical routine and research. In general, a stronger main magnetic field offers an increased signal-to-noise ratio (SNR) which can be used to improve the spatial resolution and/or to reduce the total acquisition time. For high-resolution 2D neuroimaging, Turbo Spin-Echo (TSE, Fast Spin-Echo, or Rapid Acquisition with Relaxation Enhancement) techniques [1] are often used, because they allow fast scanning with high SNR and are robust in the presence of field inhomogeneities. TSE imaging provides the relevant clinical contrasts, i.e. proton density (PD), T1- and T2-weighting. A major drawback of TSE is the high radio-frequency (RF) power deposition due to the large number of refocusing pulses per unit time. The RF power deposition is characterized by the specific absorption rate (SAR) and corresponding safety limits need to be followed to keep tissue heating to a minimal level. The high RF power deposition is particularly a problem at higher field

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strengths because the SAR increases both with the square of the magnetic field strength and the square of the flip angle of the applied pulse [2]. Thus, at high-field strengths standard TSE protocols often exceed SAR limitations and force the operator to perform undesired parameter changes in order to reduce the power deposition. This may include reducing the number of slices per repetition time (TR), increasing TR, reducing the echo train length (ETL) or reducing the flip angles of the refocusing pulses. In addition, refocusing flip angles lower than the ideal 180° are typically used at 3 T and higher [3]. Since, the reduced flip angles decrease the echo amplitude and therefore the SNR, hyper-echoes and TRAPS [4,5] have been introduced and present a well-established method for SAR-reduced MR imaging. However, a smaller refocusing flip angle and the intrinsic T1-sensitivity of hyper-echoes may lead to an undesired change of T2 image contrast if not accounted for by adjusting the effective echo time [6]. Alternatively, longer pulse durations can reduce the SAR, but at the cost of relaxation effects during RF transmission.

In addition to the already mentioned techniques, hybrid techniques are alternative approaches to overcome the SAR limitations. A hybrid sequence with intrinsic SAR-reduction is the gradient- and spin-echo (GRASE) technique [7,8]. The sequence is based on a TSE sequence, but instead of one echo, multiple gradient echoes are acquired per refocusing pulse. In that way, the number of refocusing pulses can be reduced keeping the total number of echoes per excitation constant. The EPI factor indicates the number of additional readout gradients per refocusing and determines the intrinsic SAR-reduction factor. The minimal EPI factor of three theoretically leads to a SAR-reduction of at least 66% compared to TSE with the same measurement parameters. Therefore, GRASE offers similar contrast like TSE and the experiments can be performed with fewer limitations due to SAR restrictions. At 7 T the reduced SAR in GRASE acquisitions allowed for a significant reduction of scan time or increased spatial coverage and presents a valid alternative to TSE [9]. Disadvantages of GRASE in combination with Cartesian sampling (Cart-GRASE) are ringing artifacts, which appear due to T2* effects caused by imperfect phase-encoding ordering schemes and phase mismatch between echoes acquired with opposite readout polarities. These artifacts can be reduced by an adequate ordering scheme [10] and/or by applying a corresponding phase correction. However, amplitude modulations due to T2* cannot be fully compensated and therefore the image quality may still be negatively affected by mild ringing artifacts. To overcome the limitations of Cartesian k-space sampling, a radial sampling scheme in conjunction with GRASE has been proposed [11]. Radial GRASE (radGRASE) can be used for fast scanning as a single-shot or as multi-shot technique for high-resolution imaging. The radial sampling scheme is less sensitive to motion and undersampling artifacts [12]. This is extended to methods like PROPELLER-GRASE which combines the rotating blade technique with EPI readouts for increased sampling efficiency and retrospective motion correction [13]. Moreover, due to the high oversampling of the k-space center, radGRASE has the ability to obtain multiple images with varying contrast from one measurement [11]. Nevertheless, all these features could not help to establish radGRASE in clinical practice. One reason may be the sensitivity to off-resonance effects due to the increased number of readout gradients within two refocusing pulses and the corresponding signal dropout artifacts.

The purpose of this work was to improve the radGRASE sequence for SAR-reduced high-resolution brain imaging as originally proposed by Gmitro et al. [11]. A robust phase insensitive image reconstruction based on parallel imaging is presented. The image reconstruction allows for the reconstruction of multiple images with different T2-weighting as well as T2*-weighting from one measurement. In addition, the phase insensitive image reconstruction offers a strong reduction of off-resonance artifacts even for high EPI factors >3. In vivo experiments were performed on healthy volunteers at 3 T and 7 T. SAR values obtained from the MR systems were provided and the influence on SAR limitations is analyzed using radGRASE and TSE. High-resolution brain images with a T2-weighting were reconstructed from all in vivo measurements and compared visually. For a quantitative comparison, SNR and contrast-to-noise ratio (CNR) were calculated and presented for the experiments at 3 T.

Methods

The working principle of a radGRASE sequence is well-known in literature [11]. In this work, the turbo factor (TF) represents the number of refocusing pulses per excitation and the echo train length ETL is the total number of echoes per excitation (ETL = TF · EPI factor). The time interval between two refocusing pulses is referred to as echo-spacing (ESP). The central echo of the EPI block is a spin-echo (SE) and all other echoes are gradient echoes (GE). The excitation with a 90° pulse is followed by a train of refocusing pulses (e.g. 180°), which satisfy the CPMG conditions [14,15]. In this work, a k-space ordering scheme based on the golden ratio [16,17] with a constant angle increment of $\varphi \approx 17°$ was implemented. This ordering scheme allows for an almost uniformly distribution in the k-space for any number of projections.

Image reconstruction

In radial imaging every acquired projection crosses the k-space center and therefore contains both low and high frequency information. In addition, in radGRASE every projection is acquired at another echo time (TE) and has therefore another contrast weighting. In this way, several images with different contrasts corresponding to distinct effective echo times (TE_{eff}) can be calculated [11]. For this, data sharing techniques like the k-space weighted image contrast (KWIC) technique [18] can be used. Here, the center region of k-space is filled with projection having the desired TE. Therefore,