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Reducing Contrast Contamination in Radial Turbo-Spin-Echo Acquisitions by Combining a Narrow-Band KWIC Filter With Parallel Imaging

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Abstract

Purpose—Cartesian turbo spin-echo (TSE) and radial TSE images are usually reconstructed by assembling data containing different contrast information into a single k-space. This approach results in mixed contrast contributions in the images, which may reduce their diagnostic value. The goal of this work is to improve the image contrast from radial TSE acquisitions by reducing the contribution of signals with undesired contrast information.

Methods—Radial TSE acquisitions allow the reconstruction of multiple images with different T2 contrasts using the k-space weighted image contrast (KWIC) filter. In this work, the image contrast is improved by reducing the band-width of the KWIC filter. Data for the reconstruction of a single image are selected from within a small temporal range around the desired echo time. The resulting data set is undersampled and therefore an iterative parallel imaging algorithm is applied to remove aliasing artifacts.

Results—Radial TSE images of the human brain reconstructed with the proposed method show an improved contrast when compared to Cartesian TSE images or radial TSE images with conventional KWIC reconstructions.

Conclusion—The proposed method provides multi-contrast images from radial TSE data with contrasts similar to multi spin-echo images. Contaminations from unwanted contrast weightings are strongly reduced.

Keywords

radial sampling; RARE; Turbo spin-echo; KWIC; parallel imaging; data sharing

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Introduction

Turbo spin-echo (TSE) imaging (1), also known as RARE and fast spin-echo (FSE) is an established fast multi-echo acquisition technique widely used in the clinic and in research. In Cartesian TSE images, echoes of different echo times and therefore different contrasts are reordered into a single k-space. This allows the generation of the clinically important proton density (PD) and T2 weighted images. However, data sharing may result in mixed contrast contributions in the images. These contributions are especially significant in PD images at high field strengths (3 Tesla (T) and higher) due to smaller T2 values, and they may reduce the diagnostic value of the images.

In general, radial sampling strategies are more robust than Cartesian sampling with regard to patient motion and flow (2,3) which has also been demonstrated in radial TSE (rTSE) (4,5). Furthermore, each echo of a rTSE acquisition samples across the k-space center and collects both contrast and high frequency information about the image. Therefore, multiple images of different contrasts can be obtained from one single radial TSE acquisition (4-7). One possibility for reconstructing multiple aliasing-free images of different contrast from a single radial TSE data set is to use data sharing between projections acquired at different echo times, for example using k-space weighted image contrast (KWIC) (8). Due to the data sharing, mixed contrast contributions are inevitable. A different approach to reconstruct radial TSE data is using a model-based iterative reconstruction method that incorporates non-linear regression to directly obtain PD and T2 maps (7). This method avoids the problems associated with data sharing and manages to reconstruct artifact-free images of improved contrast. However, the high dimensionality of the problem results in a large computational load.

In this work, a conceptually simple method for the reconstruction of multi-contrast images from a single radial TSE measurement is presented using a combination of a narrow-band KWIC reconstruction and parallel MRI. An adapted golden-angle reordering scheme (9) was implemented for rTSE acquisitions to allow a free choice of the echo train length (ETL). To reduce contributions of different contrasts in the characteristics of each image, the amount of data used for the reconstruction is reduced significantly by incorporating only data collected within a small temporal range of the desired echo time. This leads to undersampled k-space data and aliasing artifacts in the images. To recover missing data, a conjugate gradient (CG) iterative SENSE reconstruction (10) is applied. Finally, prior knowledge about the temporal behavior of each pixel is incorporated using a mono-exponential fit to remove remaining artifacts and to increase SNR. Reconstructed images from undersampled brain data are shown and compared to images obtained with a multi spin-echo (MSE), a Cartesian TSE, and a conventional KWIC reconstruction from radial TSE data. It is demonstrated that contributions from undesired contrast information are significantly reduced.

Methods

Radial TSE sequence with a modified golden angle reordering

In radial TSE, one projection of a certain angle is acquired for each echo. An uneven distribution of data belonging to the same echo time leads to larger gaps in k-space and can

negatively affect image quality. Therefore, it is mandatory to achieve a uniform sampling of k-space built from data from both a single echo time and an arbitrary number of adjacent echoes. This will be especially important for the performance of the CG-SENSE algorithm. Previously, a projection reordering for rTSE measurements has been implemented based on the bit reverse operation (11) that yields reduced image artifacts when compared to linear reordering. A drawback to bit-reversed reordering is the requirement for the ETL to be a power of two. An alternative reordering is the golden ratio sampling scheme (9), which guarantees optimal k-space coverage while retaining high flexibility in the choice of data used for reconstruction. Standard golden ratio reordering increases the projection angle by the golden angle increment $\alpha_G = 180^\circ/\gamma \approx 111.25^\circ$ with $\gamma = (\sqrt{5}+1)/2$ for subsequent projections. This sampling scheme has been combined with rTSE acquisitions by linearly increasing the projection angles in a single TR and by α_G for subsequent echo trains. In this way, all the projections acquired at the same echo time are distributed uniformly according to the golden ratio (12). As a further modification, in this work the linear increment is chosen such that not only data from a single echo time are reordered according to the golden ratio, but also the combined data from an arbitrary number of adjacent echoes in the echo train. To that end, the projection angle is calculated according to

$$\alpha(Echo, Seg) = (Echo \cdot N_{seg} + Seg) \cdot \alpha_G, \quad [1]$$

where $Seg = (0, 1, \dots, N_{seg}-1)$ is the current segment and $Echo = (0, 1, \dots, ETL-1)$ is the position in the echo train. The modified reordering is depicted in Figure 1 for $ETL=2$ and 5 segments. It leads to a projection distribution according to the golden ratio using an arbitrary number of different adjacent echoes for reconstruction. This reordering is optimal if the total number of segments is chosen to be a Fibonacci number, but no restrictions are made towards the echo train length.

Data reconstruction

The reconstruction of images with different contrasts from a single rTSE data set is performed in three steps. First, a narrow-band KWIC reconstruction is applied using less data than conventional KWIC, resulting in an undersampled image data set. Second, to reconstruct missing data with parallel imaging, a small number of CG-SENSE iterations are performed. Finally, noise and remaining aliasing artifacts are reduced by performing a mono-exponential fit for each pixel. All reconstruction steps were implemented in Matlab (The Mathworks, Natick, MA) and are summarized in Figure 2 a).

Each projection in a single echo train contains a different image contrast due to the T2-decay of the signal. By acquiring N_{seg} segments, there are N_{seg} projections available for the reconstruction of each individual image at a specific echo time without making use of data sharing.

Due to the long recovery times necessary for signal relaxation, a multi spin-echo acquisition of fully sampled high resolution data sets for each contrast is not feasible. Instead, KWIC can be applied to radial TSE data with a limited number of segments to reconstruct images of different contrasts, which is depicted in Figure 2 b). Hereby, the k-space is divided into

annular regions. While for the center region the Nyquist criterion is fulfilled using only projections corresponding to the desired contrast, outer annular regions are sampled below the Nyquist criterion. Each annular segment is filled with projections of the echo times closest to the desired contrast until the Nyquist criterion is met. Due to this data sharing, employing a KWIC-filter for reconstruction of PD and T2 weighted images from the same radial dataset necessarily leads to a mixed contrast in the results.

To reduce undesired contrast contributions in the reconstructed images, it is necessary to use a narrow temporal window. This is done by using only the nearest neighboring echoes for reconstruction as depicted in the right hand side of Figure 2 b).

Without the acquisition of a higher number of projections, the undersampled data will result in aliased images. Parallel imaging or compressed sensing can be employed subsequently to obtain unaliased images. In this work, a CG-SENSE algorithm with Tikhonov-regularization was chosen due to its ability to reconstruct arbitrarily sampled data and its stable convergence properties (10). Hereby, the KWIC-filtered data were used as input. Coil sensitivity maps necessary for the CG-SENSE algorithm were obtained by gridding the full radial TSE datasets and performing array correlation statistics (13). All gridding and degridding operations were performed using non-uniform Fourier transform (14). Density compensation was applied for each gridding step with the method proposed by Bydder et. al. (15).

As with all parallel imaging reconstructions, increased noise (i.e. geometry-factor) as well as remaining aliasing artifacts may affect image quality. To improve on the result, additional redundancy of the images can be exploited. In the reconstructed rTSE image series, each image pixel time-course exhibits an approximate temporal exponential decay. To reduce noise and residual aliasing artifacts, a mono-exponential fit is performed for each pixel and synthetic images are obtained corresponding to the original echo times.

In-vivo Experiments

All experiments were performed on a standard clinical scanner with a field strength of 3T (Skyra, Siemens Healthcare, Erlangen, Germany) using a 32 channel head receiver array. Two different sets of brain data of two healthy volunteers were acquired using rTSE with the modified golden angle reordering. Written informed consent was obtained from the volunteers prior to the imaging session.

A rTSE data set was acquired in axial orientation with base resolution of 256, field of view of $200 \times 200 \text{ mm}^2$, slice thickness of 4 mm, echo-spacing of 8.8 ms and repetition time $TR=5\text{s}$. For an optimal distribution of the projections, 34 excitations (= Fibonacci number) were performed. With an ETL of 15, this corresponds to a total number of 510 projections and a total acquisition time of 2:50 minutes for the single-slice experiment. As gold standard, a radial multi spin-echo dataset was obtained with identical parameters. To keep the acquisition time (24:25 min) within tolerable limits for the volunteer, only 293 projections were acquired per image. Furthermore, two Cartesian TSE images (acquisition time 1:30 min each) were obtained with effective echo times of 8.8 ms and 132 ms corresponding to the first and last echo of the rTSE measurement.

An additional, high-resolution rTSE data set of 510 projections was acquired in sagittal orientation with identical parameters except base resolution 384 and field of view of 220×220 mm². Due to the higher readout gradient amplitude at higher resolution, the echo-spacing was increased to 9 ms.

For both rTSE data sets, the reconstruction depicted in Figure 2 a) was performed applying 8 iterations of CG-SENSE using a moderate amount of regularization. To reduce reconstruction time, the number of channels were reduced to 12 via channel compression using a principal component analysis (16,17). For each image of the series, 102 projections were used belonging to the 3 nearest echoes. The KWIC filter was hereby implemented as shown in Figure 2 b). To show the influence of the band-width of the KWIC-filter on the contrast, additional images were reconstructed from the high-resolution data set using a width of 1, 5 and 7 echoes. Additionally, images were obtained by employing conventional KWIC reconstruction using all available data.

Results

In Figure 3, images obtained with MSE (row 1), with Cartesian TSE (row 2) and with radial TSE are compared for both PD weighting (left column) and T2 weighting (right column). Images from radial TSE reconstructed with conventional KWIC using all projections (row 3) and the proposed combination of a narrow KWIC filter and CG-SENSE (row 4) are shown. In the PD images, undesired T2 contrast contributions can be clearly observed in both the Cartesian TSE and the standard KWIC images. Contributions of undesired contrast can also be observed in the T2 weighted images, although less apparent. These contributions are hardly visible in the image obtained with narrow KWIC, which in both cases exhibit a similar contrast to the MSE results. Figure 4 shows the PD and T2 maps obtained from a temporal fit after image reconstruction with conventional KWIC and the proposed method. While good agreement between the T2 maps can be observed, the PD map from the conventional KWIC reconstruction exhibit contrast contamination (see regions with CSF).

Figure 5a demonstrates the impact of the KWIC filter band-width on the images reconstructed with CG-SENSE. PD-weighted high-resolution radial TSE brain images are shown reconstructed from 1, 3, 5 and 7 echoes. For 1 echo, the undersampling is too severe and the reconstruction fails to generate an aliasing-free image. The images reconstructed from 5 and 7 echoes exhibit undesired T2 contributions in their contrast (see arrow).

Figure 5b shows PD and T2 weighted images from the same data set after the CG-SENSE reconstruction with and without the additional temporal mono-exponential fit. Residual aliasing artifacts after CG-SENSE are greatly reduced and cannot visibly be detected after exploiting the temporal correlation between the single images in this manner.

Discussion

KWIC reconstruction allows the generation of multiple images with different contrast from a single rTSE data set. Especially for T2-weighted images the result is very close to that of a multi spin-echo image. Nonetheless, some minor differences remain. When looking at images with a short echo time, undesired T2 contrast influences in the images are obvious,

and no true proton-density contrast can be obtained. This characteristic is also present in Cartesian TSE images, where data sharing is applied through a different ordering in k-space. The impact of this effect increases with the B0 field strength because of the shortened T2 constants.

In the proposed method, only data with the same or at least similar contrast are used for the reconstruction of each image. This means that only a part of the acquired data can be used and the resulting images will exhibit aliasing artifacts and reduced SNR. Using a radial data set of 510 projections, this relates to undersampling factors of $R=2.8$ (matrix size 256) and $R=4.0$ (matrix size 384) when compared to nearly fully sampled data sets with 256 and 384 projections respectively.

Residual aliasing artifacts are removed using CG-SENSE. Further reduction of residual aliasing artifacts and significant SNR improvements are achieved by a pixel-by-pixel mono-exponential fit. It should be mentioned, that the signal curve does not follow a true mono-exponential decay due to stimulated echo contributions. To account for these contributions and to obtain improved T2 maps, the signal decay could instead be modeled using the extended phase graph formulation (18) as proposed by Lebel et al. (19). Alternatively, a principal component analysis could be performed, which is computationally fast and not model-dependent. As advantage of the proposed method, only standard methods are used in the reconstruction process, which can be highly parallelized and are already implemented on a number of modern clinical scanners. The reconstruction used in this work was implemented in Matlab without optimization for speed and took 1:24 min and 2:50 min for base resolutions 256 and 384 respectively. Computation times for each individual step are listed in table 1. With optimization (e.g. GPU implementation (20)), it may be possible to push reconstruction time well below 10s per slice. When compared to two separate Cartesian TSE acquisitions yielding the diagnostically important PD and T2-weighted contrasts, the acquisition of 510 radial projections decreases measurement time by 5.5% and by 34.6% for the two different resolutions.

The proposed method uses a smaller set of projections in a KWIC filter to reduce the problems associated with data sharing and subsequently removes the occurring aliasing artifacts using parallel imaging. A similar approach has already been used for cardiac imaging (21). An important parameter to be considered is the band-width of the KWIC filter, which has to be adjusted for different applications, according to the dynamics of the data at hand and the parallel imaging capacity of the receiver array. In general, there is a tradeoff between mixed-contrast contributions and the severeness of streaking artifacts due to undersampled k-space. In the examples presented here, a filter band-width of only 5 to 7 echoes already led to visible T2 contributions in PD weighted images. These contributions may render the images undiagnostic for different pathologies, for example meningioma and medulloblastoma. The proposed method minimizes those T2 contributions to PD images, which can conventionally only be achieved with an unfeasibly long MSE acquisition. The clinical evaluation of this acquisition and reconstruction approach is planned as an ongoing project.

Conclusion

The combination of a narrow-band KWIC filter and parallel MRI allows the reconstruction of images with different contrast from a single radial TSE measurement. The achieved contrast is very similar to that of a fully sampled multi spin-echo acquisition. This is a major improvement, especially in proton density-weighted images, where conventional KWIC reconstructions or Cartesian TSE images exhibit undesired T2-weighted contributions. The proposed acquisition and reconstruction strategies could be valuable for implementing radial TSE in clinical practice. It uses a combination of established methods already implemented on modern scanners, imposes no restrictions on the echo train length and doesn't require long reconstruction times even for high-resolution images.

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Figure 1.

The modified golden angle reordering scheme for radial TSE acquisitions is depicted for 5 segments and ETL=2. The projection angle is increased by the golden angle α_G for subsequent segments (i.e. excitations), so that the projections acquired at the same echo time are distributed according to the golden ratio. To guarantee golden ratio distribution for the whole set of projections, all projections belonging to TE_2 are rotated by $5\alpha_G$ compared to those acquired at TE_1 .

Figure 2.

a) Proposed reconstruction process: Images of different contrasts are obtained using a narrow-band KWIC-filter. The CG-SENSE reconstruction is followed by a mono-exponential fit in each pixel. Synthetic images corresponding to the original echo times are computed to further remove residual aliasing artifacts and to improve SNR. b) KWIC-filter schemes for a radial TSE acquisition with an echo train length of 15 generating an image with a contrast of the 6th echo. Shown are both standard KWIC (left) leading to a fully sampled k-space and the narrow-band KWIC filter (right) resulting in undersampled images exhibiting aliasing artifacts.

Figure 3.

Proton density and T2-weighted images of the brain of a healthy volunteer obtained with a multi spin-echo (MSE) acquisition, a standard Cartesian TSE acquisition and a radial TSE acquisition applying both standard KWIC and the proposed method using a narrow KWIC filter for reconstruction. In the Cartesian TSE and KWIC images, mixed contrast contributions are visible (see arrows).

Figure 4.
Proton density and T2 maps obtained with a temporal fit after reconstruction with conventional KWIC and the proposed method.

Figure 5.

Sagittal brain images of a healthy volunteer, obtained with a radial TSE acquisition. a) PD weighted images after CG-SENSE reconstruction, using different band-widths of the KWIC filter. Using a single echo for the reconstruction leads to severe aliasing artifacts. Images reconstructed from 5 and 7 echoes already exhibit undesired T2 contributions to the image contrast (see arrow). b) PD and T2 weighted images are shown both before and after the final fitting step. After the CG-SENSE reconstruction, some remaining aliasing artifacts can be observed in the radial images. This aliasing can be significantly reduced by exploiting the temporal correlation between the images.

Table 1

Computation times for each individual reconstruction step. The reconstruction was implemented in MATLAB on a standard PC with an intel core 2 quad CPU with 2.83GHz and 8GB RAM.

Computation times		
	Base resolution	
operation	256	384
Generate coilmaps	22s	44s
CG-SENSE reconstruction	55s	107s
Mono-exponential fit	7s	19s
	1:24 min	2:50 min