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Experimental O-Space Turbo Spin Echo Imaging

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Abstract

Purpose—Turbo Spin Echo (TSE) imaging reduces imaging time by acquiring multiple echoes per repetition (TR), requiring fewer TRs. O-Space also can require fewer TRs by using a combination of nonlinear magnetic gradient fields and surface coil arrays. Although to date, O-Space has only been demonstrated for gradient echo imaging, it's valuable to combine these two techniques. However, collecting multiple O-Space echoes per TR is difficult because of the different local k-space trajectories and variable T2-weighting.

Theory and Methods—A practical scheme is demonstrated to combine the benefits of TSE and O-Space for highly accelerated T2-weighted images. The scheme uses a modified acquisition order and filtered projection reconstruction to reduce artifacts caused by T2-decay, while retaining T2 contrast that corresponds to a specific echo time.

Results—The experiments illustrate the proposed method can produce highly accelerated T2-weighted images. Moreover, the proposed method can generate multiple images with different T2 contrasts from a single dataset.

Conclusions—The proposed O-Space TSE imaging method requires fewer echoes than conventional TSE and fewer repetitions than conventional O-Space imaging. It retains resilience to undersampling, clearly outperforming Cartesian SENSE at high levels of undersampling, and can generate undistorted images with a range of T2 contrast from a single acquired dataset.

Keywords

nonlinear gradients; turbo spin echo; fast spin echo; rapid acquisition with refocusing echoes; O-Space imaging; parallel imaging

Introduction

Spin Echo (SE) imaging is a foundational workhorse of Magnetic Resonance (MR) imaging, but with conventional Cartesian sampling the acquisition time can be very long. To speed up SE imaging, multiple echoes are often acquired successively as trains in a pulse sequence known as Turbo Spin Echo (TSE), also known as Fast Spin-Echo (FSE) or Rapid

Acquisition with Refocusing Echoes (RARE) (1). TSE generates a train of spin echoes after a single excitation and uses each echo to sample one line in k-space. There are many ways to study and accelerate TSE MR imaging (2–13). TSE typically shortens scan times by factors of 2 to 32 directly dependent upon the number of echoes in the echo train. Longer echo trains bring reduced data acquisition time and can also lead to blurring due to T2-decay (3).

More recently, scan time has been reduced by spatial encoding with nonlinear magnetic fields, such as in PatLoc imaging (14), O-Space imaging (15, 16), Null Space Imaging (17), 4D-RIO (18), EPI-PatLoc (19–21), and others (22–36). Here we focus on O-Space imaging, which encodes spatial information through a radially varying magnetic gradient field $B_1 = z^2 - 1/2((x - x_i)^2 + (y - y_i)^2)$ centered at different center placements (x_i, y_i) , which form a ring about the FOV center (15). In terms of acquisition time, center placements are equivalent to phase encode steps in Cartesian sampling but with the advantage that, with parallel imaging, fewer center placements than phase encode steps are needed to reconstruct a high quality image (15, 16). However, previous O-Space sequences have incorporated gradient echo imaging only, and used single echo sequences.

O-Space turbo spin echo (O-Space TSE) imaging presents two major obstacles to creating T2-weighting that both minimizes artifacts and creates specific T2 contrast in the image. The first challenge is that the order in which we acquire center placements can create discontinuities in measurements of the edge of Cartesian k-space. This problem can be mitigated with a previously described modified acquisition order (32). The second challenge is that, even with an ideal acquisition order, a wide range of T2-weighting remains at the center of k-space, which is sampled throughout the echo due to the spatially varying encoding of nonlinear gradients. For a more thorough description of how O-Space data samples Cartesian k-space, see (15, 16). This second obstacle can be addressed by applying a previously described filter during the reconstruction (32). A preliminary account of part of this work was presented in (33).

In this paper, these methods are implemented, tested and refined, to illustrate that the proposed methodology can inherit the advantages of both TSE and O-Space to accelerate the data acquisition. In addition, the fact that each time-point and echo contains low frequency information can be turned into a feature rather than a problem, allowing for reconstruction of a range of images with different T2-weighting from a single dataset.

Theory

The O-Space TSE sequence is proposed as seen in Figure 1, here shown for 4-fold acceleration. This sequence applies slice-selective excitation followed by multiple 180° refocusing pulses and z gradients with crushers. The repetition time is TR; the time between 90° RF pulse and the first echo is called the initial echo spacing (TE_1); the interval between subsequent echoes is called the echo spacing (ESP); the number of refocusing pulses equals the echo train length (ETL). Because there is no phase encoding, an effective TE (TE_{eff}) is the time between the excitation and the center of the echoes meant to collect low frequency encoding information (13, 35–38). On each gradient channel, prephasing and rewinding

lobes are applied before and after each readout lobe, both to minimize eddy current effects and to return to the center of k-space after each echo.

Images are reconstructed via a Kaczmarz algorithm (15, 16, 22, 23, 27–33, 39, 40). Generally, in a traditional Kaczmarz reconstruction, the update step is normally performed with the following equation:

$$I_i(x, y) = I_{i-1}(x, y) - \lambda \cdot \beta_i \cdot A_i(x, y), \quad [1]$$

where I_{i-1} is the previous image estimate; I_i is the new image estimate, updated to incorporate A_i , the i^{th} line of the encoding matrix. β_i is calculated from the observed data associated with that encoding ($\beta_i = D_i - A_i \cdot I_{i-1}$, where D_i is the experimental data associated with that encoding), and it predicts the extent to which the basis function A_i is missing from the previous image estimate.

In a standard reconstruction, λ in Eq. [1] is simply a scaling parameter that controls the convergence properties of the calculation. Instead, to control how different datapoints influence the low frequency features of the image, λ can be a spatially varying function of echo time:

$$\lambda(x, y, t, \tau(t)) = 1 - e^{-(|\mathbf{r} - \mathbf{CP}(\tau(t))|^2 / \sigma(t)^2)}, \quad [2]$$

where $\mathbf{r} = (x, y)$, $\tau(t)$ is a function of the echo time, t , of the associated datapoint; $\mathbf{CP}(\tau(t))$ gives the coordinates of the gradient center placement (CP) for that echo, and $\sigma(t)$ is a time-dependent parameter that controls the width of the filter. Explicitly,

$$\sigma(t) = \begin{cases} \sigma_0 \sqrt{\frac{k_{x,\max}^2 + k_{y,\max}^2 + (\text{FOV}/2)k_{z,2,\max}^2}{k_x^2(t) + k_y^2(t) + (\text{FOV}/2)k_{z,2}^2(t)}} & (t \notin \Gamma) \\ \Sigma & (t \in \Gamma) \end{cases} \quad [3]$$

Here, σ_0 is a scale factor; $k_x(t)$, $k_y(t)$ and $k_{z,2}(t)$ are the integrated gradient moments for a given acquisition time.

When t is not part of the target echo set Γ , relatively flat areas near the center placement are suppressed, so low frequency, un-modulated parts of the encoding function do not contribute to the reconstruction. This represents a small part of the field of view for encoding functions corresponding to the edge of the echo, and a large region (eventually the entire field of view) at the center of the echo. Therefore, $\sigma(t)$ evolves accordingly, so that λ suppresses just the low frequency part of each encoding function for all t outside the target set.

When t does fall in our target echo set, (which can be theoretically either null set or universal set), $\sigma(t)$ defaults to a very small number $\Sigma \ll \sigma_0$. For these times, the exponential term in Eq. [3] approaches $e^{-\infty}$, i.e. zero, $\lambda(x, y, t, \tau(t))$ no longer varies spatially, and almost nothing is suppressed. Therefore, echoes with that TE are the main ones that contribute low frequency information and thus control the image contrast and T2-weighting. Furthermore, simply by reprocessing the same data for different target echo times, we can

generate images with different T2 contrast by changing the target echo set, Γ , to generate the desired T2 contrast.

Methods

Phantom experiments were conducted using a 3T MRI scanner (Siemens Healthcare, Erlangen, Germany) with an 8-channel receive coil and a gradient insert (Resonance Research Inc., MA, USA) that generates the nonlinear field (16). Imaging parameters were TR: 1000ms; BW: 80Hz/pixel; FOV: 25×25cm²; flip angle: 90°; the Z2 strength of O-space imaging system: 20mT/m²; matrix size: 128×128. Some images were also collected at a higher resolution by a longer acquisition window to collect 256 datapoints in each echo. This high resolution data was reconstructed to a matrix size of 256×256. In all images, the linear gradient strength is set by the typical Nyquist prescription, and an additional nonlinear field is added such that the quadratic field is centered at the edge of the FOV. The values of TE₁, ESP, and ETL are specified individually for each experiment in the Results. Standard O-Space spin echo (O-Space SE) images were generated by collecting 1 echo over each of 256 shots. O-Space TSE images were collected with ETL echoes per shot and a total number of echoes corresponding to the matrix size divided by the reduction factor (R). Cartesian TSE images with equivalent echo train length and total number of echoes were acquired and reconstructed via SENSE (41–47) for comparison. Standard O-Space TSE images were collected with normal sequential center placement ordering, whereas the proposed images were collected with the modified order of center placements prescribed in Ref. (32).

All calculations were performed in MATLAB (The MathWorks Inc, Natick, MA, USA), and all O-Space reconstruction was done via a Kaczmarz algorithm (15, 16) using ten iterations. Cartesian images were reconstructed by SENSE (41). Images marked as “proposed O-Space” also applied a filter to the reconstruction basis targeting the middle echo as the target echo set, Γ , unless otherwise stated. In other words, the target echo was the third echo in a four echo train (TE_{eff} = 90ms for ESP = 30ms), or the fifth echo in an eight echo train (TE_{eff} = 150ms for ESP = 30ms). The theory behind this filter is explored in Ref. (32), but qualitatively the intent of the filter is to not add low frequency information to the reconstructed image unless the datapoint is associated with the desired TE.

Results

Figure 2 compares images acquired with ETL=8 using Cartesian TSE (1–8), standard O-Space TSE, and the proposed O-Space TSE methods sampled at R of 1, 2, 4 and 8. To better highlight the advantages of O-Space, these images acquired 256 points per echo. The high resolution readout does not remove artifacts in a Cartesian readout, but it does improve O-Space images because of the 2D nature of nonlinear readout encoding. Reconstructing the Cartesian images at lower resolution (not shown) by SENSE (41) improves the signal-to-noise ratio (SNR) of those images, but unfolding artifacts become more noticeable, particularly at R = 4. The results show that the proposed method decreases, though it does not completely eliminate, the aliasing and blurring artifacts seen in standard O-Space TSE even at a relatively modest echo train length of 8. Furthermore, like conventional O-Space, the proposed method shows resilience to undersampling compared to Cartesian SENSE,

especially at the highest acceleration factors. It is notable that the last column in Figure 2 is reconstructed from just 16 CPs (echoes) acquired in only 2 TRs. Finally, some of the banding/shading artifacts in the O-space images in Figure 2 may be caused by distortions in the applied encoding fields, and better field mapping strategies continue to be an active area of research.

We also examined the ability to maintain T2 image contrast by changing the echo spacing with an ETL of 4. In these images there are four bottles: one is pure water (right); one is 1g/L Glycine (left); one is 1g/L cupric sulfate (top); and the last is 2g/L cupric sulfate (bottom). The first row of Figure 3(a) shows fully sampled reference Cartesian images for ESPs of 25, 50, 70, and 90ms, corresponding to TE_{eff} of 75, 150, 210 and 270ms across the columns. The second row in Figure 3(a) shows O-Space TSE reconstructions based on a universal-set target echo (Γ is universal set), so that contrast is for an average T2 weighting across the echoes. This reconstruction approach has the advantage of fully sampling the center of k-space and gives a contrast similar to that expected for a TE corresponding to the middle echo. However, by setting the 3rd echo as the target echo, the proposed reconstruction can specifically retain T2 contrast corresponding to a particular TE.

While Figure 3(a) demonstrates that we can retain the target T2 contrast of the middle echo, Figure 3(b) demonstrates that the presented reconstruction filter can deliver multiple T2 images from a single dataset (TR = 1000ms; ESP = 30ms; ETL = 8; R = 1; Matrix = 128²; FOV = 25cm; 128 points per echo). The first two rows of Figure 3(b) show results from a single dataset reconstructed with filters that designate different effective TEs when evaluating Eq. [3]. The images show increasing T2 contrast consistent with that shown in Figure 3(b). Furthermore, the third row shows a Cartesian image where the center of k-space is acquired in the 5th echo (TE_{eff} = 150ms), and its contrast agrees well with the O-Space TSE reconstruction targeting the 5th echo (TE_{eff} = 150ms).

To make this comparison quantitative, we labeled four bottles as A, B, C and D as shown in Figure 3(b). Intensity ratios among A, B, C and D are both reported and visualized in Figure 3(c), which show good agreement between the image recovered from the 5th target echo (TE_{eff} = 150ms) and the reference Cartesian TSE image, as expected. These experiments illustrate that the proposed time-varying filtered Kaczmarz algorithm can generate artifact free images with different T2 contrast from a single dataset, simply by changing the parameters in the reconstruction.

To demonstrate the utility of the O-Space TSE method, we also present a study of σ_0 and Σ , the new parameters introduced in the modified reconstruction. Figure 4 shows the effect of varying the two filter parameters, σ_0 and Σ from Eq. [3]. In these images, T2-decay is minimized by the very long T2 of the sample (1200ms) relative to the echo times (ESP = 30ms; ETL = 4; Matrix = 128²; R = 2, with a reconstruction targeting echo number 3, so TE_{eff} = 90ms, with six iterations), isolating the effects of the reconstruction parameters. In the first row in Figure 4, we show the effect of changing σ_0 from 11.6cm to 366cm when Σ = 4cm. Like the simulations given in Ref. (32), these results corroborate that at very high σ_0 values (suppressing a larger area of each basis function), the image is somewhat denoised, but the point spread function (PSF) suffers, leading to blurriness in the final image. Whereas

a small filtering area suppresses only the lowest spatial frequencies, which anyway tend to be oversampled, larger filter areas also suppress the medium spatial frequencies that create the smaller features in the image. Losing these leads to the blurring observed from left to right.

In the second row, we explore changing Σ from 0.003cm to 3cm when $\sigma_0 = 30\text{cm}$. Since the spatially varying lambda alters the relative scales of the basis functions used to construct the image, we need to take care that the coefficient on the spatially invariant lambdas (i.e. those of target echoes) are similarly scaled. We do this by adjusting the value of Σ , since for datapoints in the target echo, the value of λ is simply $1 - e^{-(r-CP)/\Sigma}$. In practice, for the present work, Σ and σ_0 were chosen by visual inspection of a single image and the same values were applied to all datasets. Future work will explore the optimization of this and other suppression filters, such as Lorentzian regions of suppression.

Finally, we also show a fully sampled experiment (ESP = 30ms; ETL = 4; Matrix = 128^2) of a grid phantom (T2 = 130ms) demonstrating that our ability to mitigate artifacts from T2-decay is still limited. In the presence of very strong T2 relaxation or very long echo trains, certain artifacts remain in O-Space TSE. Figure 5 shows reconstructions of a single phantom at increasingly large echo spacings and long echo train lengths. Noise and distortions remain, especially at the very highest TE values. With shorter echo spacing however these are not limiting factors.

Discussion

The results prove that challenges which may seem to preclude the possibility of combining nonlinear gradient imaging and TSE acquisition are actually surmountable. The strategy we present provides T2 weighted contrast and reduces the number of needed repetition times, while still maintaining resilience to undersampling. However, other strategies share features with this work, including multi-contrast encoding schemes (8, 10–13, 35, 48, 49), extended two-dimensional trajectories with multi-contrast properties (50–56), and single shot non-linear gradient encoding strategies (20, 21, 27, 29, 57–61).

For example, it is known that linear trajectories that repeatedly sample the center of k-space have the potential to produce images of various contrast. One method (55) describes single-shot multi-echo imaging with rosette trajectories using off-resonance correction and a sliding window reconstruction to generate images with various effective echo times, as well as off-resonance images for each echo time. Another method (56) employed the Rosette trajectory with RF encoding and compressed sensing to generate randomly encoded data that can be used to reconstruct proton density, T2, and field maps. However, since both these methods rely on dynamic waveforms, accurate mapping of the gradient trajectory is crucial and challenging. More recently, MR fingerprinting (62) has been proposed as a general random encoding strategy that can also be used to generate maps with of various contrast parameters.

Radial imaging also repeatedly samples the center of k-space, and so can be used to generate multiple T2 contrasts from a single TSE dataset (8, 10–13, 35, 48, 49). For example, the

KWIC filter (8, 13, 48) is a traditional method to reconstruct multiple aliasing-free images of different contrast from a single radial TSE dataset by using different filters to enhance or reduce the amount each echo time contributes to the center of k-space. Another approach to generating multiple echo images from radial data (12) uses a model-based iterative reconstruction method to avoid the problems associated with data sharing. This method can be used to reconstruct artifact-free images of improved contrast, though it suffers from a large computational load.

In addition, various papers have presented single shot trajectories that use nonlinear gradients (20, 21, 27, 29, 57–60). More recently, experimental results acquired with these single-shot multi-echo sequences were improved with better methods of mapping the gradient trajectories (61). However, these papers used relatively short echo trains and disregarded the contrast and artifacts generated by T2 or T2* decay. Furthermore, the multi-echo sequences cited above focus on modest undersampling factors.

The work presented here is different from previous studies in that it tries to reconcile T2 weighted imaging, which provides important contrast, with projection encoding by nonlinear gradients, which provides potential for high undersampling. Strategies developed for radial TSE or other linear encodings cannot be directly applied, since individual datapoints in nonlinear sequences are not easily categorized as high or low frequency information. Meanwhile, previously presented multi-echo acquisitions with nonlinear gradients have not addressed the contrast and possible artifacts generated by relaxation. Previous multi-echo nonlinear gradient strategies have not presented a scheme that would allow multiple T2 weighted images to be reconstructed from a single highly undersampled dataset.

Conclusions

In this study, we demonstrate the feasibility of applying multi-echo acceleration strategies to O-Space imaging. The experimental results illustrate that the proposed O-Space TSE pulse sequence, with the modified acquisition order and the filtered reconstruction scheme can decrease artifacts introduced by a multi-echo acquisition while still exploiting the high reduction factors associated with O-Space imaging. The proposed reconstruction filter is shown to reduce artifacts from T2 decay, but too much filtering in central k-space can also introduce an artifactual mottled appearance to the image. However, since a single dataset can be reconstructed with selected target T2-weighting, this tradeoff can be assessed offline on a case by case basis. Furthermore, the filtered reconstruction ultimately allows one to generate multiple images with various T2-weighting from a single dataset, which is not possible with a Cartesian TSE acquisition.

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Figure 1.

Pulse sequence diagram of proposed O-Space turbo spin echo (TSE) sequence. Here, the echo train length (ETL) is 4, and echo spacing (ESP) as well as the initial delay before the first echo (TE_1) are labeled. Effective TE (TE_{eff}) is traditionally defined as the time at which the center of k-space is collected, often the $(N/2+1)^{th}$ echo, but this designation is more arbitrary in an O-Space sequence. Each readout gradient is prephased and rephased before the next refocusing pulse in a nonlinear projection imaging scheme.

Figure 2.

Comparisons (256×256) of Cartesian TSE, standard (std) O-Space TSE, and proposed O-Space TSE. Single echo Cartesian and O-Space images are shown at left for reference. The data are acquired with an echo train length of 8, and reduction factors (R) of 1, 2, 4 and 8. The data are acquired with 256 points per readout, with an echo train length of 8 and reduction factors of 1, 2, 4 and 8. The proposed modifications improve O-Space TSE, especially at high echo train lengths. Like O-Space, modified O-Space TSE yields better images than Cartesian SENSE at high levels of undersampling.

(b)

(c)

Figure 3.

(a) T2 weighted images with different echo spacings and effective TEs using Cartesian TSE (first row), and modified O-Space TSE (second and third row). In the second row, the modified acquisition order is applied, but reconstruction does not select a target echo (i.e. Γ is the universal set). This has the benefit of allowing a full sampling of the center of k-space, but every echo in the train also contributes T2 weighting. This will generally lead to a nonspecific T2 contrast, though images can closely resemble the T2 weighting expected at the middle echo. The third row is reconstructed using a filter that targets the middle echo and shows similar contrast. Panel (b) shows that contrast generated by the filter is specific, and it reflects the timing of the targeted echo window. Each image in this series is generated from the same data but uses reconstruction that targets a different echo for contrast. Intensity ratios (c) for the different bottles labeled in the figure show that the image targeting the 5th target echo is most similar to the Cartesian reference image that collects the center of k-space in the 5th echo.

Figure 4.

Image quality is influenced by σ_0 and Σ . σ_0 controls the minimum area of the suppressed region in non-target echoes; Σ sets the (small) suppression area when t falls in the proposed target echoes Γ . All images (128×128) are reconstructed from datasets obtained with $TR = 1000\text{ms}$, $TE_1 = 30\text{ms}$, $ESP = 30\text{ms}$, $R = 2$ and $ETL = 4$, and they are reconstructed by the proposed O-Space TSE method with six iterations.

Figure 5.

Distortions and noise still appear in proposed O-Space TSE imaging in the presence of very strong T2 decay or very long echo train length. Here we show images taken with the same TR (1000ms) and no undersampling, but different TE_1 s (30, 50, 70 and 90 ms), ESPs (30, 50, 70 and 90 ms) and ETLs (4 and 8). All images (128×128) are reconstructed from fully sampled datasets and reconstructed by the proposed O-Space TSE method.