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Single echo reconstruction for rapid and silent MRI

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Synopsis

This work introduces a reconstruction-only approach, dubbed "single echo reconstruction" (SER) to demonstrate (i) the first, rapid 128 x 128 MRI without phase encoding using a 64-channel coil; (ii) significant reduction of RF power, PNS, and gradient noise; (iii) using only a commercially available coil with no external sensors (iv) comparison with gold-standard 2D spin-echo (SE) and accelerated acquisitions for T_2 weighted imaging as an application. For imaging 11 slices with TE = 80ms, the acquisition time was 1.8s with 10.8W total RF deposition, 12.09% peripheral nerve stimulation and no blurring artifacts.

Introduction

Acquisition time (T_{acq}) of a 2D MR image depends on repetition time (TR), number of views (N_v or phase encodes for Cartesian imaging), and number of signal averages (NSA) i.e. $T_{acq} = TR * N_v * NSA$. Further, the acquisition speed is subject to radio-frequency (RF) power deposition, peripheral nerve stimulation (PNS), and gradient noise constraints. Reconstructing a 2D MR image from a single echo mitigates these multiple constraints. However, previous formulations (1, 2) and the associated study (2) using single echo acquisitions with a short Cartesian readout required the number of receive channels using stripline coils equal to N_v (2); or used external magnetosensors (3). In contrast, this work uses a reconstruction-only approach, dubbed "single echo reconstruction" (SER) to demonstrate (i) the first, rapid 128 x 128 MR imaging without phase encoding using a 64-channel coil, i.e., $T_{acq} = T_{encode} * NSA$ where T_{encode} is the time to acquire one echo; (ii) significant reduction of RF power, PNS, and gradient noise; (iii) using only a commercially available coil with no external sensors (iv) comparison with gold-standard 2D spin-echo (SE) and accelerated acquisitions for T_2 weighted imaging as an application.

Methods

Acquisition: The gold standard (GS) method included a 2D multi-slice spin-echo (SE) acquired at two different echo times (TE = 40ms, 80ms). Accelerated sequences included turbo SE (TSE) with a GRAPPA factor of 6, an echo-train-length of 7 and, the half Fourier acquisition single-shot TSE (HASTE). The SER protocol and pulse sequence are shown in fig. 1. Briefly, the pypulseq coded (4,5) sequence acquires only one readout without phase encoding gradients. The reference scan was a pypulseq 2D SE multi-slice with TR/TE = 500/15ms. All acquisitions were acquired on an in vitro phantom (fig. 2) using a 64-channel head coil, had a field-of-view of 256 x 256mm^2, slice thickness=5mm, and eleven slices. The GS, accelerated sequences, and SER were evaluated for acquisition time, total RF power deposited, PNS stimulation, and contrast compared to GS, by recording values from the vendor's user interface (UI).
Reconstruction: The SER method illustrated in figs. 2,3 consists of three steps. Let S be the signal collected over time (t) and channels (q). Let $M(x,y)$ be the object and $C(x_l, y_n, q_o)$ be the coil sensitivity at the location (x_l, y_n) for channel q_o. Then the signal S is given by:

$$S(q,t) = \int_{x,y} M(x,y)C(x,y,q)e^{-i2\pi k_x(t)x} dx\ dy\ [1]$$

Step 1 computes the 1D discrete Fourier transform of S to provide coil-sensitivity weighted projections p. These projections are then concatenated (Eq. [2], fig. 2)

$$p(q_1,k) = F(S(q_1,t))\ [2a]$$

$$P(q,k) = \begin{bmatrix} p(q_1,k) \\ p(q_2,k) \\ . \\ . \\ p(q_{64},k) \end{bmatrix}\ [2b]$$

Step 2 computes the line-intensity profiles of the object's estimate $\hat{M}(x,y)$ by inverting the coil sensitivities for a particular column for all rows and channels (eq. [3], fig. 2 – step 2)

$$\hat{m}(x,y_n) = C_T^{-1}(x,y_n,q)P(q,k_n)\ \mid n = 0,1,\ldots,N-1\ [3a]$$

$$\hat{M}(x,y) = [\,\hat{m}(x,y_1)\ \hat{m}(x,y_2)\ \ldots\ \hat{m}(x,y_{128})\,]\ [3b]$$

Step 2 represents an underdetermined system resulting in a spatially varying point spread function (PSF) blurring corrected in step 3 using a U-net (6) trained for 100 epochs, dubbed the PSFdeblurNet. This operation is analytically equivalent to characterizing the spatially varying PSF at each location and then inverting the entire PSF system matrix (fig. 3c-e). This inversion becomes untenable due to the large matrix size (16384 x 16384), leading to poor condition numbers. The deep learning equivalent PSFdeblurNet's training inputs are generated by forward-modeling the reference scan image using Eqs. [1-3] and corrupting the image by randomly varying amplitude and noise. Fig. 3 f,g shows an example of the training dataset. The models are trained per slice, and inferences are made on images from Eq.[3b] (see fig.3 h,i).

Results and Discussion

Fig. 4 shows the representative reconstructions of one of eleven slices at two TEs for all the methods considered. SER has similar contrast compared to GS without any blurring or saturation of intensities. Fig. 5 shows SER providing the i) highest acceleration (R=128), ii) least power deposited, and iii) the least PNS stimulation (also least gradient noise). In addition to the features in the introduction section, SER (i) does not require additional RF transmit channels for spatial encoding (fig. 1); (ii) does not suffer from blurring artifacts associated with multi-echo sequences (fig. 4); (iii) acceleration methods such as GRAPPA typically provide a reduction factor, $R << N_v$ while SER achieves an $R = N_v$ (figs. 1, 2, 5). SER requires a pre-scan to learn coil sensitivities similar to partial parallel imaging methods. The SER approach does not restrict its acquisition to any particular pulse sequence. This implementation is one of many possible pulse sequences and contrasts. Future work involves in vivo demonstration. SER can significantly accelerate multi-contrast imaging, improve temporal resolution, and enhance SNR through increased averaging.

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Figures

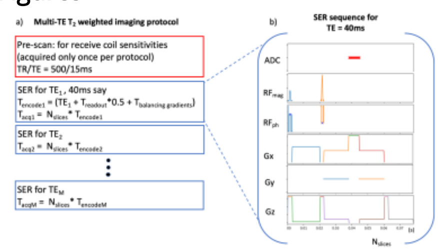

Fig. 1: Acquisition a) A SER protocol requires one pre-scan for coil sensitivities. Application to multi-TE imaging entails acquiring SER data with different TE with the encoding time (T_{encode}) shown in the blue box. (T_{encode}) is not dependent on TR and the number of views but on TE. The number of signal averages was one in this work; b) the implemented pypulseq (4,5) SER pulse sequence timing diagram with no phase encoding (Gy=0). Multi-slice implementation involves repeating the block in blue parentheses for N_{slices} number of slices, 11 in this work

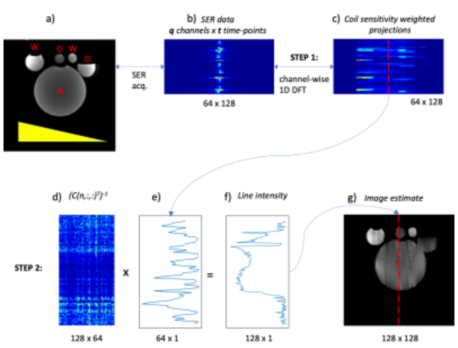

Fig. 2: Reconstruction a) five-cylinder in vitro phantom filled with water (W), vegetable oil (O), or Nickel Sulphate (N) doped water and, the yellow triangle indicates the readout gradient b) corresponding SER data from a 64 channel head coil; c) coil sensitivity weighted projections with the red line marking the 64th column, for a reconstruction example; d) inverse of the relevant coil sensitivity matrix; e) the 64th column of the projection data; f) the resulting line-intensity from the underdetermined system in d),e); g) horizontal concatenation provides the image estimate.

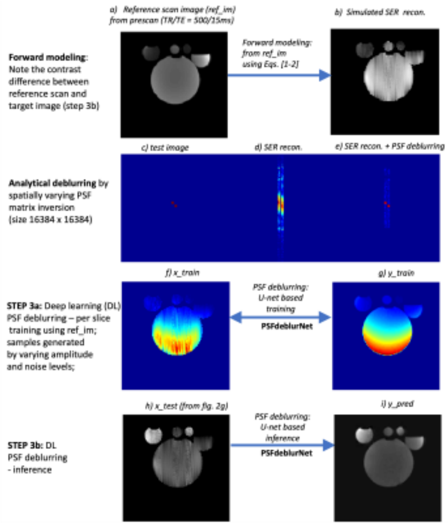

Fig. 3: Spatially varying point spread function (PSF) deblurring a) the reference image (ref_im) used for coil sensitivity mapping; b) corresponding simulated single echo reconstruction (SER) image using Eqs. [1-3] c) a test example depicting the vertical blurring in the SER recon. (d) deblurred by inverting a spatially varying PSF system matrix (e); alternatively, a U-net can be trained (PSFdeblurNet) per slice (f,g) by varying the amplitude and noise levels of ref_im; h) the SER recon. from 2g; i) the corresponding inference using PSFdeblurNet

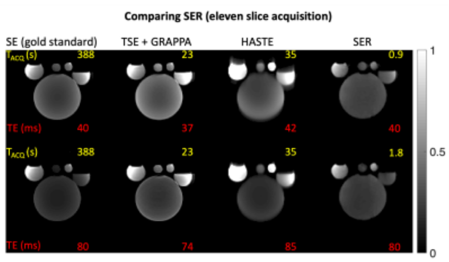

Fig.4: Comparison of SER with other methods for eleven slices - the top row shows vendor-provided gold standard spin-echo (SE), a turbo SE with an ETL of 7 and a GRAPPA factor of 6, a half-Fourier acquisition single-shot TSE (HASTE) at echo times (TE) shown in red font. The corresponding acquisition times (T_{acq}) are shown in yellow font and were recorded from the vendor's user interface. The bottom row shows the corresponding images at TEs close to 80ms allowed by the vendor. SER images acquired using pypulseq at **similar slice locations**, do not suffer from saturation or blurring artifacts.

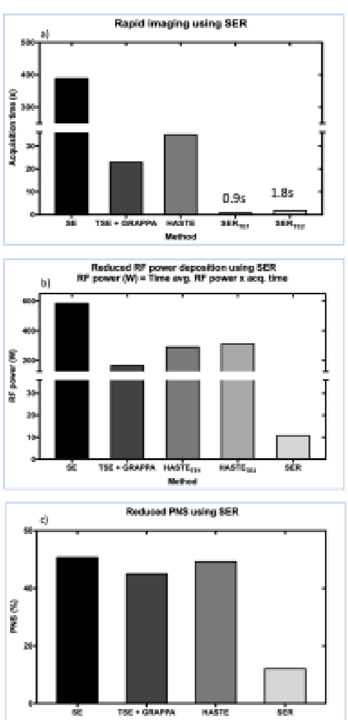

Fig. 5: Single echo reconstruction (SER) imaging performance a) SER provides the fastest acquisition time for the four methods, depends on echo time (TE) rather than repetition time (TR) and phase encoding steps, and is faster than TSE + GRAPPA by an order of magnitude; b) SER delivers the lowest RF power to the phantom among the

methods, due to the one-time use of the 90^0 and 180^0 pulse; c) SER is the most silent scan with the least peripheral nerve stimulation (PNS) percentage due to the one-time use of the readout gradient

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