Single-coil two-fold accelerated spin-echo phase-SENSE imaging of the rodent brain at 9.4T

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INTRODUCTION: The purpose of this work is to extend a two-fold acceleration SENSE-like acquisition method to the family of available acceleration methodologies in spin-echo imaging for single RF coil systems. While SENSE requires spatially varying receive coil sensitivities for image unaliasing (1), phase SENSE (P-SENSE) includes the manipulation of spatially varying magnetization phase of the object being imaged to replace the need for spatially varying coil sensitivities. This method, in turn, relies upon the assumption of real valued reconstructed images, similar to partial-NEX reconstruction (2). The P-SENSE unaliasing technique in two-dimensions is mathematically equivalent to the separation of two simultaneously excited slices in the special case of reception with a single coil (3), where magnetization phase is manipulated in the direction of aliasing in both cases. This is an extension of a gradient recalled echo method presented previously (4).

OVERVIEW OF THE METHOD: A modified two-fold accelerated SENSE acquisition is made, with the addition of a subset of Nyquist critically sampled k_y lines in the center of *k*-space and a shift of all k_y lines. The k_y lines are shifted by Δk_y=0.5 by G_y gradient encoding to create a varying magnetization phase in the direction of image aliasing by means of the Fourier shift theorem. This shift yields a phase that varies linearly in image-space by 180-degrees such that aliased voxels contain signal that differs in phase by 90 degrees. The critically sampled *k*-space lines are extracted as a low spatial resolution reference image of the spatially varying phase.

Image unaliasing proceeds by extending the assumption of a real-valued reconstructed image, common in partial-NEX imaging, to the SENSE equation. A real-valued isomorphism of the complex-valued SENSE method is shown in the below matrix equation, where ***b*** is a vector of the aliased complex image data from one coil, ***x*** is a vector of the true unaliased complex image data, and **A** is the SENSE encoding matrix including the magnitude, **S**, and phase, **θ**, of the known coil sensitivity profile in the voxels that are aliased. In the case of P-SENSE, the assumption of a real-valued reconstructed image halves the number of elements of the reconstructed image vector by eliminating the even elements of the ideal image and the even columns of the encoding matrix thereby yielding a tractable set of equations even if a single coil is utilized. The sensitivity map is set to unity with a single coil while the phase is extracted from the low spatial resolution map. The drawback of this single-coil method is that the generation of the unaliased image may rely upon the solution of an ill-conditioned system of equations if aliased voxels differ in phase by n*180 degrees. Similarly, if an array of coils is used, this method yields a more over determined system of equations, enabling improved unaliasing.

EXPERIMENTAL METHODS: The study was performed on a 9.4T Bruker Biospec 94/30 USR In-Vivo Spectroscopy Imaging System with a quadrature head coil (Doty Scientific). A standard spin-echo pulse sequence was used with manual phase encoding modification. Acquisition parameters were: TR 1000 ms, TE 15 ms, BW 50 kHz, FOV 4 cm, slice thickness 1 mm, 128x128 reconstructed matrix, reduction factor 2, and 32 auto-calibrating lines yielding an acceleration factor of 1.5.

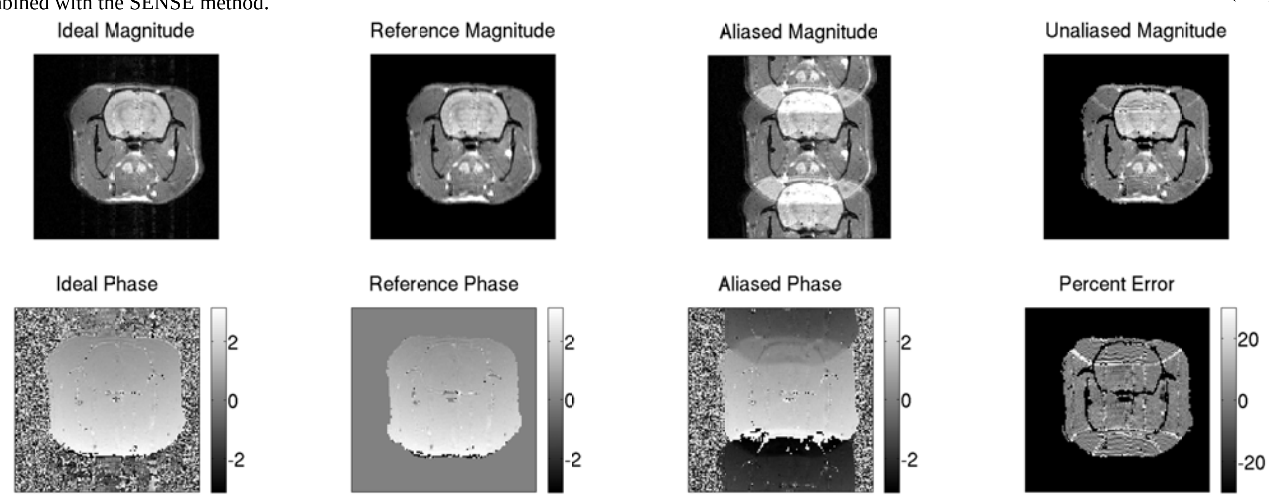
RESULTS and DISCUSSION: Results are shown below. The first three columns show the magnitude (first row) and phase (second row) of the ideal, auto-calibration and aliased image data. The unaliased image is the final image of the first row and percent error with respect to the ideal image is the final image of the second row. Compared to GRE acquisitions, the phase smoothly varies, yielding better controlled phase aliasing in the spin echo method.

In the presented study, a fully sampled data set was decimated for synthetic acceleration. This decimation allows un-confounded comparision between ideal and unaliased images, while preserving identical assumptions to the implemented P-SENSE model. The phase map was thresholded to include voxels with magnitudes greater than 15% of the maximal reference amplitude image. In pixels where the second column of matrix **A** had zero values, the amplitude of ***b*** was copied to the top image half $\boldsymbol{x}_{1R}$. Similarly, the bottom half $\boldsymbol{x}_{2R}$ was created when the first column had zero values. It must be noted that in such pixels the determinant of **A** is zero and the use of the inverse matrix $\mathbf{A}^{-1}$ to solve equations is futile. The byproduct of this procedure is a substantial elimination of noise from the areas outside the phantom.

Artifacts are apparent at the locations where an edge of the image was aliased with a central portion of the image. This high spatial frequency artifact is associated with the use of a low spatial resolution reference image. In this case, spatial smoothing yields imperfect estimation of high spatial frequency components like edges. This artifact is preferentially in the phase encoding direction because only high spatial frequencies in the phase encoding direction are not sampled in the reference data. Because of this preferential artifact, creative image processing procedures can effectively remove the artifact. Specifically, applying a median filter in the phase encoding direction with a width of 3 voxels greatly attenuates this artifact (not shown).

CONCLUSION: This abstract shows that when assuming a real-valued reconstructed image, sensitivity encoding can be performed, utilizing the phase of the acquired image even if the receiver sensitivity is uniform. Previous work has shown that magnetization phase in GRE acquisitions can be modulated by proper shimming and tailored RF pulses. Here the method is extended to spin echo imaging through the use of the Fourier shift theorem. This enables a P-SENSE acceleration factor of 2 in a spin echo acquisition with a single coil. This work shows that a spin echo experiment yields better controlled phase information exists for unaliasing than in previous GRE studies. In a multi-coil environment, final images can be obtained in the complex form and further processing like half-NEX and/or multi-slice excitation can be combined with the SENSE method.

$$\begin{pmatrix} \cos(\theta_1)S_1 & -\sin(\theta_1)S_1 & \cos(\theta_2)S_2 & -\sin\theta_2 S_2 \\ \sin(\theta_1)S_1 & \cos(\theta_1)S_1 & \sin(\theta_2)S_2 & \cos(\theta_2)S_2 \end{pmatrix} \begin{pmatrix} x_{1R} \\ x_{1I} \\ x_{2R} \\ x_{2I} \end{pmatrix} = \begin{pmatrix} b_R \\ b_I \end{pmatrix}$$



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