Banding artifacts in steady state free precession (SSFP) magnetic resonance imaging (MRI) are reduced by acquiring and combining multiple SSFP images in an augmented matrix where an acquisition vector in k-space is equal to a Fourier matrix of the trajectory on a known distortion operator for each trajectory in k-space.
FIG. 1A
(Prior Art)

FIG. 1B
(Prior Art)
In accordance with the invention, multiple acquisition SSFP is posed as a generalization of sensitivity encoding (SENSE; see Pruessman et al., "Advances in Sensitivity Encoding with Arbitrary k-Space Trajectories", MRM2001; 46:638-651), or as a super Field of View (sFOV) image reconstruction. In sFOV imaging, a set of distorted aliased small sFOV representations of a larger FOV object are obtained, and a full FOV undistorted object is obtained from k-space data using an acquisition vector and an encoding matrix based on a known distortion operator and the Fourier matrix of the specific k-space trajectory.

More specifically, a steady state is established at one resonant frequency with a specific banding pattern. A first subset of a full data set is acquired, and then a steady state is established at a different resonant frequency and banding pattern, and again a second subset of a full data set is acquired. These steps are repeated until a full data set is acquired. A spatial banding pattern is estimated for each frequency, and then the image is reconstructed using the estimated spatial banding patterns.

Using the invention, banding artifacts in SSFP imaging are reduced while magnetic resonance scan time is also reduced.

The invention and objects and features thereof will be more readily apparent from the following detailed description and appended claims when taken with the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1A, 1B illustrate a SSFP phase sequence in accordance with prior art.

FIG. 2 illustrates SSFP transverse magnetization and phase as a function of off-resonance frequency for a SSFP profile.

FIGS. 3A-3C are outlines of the imaging and reconstruction processes for 2D and 3D Cartesian, radial, and spiral acquisitions, respectively.

FIG. 4 illustrates a comparison of the sFOV method with the conventional full k-space multiple acquisition SSFP for radial imaging.

DUEATED DESCRIPTION OF THE PREFERRED EMBODIMENTS

As illustrated in FIGS. 1A, 1B, a refocused SSFP sequence includes a single RF excitation which is repeated periodically. All gradients used for slice selection or imaging are fully rewound over each repetitive time, TR. In the steady-state, the magnetization at points a and d is the same.

Magnetization is tipped about a traverse axis through an angle $\alpha$. Between excitations, the magnetization undergoes a precession by an angle $0=2\pi \Delta f T R$ about the $z$-axis (direction of $B_0$), where $\Delta f$ is the tissue off-resonance, and also experiences both T1 and T2 relaxation.

During the sequence each spin is affected by RF pulses, relaxation and free precession. The steady-state magnetization for SSFP is a function of the sequence parameters flip angle $(\alpha)$, repetition time (TR) and echo time (TE) as well as the tissue parameters T1, T2, and resonant frequency shift $\Delta f$. 

In accordance with the invention, banding artifacts in SSFP imaging are reduced while magnetic resonance scan time is also reduced.

SUMMARY OF THE INVENTION

In accordance with the invention, banding artifacts in SSFP imaging are reduced while magnetic resonance scan time is also reduced.
[0020] Signal readout is performed each period, and low spatial frequency information can be acquired at an echo time TE typically spaced midway between the RF excitation pulse. The resultant steady-state MR signal is a strong function of the local resonant frequency, as shown in FIG. 2, which shows magnetization or signal profiles (i.e., off-resonance spectra). SSFP transverse magnetization magnitude (top) and phase (bottom) are shown as a function of off-resonant frequency. Each graph shows three different tip angles: the solid line corresponds to a 90° tip angle, the dotted line 60°, and the dashed line 30°. Profiles are shown for three different TI/T2 combinations: TI/T2=200/100 ms (left), TI/T2=600/100 ms (middle), and TI/T2=1000/100 ms (right). TE=TR/2 in all cases. The periodic nulls in the signal profile, separated by a frequency of 1/TR, are the source of off-resonance banding artifacts. If the phase ϕ of the RF excitation pulse is incremented by a constant value Δϕ for each RF pulse to achieve “phase cycling” [0021] In accordance with the invention, the multiple acquisition SSFP imaging process is treated as a sFOV reconstruction to produce an image with reduced or no banding artifact without the time penalty of multiple acquisition SSFP. [0022] In an sFOV setting one measures a set of distorted, aliased small FOV representations of a larger FOV object. The distortion for each image is different, known and linear. For example, a distortion can be due to motion, blur, sensitivity mask or geometric distortion. The k-space trajectory is arbitrary and can be different for each of the images. This is a generalization of SENSE, where the distortion is due to the sensitivity of the receiver coil and the k-space trajectory is the same for all the coil images. The k-space data yᵢ for each image version can be written as,

\[ yᵢ = Sᵢm \]  

where m is the full FOV undistorted object, Sᵢ is the known distortion operator of the i'th image and Fᵢ is the Fourier matrix of the specific k-space trajectory. We can write this in an augmented matrix as,

\[ Y = [y₁^T, ... , yₙ]^T \]

\[ S = [S₁, ... , Sₙ] \]

[0023] where Y = [y₁, ..., yₙ]^T is the acquisition vector and E = [E₁, ..., Eₙ] is an encoding matrix. This is a linear set of equations and can be solved for m in many ways. See Pruessmann et al., “Advances in Sensitivity Encoding with Arbitrary k-Space Trajectories”, MRM2001; 46:638-651, supra, for example. We can now formulate the multiple acquisitions SSFP as an sFOV problem. The SSFP signal exhibits a high sensitivity of both magnitude and phase to off-resonance frequency. By changing the RF phase cycling the response is shifted in frequency. This can be thought of as different distortions that operate on the object. Since in general, off-resonance is slowly varying, the SSFP sensitivity (Sᵢ) can be measured from low-resolution information with little or no overhead. Alternatively, the sensitivity maps can be estimated from frequency maps and the SSFP signal sensitivity to off resonance frequency (FIG.2). Therefore, instead of acquiring multiple full k-space images we can sub-sample k-space and acquire aliased small FOV image versions with different RF phase increments. We then use Eq. 2 and unfold the aliasing using the measured low-resolution sensitivity information (Sᵢ). This approach is general and can, in principle, be used in Cartesian, radial or spiral trajectories (FIGS. 3A-3C). [0024] FIG. 3A is an outline of the imaging and reconstruction process for 2D and 3D Cartesian acquisition. N separate under sampled k-space images are acquired, each with a different RF phase increment. The k-space lines for each image are chosen in such a way that a full-FOV low resolution image can be reconstructed. The images from each RF phase increment acquisition suffer from aliasing artifacts as well as banding artifact. Sensitivity maps are calculated from the low resolution information. A banding free, aliasing free image is reconstructed from the k-space and the sensitivity maps using Eq. 2. [0025] FIG. 3B is an outline of the imaging and reconstruction process for 2D and 3D radial acquisition. N separate under sampled k-space images are acquired, each with a different RF phase increment. In radial imaging the center of k-space is over-sampled and a full-FOV low resolution image can be reconstructed. The images from each RF phase increment acquisition suffer from aliasing artifacts as well as banding artifact. Sensitivity maps are calculated from the low resolution information. A banding free, aliasing free image is reconstructed from the k-space and the sensitivity maps using Eq. 2. [0026] FIG. 3C is an outline of the imaging and reconstruction process for a spiral acquisition. N separate under sampled k-space images are acquired, each with a different RF phase increment. In variable density spiral imaging the center of k-space is over-sampled and a full-FOV low resolution image can be reconstructed. The images from each RF phase increment acquisition suffer from aliasing artifacts as well as banding artifact. Sensitivity maps are calculated from the low resolution information. A banding free, aliasing free image is reconstructed from the k-space and the sensitivity maps using Eq. 2. [0027] When acquiring several images at different RF phase increments, there is a small penalty in the time it takes to get into the steady state. An extension of our method with frequency modulated SSFP can be used to eliminate the transitional state time. [0028] FIG. 4 shows the result of an in-vivo radial acquisition experiment and a comparison of the sFOV method with the conventional full k-space multiple acquisition SSFP for radial imaging. Both the sFOV and multiple acquisition methods exhibit similar quality. However, the sFOV method requires 25% of the scan time for the full k-space multiple acquisition method. a) Undersampled images with different RF phase increments. b) sFOV reconstruction. c) Multiple acquisition sum of squares SSFP. The experiment was conducted on a 1.5T GE Signa scanner with gradients capable of 40 mT/m and 150 mT/m/ms maximum slew-rate. Four images with corresponding 0, 90, 180 and 270 RF phase increments of an axial slice through the head (FOV=24 cm, res=1 mm) were acquired using a 2D radial balanced SSFP sequence (TR=8.32 ms, TE=1.3 ms, n=30). Each image was obtained by collecting 133 spokes with a 3 ms readout, which is 25% of the actual FOV (full FOV corresponds to 552 spokes). The inherent oversampling of the k-space origin was used for sensitivity estimation. The image was reconstructed using iterative conjugate-gradient method with min-max mFFT. See Fessler et al. “Nonuniform Fast Fourier Transforms Using Min-Max Interpol-
tion”, IEEE Trans on Sig Proc, 2003; 51:560-574. The result was compared to a full FOV multiple acquisition sum-of-squares. It is important to note that since we acquire several different images one after the other, the k-space trajectory is different for each of the images. For example, in the radial case the first image will have the 1st, 5th, 9th ... spokes, the second image will have the 2nd, 6th, 10th, ... spokes etc. Because of this, the encoding matrix is well conditioned and the reconstruction does not suffer a significant loss in SNR as can happen in SENSE imaging.

While the invention has been described with reference to specific embodiments, the description is illustrative of the invention and is not to be construed as limiting the invention. Various modifications and applications may occur to those skilled in the art without departing from the true spirit and scope of the invention as defined by the appended claims.

1. In magnetic resonance imaging using steady state free precession (SSFP), a method of reducing banding artifacts comprising the steps:
   a) establishing a steady state at one resonant frequency, with a specific spatial banding pattern,
   b) acquiring a first subset of a full spatial frequency data set,
   c) changing to a steady state having a different resonant frequency and banding pattern,
   d) acquiring a second subset of the full spatial frequency data set,
   e) repeating steps c) and d) until a full data set is collected,
   f) estimating a spatial banding pattern for each frequency, and
   g) reconstructing an image using the estimated spatial banding patterns, and the known spatial frequency encoding of the acquired data using an inversion of the matrix equation
   \[ Y = E m \]
   where \( Y \) is the vector of the acquired data, \( Y = [y_1^T, \ldots, y_n^T]^T \), \( E \) is the encoding matrix, \( E = [F_1 S_1^T, \ldots, (F_n S_n^T)]^T \), \( m \) is the object being imaged,
   \( S_i \) is a known distortion operator of the \( i \) th image,
   \( F_i \) is the Fourier matrix of a specific k-space trajectory.

2. The method of claim 1, where the spatial banding patterns are estimated from low resolution images.

3. The method of claim 1, where the spatial banding patterns are estimated from low resolution field map information.

4. The method of claim 1, where the spatial frequency data subsets b) and d) are small field-of-view aliased images.

5. The method of claim 1, where the spatial frequency data subsets b) and d) are obtained in a single acquisition while the banding pattern is continuously changed by modulating the frequency.

6. The method of claim 1, where the full spatial frequency data set is acquired using a radial trajectory in spatial frequency space.

7. The method of claim 1, where the full spatial frequency data set is acquired using a Cartesian trajectory in spatial frequency space.

8. The method of claim 1, where the full spatial frequency data set is acquired using a Spiral trajectory in spatial frequency space.

9. (canceled)

10. The method of claim 1 wherein step a) employs Cartesian 2 Dimensional acquisition.

11. The method of claim 1 wherein step a) employs Cartesian 3 Dimensional acquisition.

12. The method of claim 1 wherein step a) employs radial 2 Dimensional acquisition.

13. The method of claim 1 wherein step a) employs radial 3 Dimensional acquisition.

14. The method of claim 1 wherein step a) employs spiral 2 Dimensional acquisition.

15. The method of claim 1 wherein step a) employs spiral 3 Dimensional acquisition.

16. The method of claim 1 where frequency modulated SSFP sequences are employed for vector acquisition.

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