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Reeder

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(54) **GENERALIZED METHOD FOR MRI CHEMICAL SPECIES SEPARATION USING ARBITRARY K-SPACE TRAJECTORIES**

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(51) **Int. Cl.**
G01V 3/00 (2006.01)

(52) **U.S. Cl.** **324/312**; 324/309

(58) **Field of Classification Search** 324/300–322; 600/407–435

See application file for complete search history.

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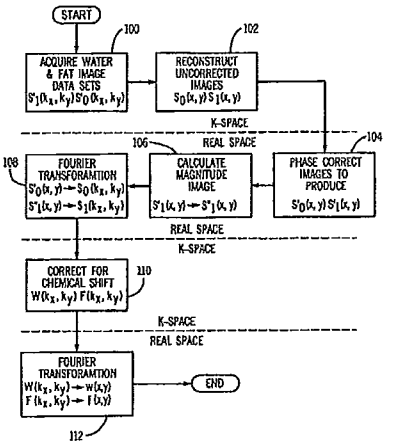
(57) **ABSTRACT**

A method for producing images of a subject containing M spin species using a magnetic resonance imaging (MRI) system includes obtaining N k-space data matrices from N k-space data sets acquired with the MRI system using a pulse sequence with an individual associated echo time. The k-space data matrices each include corresponding data at the same plurality of k-space locations and time stamps are tracked for each k-space location. For each k-space location, a set of linear equations in k-space is solved. The set of linear equations relates corresponding data from the N k-space data matrices, echo times and time stamps to desired calculated k-space data. Calculated data in k-space which is corrected for chemical shift is produced corresponding to each k-space location and aggregated to obtain a k-space calculated data set. The k-space calculated data set is transformed to image space to obtain a corresponding image.

35 Claims, 8 Drawing Sheets



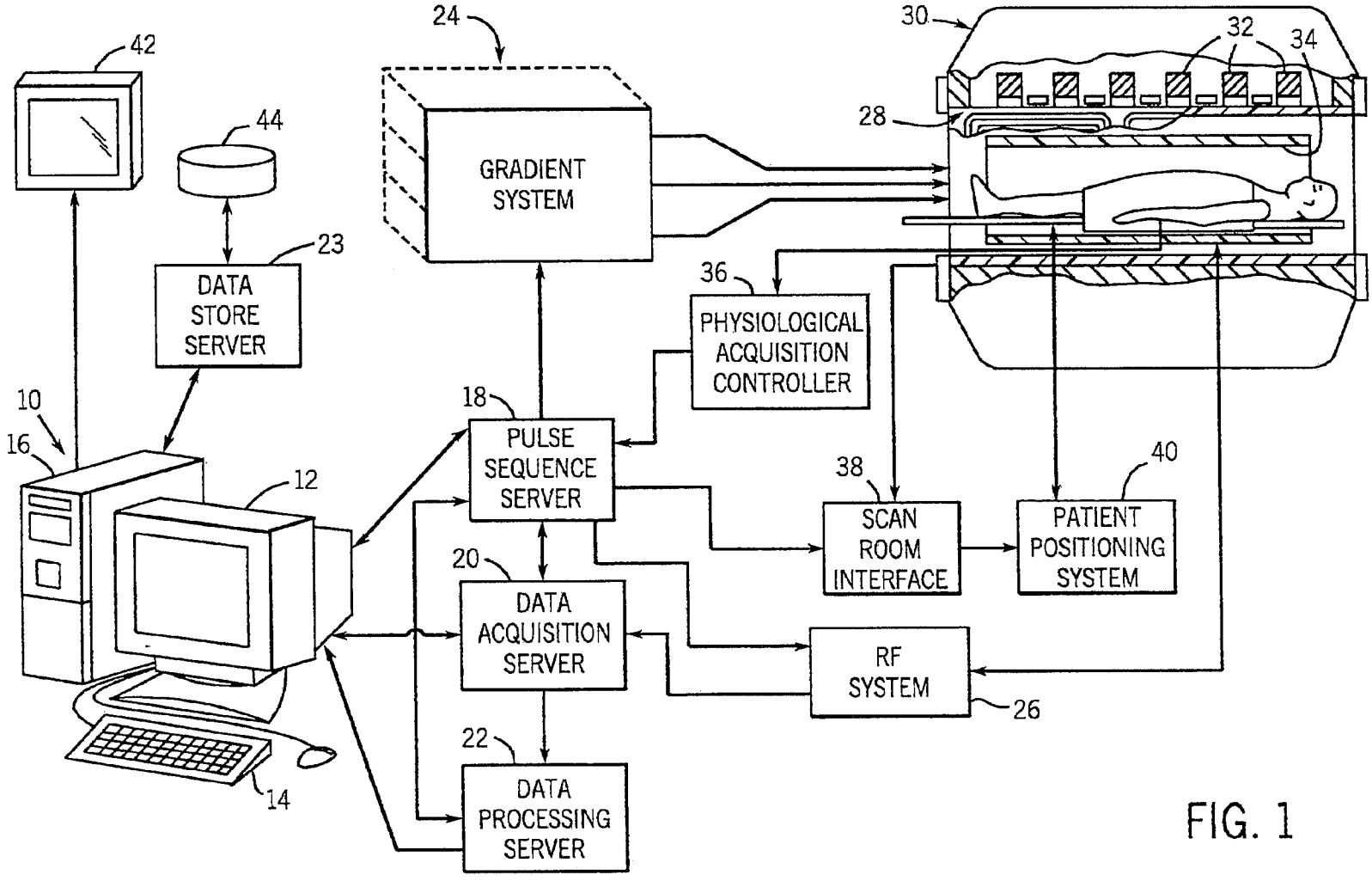

42
44
23
DATA STORE SERVER
24
GRADIENT SYSTEM
30
32
34
28
36
PHYSIOLOGICAL ACQUISITION CONTROLLER
10
16
12
18
PULSE SEQUENCE SERVER
38
SCAN ROOM INTERFACE
40
PATIENT POSITIONING SYSTEM
20
DATA ACQUISITION SERVER
RF SYSTEM
26
22
DATA PROCESSING SERVER
14

FIG. 1

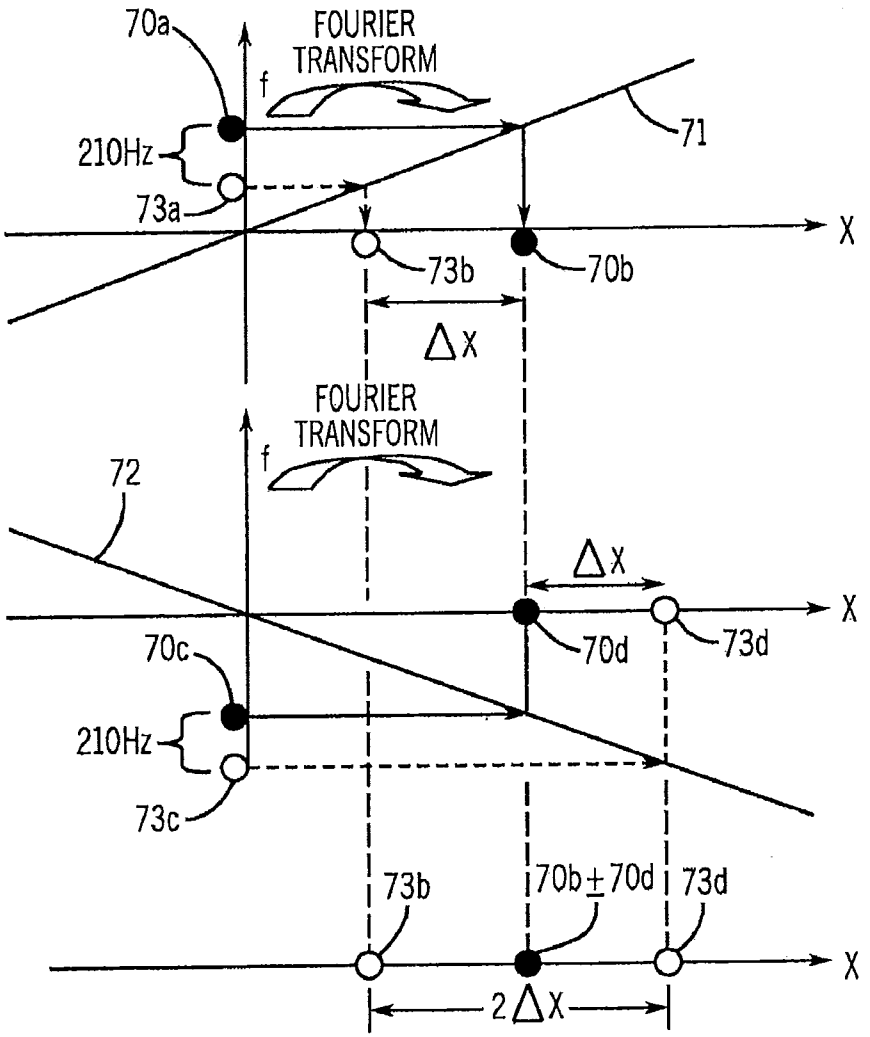

70a
FOURIER TRANSFORM
f
71
210Hz
73a
X
73b
70b
ΔX
FOURIER TRANSFORM
f
72
ΔX
X
70d
73d
70c
210Hz
73c
73b
70b±70d
73d
X
2ΔX

FIG. 3

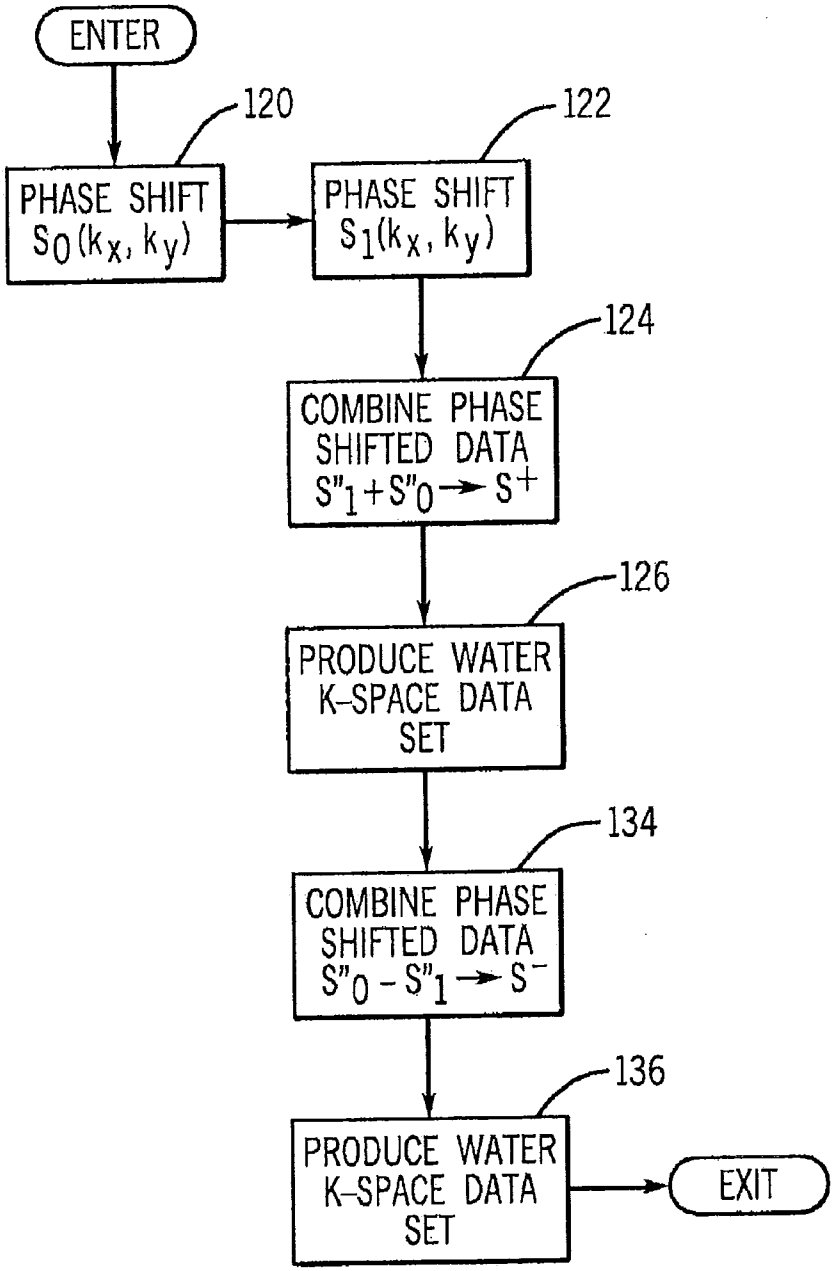

ENTER
120
PHASE SHIFT $S_0(k_x, k_y)$
122
PHASE SHIFT $S_1(k_x, k_y)$
124
COMBINE PHASE SHIFTED DATA $S''_1 + S''_0 \rightarrow S^+$
126
PRODUCE WATER K-SPACE DATA SET
134
COMBINE PHASE SHIFTED DATA $S''_0 - S''_1 \rightarrow S^-$
136
PRODUCE WATER K-SPACE DATA SET
EXIT

FIG. 5

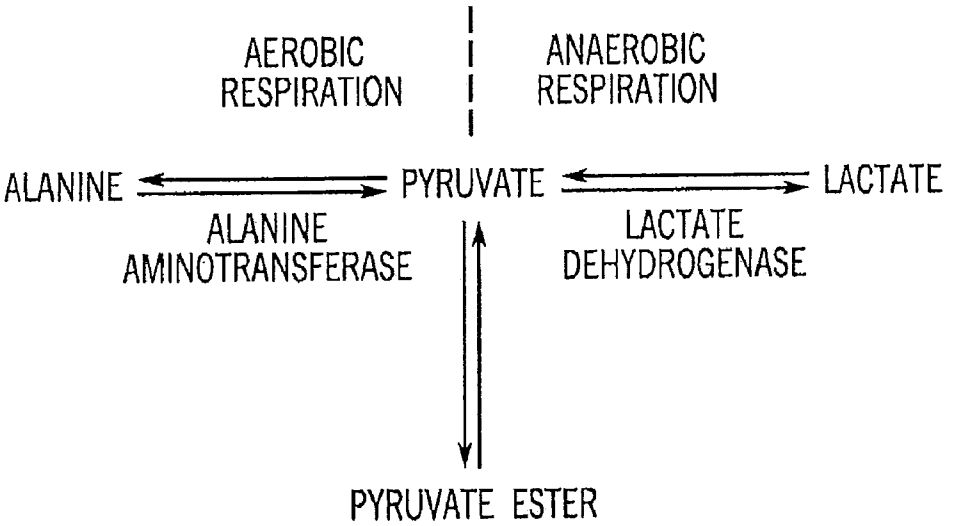

AEROBIC RESPIRATION
ANAEROBIC RESPIRATION
ALANINE
PYRUVATE
LACTATE
ALANINE AMINOTRANSFERASE
LACTATE DEHYDROGENASE
PYRUVATE ESTER

FIG. 7(a)

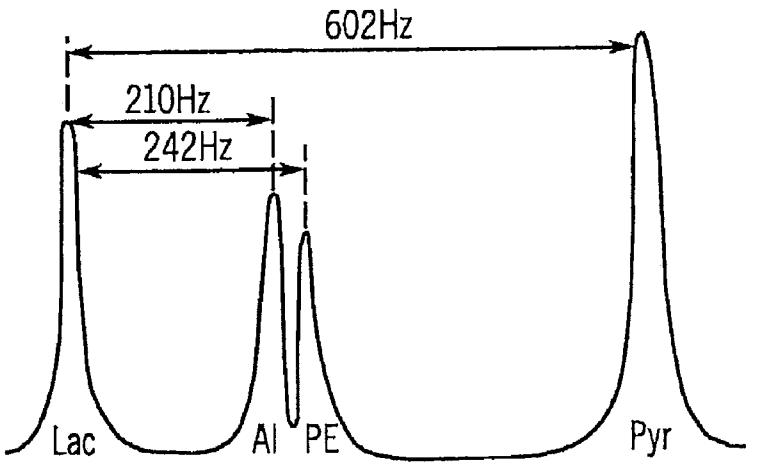

602Hz
210Hz
242Hz
Lac
Al
PE
Pyr

FIG. 7(b)

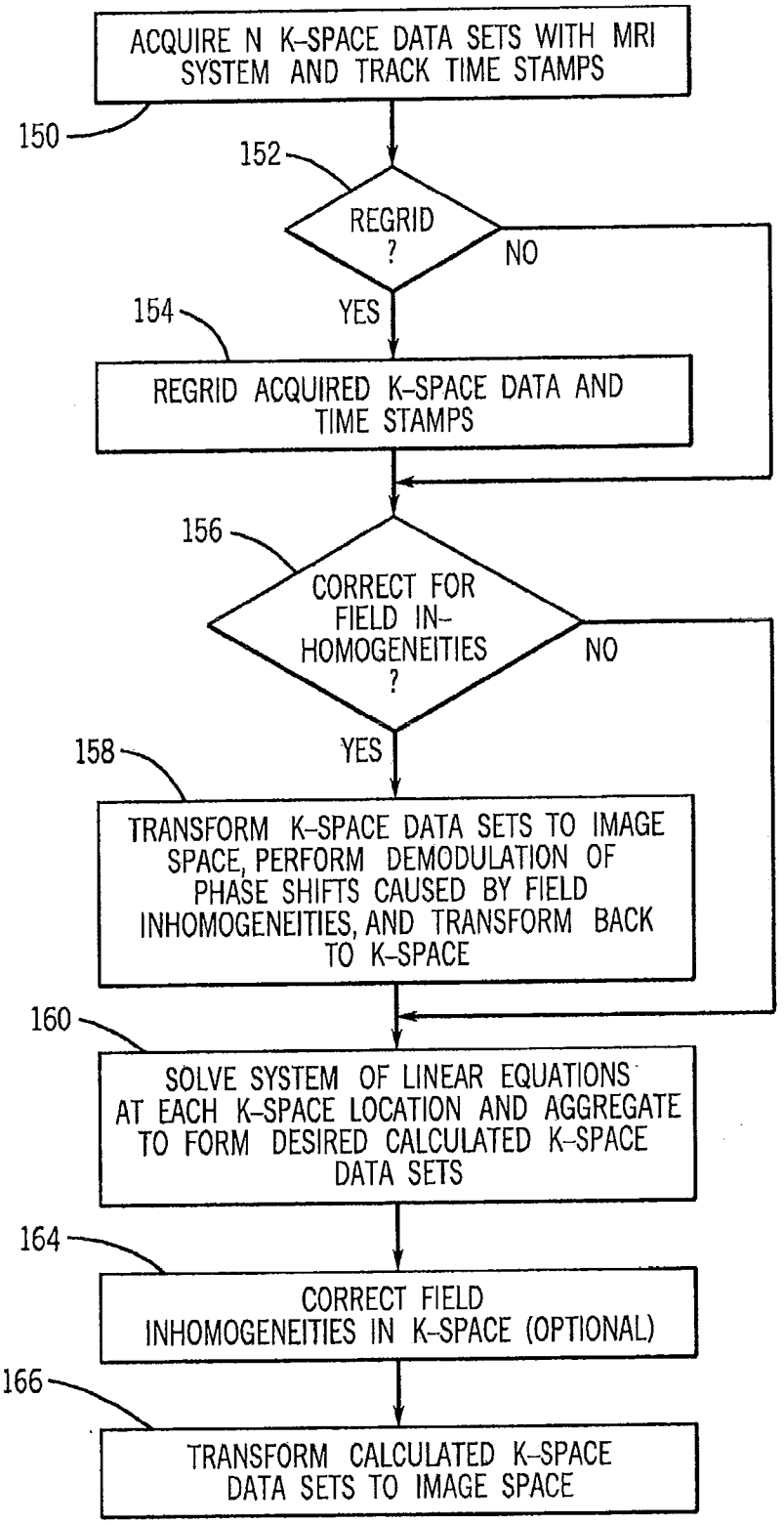

ACQUIRE N K-SPACE DATA SETS WITH MRI SYSTEM AND TRACK TIME STAMPS
150
152
REGRID ?
NO
YES
154
REGRID ACQUIRED K-SPACE DATA AND TIME STAMPS
156
CORRECT FOR FIELD IN-HOMOGENEITIES ?
NO
YES
158
TRANSFORM K-SPACE DATA SETS TO IMAGE SPACE, PERFORM DEMODULATION OF PHASE SHIFTS CAUSED BY FIELD INHOMOGENEITIES, AND TRANSFORM BACK TO K-SPACE
160
SOLVE SYSTEM OF LINEAR EQUATIONS AT EACH K-SPACE LOCATION AND AGGREGATE TO FORM DESIRED CALCULATED K-SPACE DATA SETS
164
CORRECT FIELD INHOMOGENEITIES IN K-SPACE (OPTIONAL)
166
TRANSFORM CALCULATED K-SPACE DATA SETS TO IMAGE SPACE

FIG. 8

opposite direction when the readout gradient is reversed. The chemical shift (in pixels) between fat signals in the two images is:

$$\Delta x = \frac{N_x \Delta f}{2BW} \tag{3}$$

where BW is readout bandwidth, typically ±20-125 kHz, N_x is the number of k-space samples in the readout matrix and Δf is the chemical shift between water and fat, about −210 Hz at 1.5 T. In the discussion below all of the chemical shift is attributed to fat because the system center frequency is tuned to water. The chemical shift can be shifted to water by changing the rf center frequency or it can be set to some value between water and fat.

The phase ϕ_0 is removed by dividing out the phase of equation (1) from both the signals of equation (1) and (2) such that,

$$s_0'(x,y)=(w(x,y)+f(x-\Delta x,y)) \tag{4}$$

and

$$s_1'(x,y)=(w(x,y)-f(x+\Delta x,y))e^{i\Delta\phi(x,y)} \tag{5}$$

where Δx is the chemical shift measured in pixels.

If the phase map $e^{i\Delta\phi(x,y)}$ is known, it can be demodulated from the second image of equation (5), and w(x,y) and f(x,y) can easily be determined. In general, we do not know $\Delta\phi(x,y)$, although we can remove its effect by taking the magnitude of equation (5). This leads to a natural ambiguity, depending on whether the pixel is water dominant (w(x,y)>f(x,y)) or fat dominant (f(x,y)<w(x,y)).

A phase unwrapping algorithm such as that described in the above-cited Jingfei Ma reference is used to resolve this ambiguity. A correct solution for the magnitude and sign of each pixel in the image $s_1'(x,y)$ yields:

$$s_1''(x,y)=\pm|w(x,y)-f(x+\Delta x,y)|. \tag{6}$$

If we take the Fourier transformation of the resulting two images of equations (4) and (6), we have the corresponding k-space data sets:

$$S_0=FT\{s_0'(x,y)\}=W(k_x,k_y)+F(k_x,k_y)e^{i\Delta x\Delta Xk_x} \tag{7}$$

and

$$S_1=FT\{s_1''(x,y)\}=W(k_x,k_y)-F(k_x,k_y)e^{-i\Delta x\Delta Xk_x}. \tag{8}$$

From these k-space data sets and noting that $\Delta X=FOV/N_x$ is the pixel dimension (cm), and k-space is sampled from $-k_x^{max}$ to $+k_x^{max}$, with $k_x^{max}=\pi/\Delta X$, we can calculate separate water and fat k-space data sets $W(k_x,k_y)$ and $F(k_x,k_y)$ as,

$$W(k_x,k_y)=\frac{S_0e^{-i\Delta x\Delta Xk_x}+S_1e^{i\Delta x\Delta Xk_x}}{e^{-i\Delta x\Delta Xk_x}+e^{i\Delta x\Delta Xk_x}}=\frac{S_0e^{-i\Delta x\Delta Xk_x}+S_1e^{i\Delta x\Delta Xk_x}}{2\cos(\Delta x\Delta Xk_x)} \tag{9}$$

and

$$F(k_x,k_y)=\frac{S_0e^{-i\Delta x\Delta Xk_x}-S_1e^{i\Delta x\Delta Xk_x}}{2}+W\frac{(e^{-i\Delta x\Delta Xk_x}-e^{i\Delta x\Delta Xk_x})}{2}=\frac{S_0-S_1}{2\cos(\Delta x\Delta Xk_x)}. \tag{10}$$

Note that the denominator will never be zero so long as $\Delta x\neq N_x$ and

$$k_x=\Delta k(n_x+1/2),\ n=\left[\frac{-N_x}{2},\ \frac{N_x-1}{2}\right].$$

Finally, the water image (w(x,y)) and fat image (f(x,y)) are reconstructed by calculating the inverse Fourier transformation of these k-space data sets of equations (9) and (10). Note that if Δx is very small (zero), equations (9) and (10) reduce to the expected solutions,

$$W=\frac{S_0+S_1}{2} \tag{11}$$

and

$$F=\frac{S_0-S_1}{2}. \tag{12}$$

Another aspect of the present invention is the recognition that these same or similar principles can be applied to spiral, projection reconstruction and other non-spin-warp (non-Cartesian coordinate) k-space trajectories. Thus, another important aspect of the present invention is a generalized method for correcting for chemical shift artifacts in k-space which allows for k-space data to be obtained using various k-space trajectories.

In particular, the generalized method includes acquiring N k-space data sets with the MRI system, with each data set acquired using a pulse sequence having an individual associated echo time t_n. A time stamp $\tau_{k,n}$ is tracked for each k-space location for which data is acquired, with the time stamp being indicative of data acquisition time relative to a reference, such as the time from the center of k-space to when the data is acquired for that particular k-space location. The acquired k-space data sets are regridded if necessary (e.g., if non-Cartesian k-space trajectories are used in the acquisition) using conventional regridding techniques so that N k-space matrices are obtained, each including corresponding data at the same plurality of Cartesian k-space locations. The acquired time stamp data are also regridded if necessary. A system of linear equations in k-space is formulated that relates, at each Cartesian k-space location, data corresponding to that same k-space location from the N obtained k-space data matrices, echo times, and time stamps to desired calculated k-space data. For each Cartesian k-space location, the system of linear equations in k-space is solved to obtain the desired calculated k-space data, and the k-space calculated data from all the k-space locations is aggregated to obtain one or more calculated k-space data sets. For example, a system of linear equations can be formulated such that the calculated k-space data sets produced are separate species k-space data sets such that chemical species such as water and fat are separated from one another. In other embodiments, in-phase or out-of-phase species combination k-space data sets can be calculated. Further, the system of linear equations can be formulated such that chemical species with multiple peaks can be separated. The calculated k-space data set is transformed to image space to obtain one or more corresponding images, such as separate species images, in-phase or out-of-phase images, or the like.

to obtain separate images for each species, free from the blurring or shifting effects of chemical shift.

In the simplified case with two chemical species such as water (W) and fat (F), and with the receive frequency of the MRI system being set to the water frequency, equation (14) can be written as follows:

$$S_n(\tau_{k,n},k)=w(k)+f(k)e^{i2\pi\Delta f_m(t_n+\tau_{k,n})} \quad (19)$$

Then the $A_{k,n}$ matrix can be expressed as:

$$A_{k,n}=\begin{vmatrix} d_{11}(k) & c_{21}d_{21}(k) \\ d_{12}(k) & c_{22}d_{22}(k) \\ \cdots & \cdots \\ d_{1N}(k) & c_{2N}d_{2N}(k) \end{vmatrix}=\begin{vmatrix} 1 & c_{21}d_{21}(k) \\ 1 & c_{22}d_{22}(k) \\ \cdots & \cdots \\ 1 & c_{2N}d_{2N}(k) \end{vmatrix} \quad (20)$$

Note that the $c_{1n}(k)$ and $d_{1n}(k)$ terms equal one because Δf_w equals zero.

This can be further simplified if a pulse sequence is used to acquire the N k-space data sets wherein the k-space trajectories are the same for all of the n echoes (such as single echo/TR or EPI with flyback readouts), according to equation (18) above with:

$$A=\begin{vmatrix} 1 & e^{i2\pi\Delta f_m(t_1)} \\ 1 & e^{i2\pi\Delta f_m(t_2)} \\ \cdots & \cdots \\ 1 & e^{i2\pi\Delta f_m(t_n)} \end{vmatrix} \quad (21)$$

$$D^H=\begin{vmatrix} 1 & 0 \\ 0 & e^{i2\pi\Delta f_m(\tau_k)} \end{vmatrix} \quad (22)$$

Here again, t_n is the echo time and τ_k is the time relative to the echo time t_n when each point in k-space was acquired. Note that τ_k is independent of the echo number, i.e., it is the same for all the images. For a Cartesian acquisition, this would be equivalent to applying a phase roll on the fat along the direction of the readout.

Another object of the invention is to extend the above k-space formulations to develop a generalized system of linear equations in k-space which can be used to calculate in-phase (W+F) images and/or out-of-phase (W−F) images, and/or other species combination images. These in-phase (IP) and out-of-phase (OP) images are a convenient clinical tool for visualization of microscopic fatty infiltration of tissue in various applications. For example, such images can provide important information regarding hepatic steatosis or adrenal adenomas. Using spin-warp imaging, there will be a simple misregistration (shift) of the entire fat image relative to the water image. Conventionally, a sinc interpolation is performed on the fat image to realign it with the water image before calculating recombined images that are free of chemical shift artifact:

1. IP=abs(W)+abs(F)
2. OP=abs(abs(W)−abs(F))

However, a generalized system of linear equations in k-space as set forth below allows for direct estimates of recombined W+F and W−F images and may offer improved SNR performance over recombining images in image space as conventionally done. Specifically, estimates of k-space for IP data can be obtained by rewriting equation (19) as follows:

$$S_n(\tau_{k,n},k)=(w(k)+f(k))+f(k)(e^{i2\pi\Delta f_m(t_n+\tau_{k,n})}-1)$$

$$S_n(\tau_{k,n},k)=ip(k)+f(k)(e^{i2\pi\Delta f_m(t_n+\tau_{k,n})}-1) \quad (23)$$

In this manner, the $A_{k,n}$ matrix becomes:

$$A_{k,n}=\begin{vmatrix} 1 & (e^{i2\pi\Delta f_m(t_1+\tau_{k,1})}-1) \\ 1 & (e^{i2\pi\Delta f_m(t_2+\tau_{k,2})}-1) \\ \cdots & \cdots \\ 1 & (e^{i2\pi\Delta f_m(t_n+\tau_{k,n})}-1) \end{vmatrix} \quad (23a)$$

The $A_{k,n}$ matrix can be separated into matrixes A and D in a manner similar to that discussed previously.

Similarly, for OP estimates the signal model becomes:

$$S_n(\tau_{k,n},k)=(w(k)-f(k))+f(k)(e^{i2\pi\Delta f_m(t_n+\tau_{k,n})}+1)$$

$$S_n(\tau_{k,n},k)=op(k)+f(k)(e^{i2\pi\Delta f_m(t_n+\tau_{k,n})}+1) \quad (24)$$

Here the $A_{k,n}$ matrix becomes:

$$A_{k,n}=\begin{vmatrix} 1 & (e^{i2\pi\Delta f_m(t_1+\tau_{k,1})}+1) \\ 1 & (e^{i2\pi\Delta f_m(t_2+\tau_{k,2})}+1) \\ \cdots & \cdots \\ 1 & (e^{i2\pi\Delta f_m(t_n+\tau_{k,n})}+1) \end{vmatrix} \quad (24a)$$

A chemical shift correction method using a system of linear equations in k-space can also be applied to the separation of species such as the different metabolites of ^{13}C labeled pyruvate, in which one or more species has more than one resonant peak. See FIG. 7(*a*), which shows a schematic of biochemical pathways of labeled pyruvate in both aerobic and anaerobic respiration and FIG. 7(*b*), illustrating the ^{13}C spectrum for various components at a polarizing field of 3 T.

In prior work, an image based formulation is used whereby the total signal from the two peaks (pyruvate and pyruvate ester) are recombined in the estimation process, using the assumption that the relative signal proportions are fixed and known a priori. However, one of the major limitations of an image based formulation is that the misregistration in the readout direction due to chemical shift artifact (using a spin-warp acquisition) is different for the two pyruvate peaks. Thus, an image based method is unable to adequately correct for chemical shift artifact using the image based method that is used for water and fat. Therefore, the final pyruvate image, which is an estimated combination of the main pyruvate peak and the pyruvate ester peak, will have its two components incorrectly aligned. Except at very high bandwidths where misregistration is small, this will lead to image artifacts in the final pyruvate image.

A k-space based formulation will remove the effects of chemical shift artifact for decomposition of systems with chemical species that have more than one resonant peak. The following example uses the case of pyruvate labeled with ^{13}C at the 1-C position but can also be extended to other groups of chemical species, including fat which may have multiple peaks depending on the type of fat.

Again ignoring the effects of the field inhomogeneity map (or assuming that the effects have previously been removed), the total signal of a voxel containing ^{13}C labeled pyruvate has contributions from pyruvate (Pyr), pyruvate ester (PE), alanine (A) and lactate (L). A schematic spectrum of these metabolites at 3 T is shown in FIG. 7(*b*). The signal model in k-space for this system can be written:

$$S_n(\tau_{k,n},k)=\rho_L(e^{i2\pi\Delta f_L(t_n+\tau_{k,n})})+\rho_A(e^{i2\pi\Delta f_A(t_n+\tau_{k,n})})+\rho_P(r_{PE}e^{i2\pi\Delta f_{PE}(t_n+\tau_{k,n})}+r_{Py}e^{i2\pi\Delta f_{Py}(t_n+\tau_{k,n})}) \quad (25)$$

where the phasor terms containing $\tau_{k,n}$ represent the phase shifts in k-space on each species due to chemical shift due to

thus be determined at any sampled point by the square root of the sum of the squares of the I and Q components:

$$M=\sqrt{I^2+Q^2},$$

and the phase of the received NMR signal may also be determined:

$$\Phi=\tan^{-1}Q/I.$$

The pulse sequence server **18** also optionally receives patient data from a physiological acquisition controller **36**. The controller **36** receives signals from a number of different sensors connected to the patient, such as ECG signals from electrodes or respiratory signals from a bellows. Such signals are typically used by the pulse sequence server **18** to synchronize, or "gate", the performance of the scan with the subject's respiration or heart beat.

The pulse sequence server **18** also connects to a scan room interface circuit **38** which receives signals from various sensors associated with the condition of the patient and the magnet system. It is also through the scan room interface circuit **38** that a patient positioning system **40** receives commands to move the patient to desired positions during the scan.

It should be apparent that the pulse sequence server **18** performs real-time control of MRI system elements during a scan. As a result, it is necessary that its hardware elements be operated with program instructions that are executed in a timely manner by run-time programs. The description components for a scan prescription are downloaded from the workstation **10** in the form of objects. The pulse sequence server **18** contains programs which receive these objects and converts them to objects that are employed by the run-time programs.

The digitized NMR signal samples produced by the RF system **26** are received by the data acquisition server **20**. The data acquisition server **20** operates in response to description components downloaded from the workstation **10** to receive the real-time NMR data and provide buffer storage such that no data is lost by data overrun. In some scans the data acquisition server **20** does little more than pass the acquired NMR data to the data processor server **22**. However, in scans which require information derived from acquired NMR data to control the further performance of the scan, the data acquisition server **20** is programmed to produce such information and convey it to the pulse sequence server **18**. For example, during prescans NMR data is acquired and used to calibrate the pulse sequence performed by the pulse sequence server **18**. Also, navigator signals may be acquired during a scan and used to adjust RF or gradient system operating parameters or to control the view order in which k-space is sampled. And, the data acquisition server **20** may be employed to process NMR signals used to detect the arrival of contrast agent in an MRA scan. In all these examples the data acquisition server **20** acquires NMR data and processes it in real-time to produce information which is used to control the scan.

The data processing server **22** receives NMR data from the data acquisition server **20** and processes it in accordance with description components downloaded from the workstation **10**. Such processing may include, for example: transformation of raw k-space NMR data to produce two or three-dimensional images, typically performed using an inverse Fourier transformation; transformation of image space data to produce k-space data, typically performed using a Fourier transformation, the application of filters to a reconstructed image; the performance of a backprojection image reconstruction of acquired NMR data; the calculation of functional MR images; the calculation of motion or flow images, etc. As will be described below, the present invention is preferably embodied in software executed by the data processing server **22**.

Images reconstructed by the data processing server **22** are conveyed back to the workstation **10** where they are stored. Real-time images are stored in a data base memory cache (not shown) from which they may be output to operator display **12** or a display **42** which is located near the magnet assembly **30** for use by attending physicians. Batch mode images or selected real time images are stored in a host database on disc storage **44**. When such images have been reconstructed and transferred to storage, the data processing server **22** notifies the data store server **23** on the workstation **10**. The workstation **10** may be used by an operator to archive the images, produce films, or send the images via a network to other facilities.

The MRI system of FIG. **1** can perform many different pulse sequences to produce images and spectroscopic information. The present invention relates to the removal of artifacts that occur due to chemical shifts. In one embodiment, when a particular situation is present in the prescribed pulse sequence, subsequent image processing in k-space removes these artifacts. In another embodiment, a generalized removal of artifacts in k-space is described. One such situation is present when the pulse sequence shown in FIG. **2** is prescribed and two images are reconstructed and combined such that either a water or fat image or both are produced. Many other situations are possible that produce the artifacts that are corrected using the present invention.

Referring particularly to FIG. **2**, a pulse sequence that enables separate water and fat images to be produced is shown. After an rf excitation pulse **50** is generated to tip longitudinal magnetization into the transverse plane a negative dephasing lobe **52** is produced along the readout gradient axis, followed by a positive readout gradient lobe **54**, which induces a first gradient-echo NMR signal **56**. The timing is selected such that the echo time TE_1 of this first NMR signal **56** is set to the point in time when the water and fat signal components in the signal **56** are 180° out of phase. In a 1.5 T system this is 2.3 msec. As is well known in the art the NMR signal **56** samples k-space along a line oriented in the same direction as the readout gradient. Exactly where that sampling trajectory is located in k-space is determined by the phase encoding gradient and slice gradient applied during the pulse sequence as is also well known in the art.

The polarity of the readout gradient is then reversed and a second readout gradient lobe **58** is produced to again rephase the transverse magnetization and produce a second gradient-echo NMR signal **60**. Because the phase encodings have not changed, the second NMR signal **60** samples along the same, linear k-space sampling trajectory, but it does so in the opposite direction. The echo time TE_2 of the second NMR signal **60** is set such that fat and water spins are in-phase. At 1.5 T this is 4.6 msec. The pulse sequence of FIG. **2** is repeated with different phase encodings to sample throughout k-space and produce two separate k-space data sets S_0 and S_1 from which fat/water in-phase and 180° out-of-phase images can be reconstructed.

If the center frequency of the rf excitation pulse **52** is set to the Larmor frequency of water, the fat signal will be shifted a small amount in the reconstructed image along the readout gradient axis direction due to chemical shift. The amount of this chemical shift (Δx) measured in image pixels is:

$$\Delta x=N_x\Delta f/2BW,$$

where:

Δf=chemical shift between water and fat which is about −210 Hz at 1.5 T;

N_x=number of k-space samples acquired during the readout; and

BW=readout bandwidth which is typically ±20 to 125 kHz.

Importantly, this chemical shift of fat signal occurs in one direction from the water signal when the readout gradient is

decomposed. The MRI system also keeps track of the time stamps $\tau_{k,n}$ corresponding to each k-space location of the acquired k-space data set.

As indicated at process block **152**, a decision is made whether regridding of the acquired k-space data sets should be performed. If so, such as is the case with non-Cartesian coordinate k-space data, processing proceeds to process block **154**. If not, processing proceeds to process block **156**.

At process block **154**, the acquired k-space data sets are regridded using conventional regridding algorithms to obtain k-space data at Cartesian coordinates. Also, the time stamps $\tau_{k,n}$ associated with each non-Cartesian k-space point are also regridded using the same kernel as for the k-space data to obtain regridded time stamps $\tau'_{k,n}$. The regridded time stamps $\tau'_{k,n}$ will then be used in the system of linear equations, and specifically in the definition of d_{mn} defined by Equation 14(b).

At process block **156**, a decision is made whether to correct for field inhomogeneities. If so, processing proceeds to process block **158**. If not, processing proceeds to process block **160**.

At process block **158**, it is assumed that a field inhomogeneity map ψ is available or can be estimated, such as by using a conventional IDEAL algorithm as described in U.S. Pat. No. 7,176,683. The field map ψ can be smoothed to improve the SNR performance of its estimation, as it is generally assumed that the field map varies smoothly in the image.

The details of process block **158** will be discussed in the context of a water and a fat decomposition. Starting with equation (19) above, a magnetic field inhomogeneity map ψ (Hz) in image space will produce an effect at each individual image pixel that can be approximated by:

$$S_n(r)=(W(r)+F(r)e^{i2\pi\Delta f_m t_n})e^{i2\pi\psi t_n};$$

where the effects of chemical shift on blurring, misregistration, etc. are ignored. Generally, the assumption that the field inhomogeneity map is smoothly varying is a good one. Thus, the N acquired k-space data sets (or the regridded k-space data sets) are transformed into image space preferably using an inverse Fourier transform to produce N complex raw images. The raw images are corrected for field inhomogeneities in image space. In particular, the phase shifts caused by the field map are demodulated in image space to produce N demodulated images, according to:

$$S'_n(r)=S_{n(r)}e^{-i2\pi\psi t_n}$$

Next, the N demodulated images are transformed back to k-space using a Fourier transform:

$$s'_n(\tau_{k,n},k)=FT\{S'_n(r)\}=w(k)+f(k)e^{i2\pi\Delta f_m(t_n+\tau_{k,n})}$$

Thus, prior to process block **160**, N k-space data matrices, $s_n(\tau_{k,n},k)$ or $s'_n(\tau_{k,n},k)$ have been obtained, each having corresponding k-space data at each of a plurality of Cartesian k-space locations. Note that if regridding is not performed and field inhomogeneity correction is not desired, then the N k-space data matrices can simply be the N acquired k-space data sets.

At process block **160**, a system of linear equations, which relates corresponding data from each of the N k-space data matrices, echo times and time stamps ($\tau_{k,n}$ or $\tau'_{k,n}$) to desired calculated k-space data, is solved at each of the plurality of Cartesian k-space locations of the obtained k-space data matrices. The calculated k-space data from all k-space locations is aggregated to obtain a complete calculated k-space data set.

Specifically, the system of linear equations can be formulated in various ways. For example, the system of linear equations can be represented by equation (14), equation (15), or simplifications thereof, and in this manner, separate species k-space data can be determined. In other embodiments, the system of linear equations to be solved can be represented instead by equation (23), such that in-phase species combination k-space data can be produced. Similarly, the system of linear equations to be solved can be represented by equation (24), and one can obtain out-of-phase series combination k-space data. Additionally, the system of linear equations can be formulated according to equation (25) or a similar manner to decompose ^{13}C labeled metabolites, including separating multiple peaks of a species. In all these cases, the decompositions and chemical shift artifact corrections are performed in k-space rather than image space.

It is important to note that if the time stamps have been regridded to Cartesian coordinates, the regridded time stamps are used in the system of linear equations, and specifically in the definition of d_{mn}, defined by equation 14(b).

Process block **164** is an optional step, wherein field inhomogeneities can be corrected in k-space using an acquired field inhomogeneity map, according to procedures such as the multi-frequency approach described by Nayak et al. in the article titled "Automatic field map generation and off-resonance correction for projection reconstruction imaging" at Magn Reson Med 2000; 43(1);151-154; or "Efficient off-resonance correction for spiral imaging" at Magn Reson Med 2001; 45(3):521-524. These methods can be applied to separate species k-space data sets to produce corrected separate species k-space data sets which will produce images with reduced distortion/blurring caused by the field inhomogeneity. These corrected separate species k-space data sets will then be transformed at process block **166**.

At process block **166**, the calculated k-space data sets from process block **162** or **164** are transformed to image space such as by using an inverse Fourier transform. In the case of separate species k-space data sets, separate species images are produced, such as separate water images and fat images. In the case of species combination k-space data sets, in phase or out of phase images are produced.

It should be apparent that unlike prior methods for producing separate images of two chemical species, the correction for chemical shift artifact is performed in k-space rather than image space. Although water and fat images are produced in one preferred embodiment of the invention, it should be apparent that the present invention is applicable to other applications as well.

In other embodiments, the order of the process blocks illustrated in FIG. **8** can be varied. For example, for a non-Cartesian acquisition, if it is not desired that the field inhomogeneity map be solved for in image space, then it is possible to perform the regridding of process block **152** after the desired calculated k-space data sets are produced in process block **160** (and prior to performing process block **166**). This can be advantageous in that the number of computationally intensive regridding calculations can be reduced when the number N of acquired k-space data sets is greater than the number M of separate species. For example, if N=6 and water and fat are being separated (i.e., M=2), it would be advantageous to perform regridding of the two separated species k-space data sets rather than perform regridding of the six acquired k-space data sets.

The present invention has been described in terms of one or more preferred embodiments, and it should be appreciated that many equivalents, alternatives, variations, and modifications, aside from those expressly stated, are possible and within the scope of the invention.

The invention claimed is:

1. A method for producing images of a subject containing M spin species using a magnetic resonance imaging (MRI) system, the steps comprising:

a) obtaining N k-space data matrices from N k-space data sets each acquired with the MRI system using a pulse sequence with an individual associated echo time t_n, the

a) obtaining N k-space data matrices from N k-space data sets each acquired with the MRI system using a pulse sequence with an individual associated echo time t_n, where n=1, . . . , N, and N≧2; wherein the k-space data matrices each include corresponding data at the same plurality of Cartesian k-space locations;

b) obtaining a time stamp corresponding to each of the plurality of k-space locations, wherein the time stamp is an indication of when corresponding data is acquired relative to a reference;

c) for each k-space location, solving a system of linear equations in k-space to produce species combination k-space data which is corrected for chemical shift, the system of linear equations relating corresponding data from the N k-space data matrices, echo times and time stamps to the species combination k-space data;

c) aggregating the species combination k-space data associated with the plurality of k-space locations to obtain a species combination k-space data set; and

d) transforming the species combination k-space data set to image space to obtain one of an in-phase and an out-of-phase species combination image.

21. The method of claim **20**, wherein step a) includes regridding the acquired k-space data sets.

22. The method of claim **21**, wherein step b) includes regridding non-Cartesian time stamps corresponding to the acquired k-space data sets.

23. The method of claim **20**, wherein step a) includes transforming the N acquired k-space data sets to image space to produce N raw images, correcting the raw images for field inhomogeneities in image space to produce N corrected images, and transforming the corrected images to k-space to produce the N k-space data matrices.

24. The method of claim **23**, wherein correcting the raw images for field inhomogeneities in image space includes performing a demodulation on the N raw images using a field inhomogeneity map.

25. The method of claim **20**, wherein step a) includes regridding the acquired k-space data sets to produce regridded k-space data sets, transforming the regridded k-space data sets to image space to produce N raw images, correcting the raw images for field inhomogeneities in image space to produce N corrected images, and transforming the corrected images to k-space to produce the N k-space data matrices.

26. The method of claim **20**, wherein step c) includes solving the equation:

$$\hat{\rho}=(A_{k,n}{}^{H}A_{k,n})^{-1}A_{k,n}{}^{H}S_k$$

at each Cartesian k-space location, wherein $\hat{\rho}=[(\rho_1+\rho_2)\rho_2]$ represents in-phase species combination data and separate species data at a k-space location;

$$S_k=\begin{bmatrix} s_1 \\ s_2 \\ \cdots \\ s_N \end{bmatrix}$$

represents the obtained k-space data with an element from each of the N k-space data matrices;

$$A_{k,n}=\begin{vmatrix} 1 & \left(e^{i2\pi\Delta f_m(t_1+\tau_{k,1})}-1\right) \\ 1 & \left(e^{i2\pi\Delta f_m(t_2+\tau_{k,2})}-1\right) \\ \cdots & \cdots \\ 1 & \left(e^{i2\pi\Delta f_m(t_n+\tau_{k,n})}-1\right) \end{vmatrix};$$

wherein Δf_m is the frequency difference between the two species; and $\tau_{k,n}$ is an obtained time stamp.

27. The method of claim **20**, wherein step c) includes solving the equation:

$$\hat{\rho}=(A_{k,n}{}^{H}A_{k,n})^{-1}A_{k,n}{}^{H}S_k$$

at each k-space location; wherein $\hat{\rho}=[(\rho_1-\rho_2)\rho_2]$ represents out-of-phase series combination data and separate species data at a k-space location;

$$S_k=\begin{bmatrix} s_1 \\ s_2 \\ \cdots \\ s_N \end{bmatrix}$$

represents the obtained k-space data with an element from each of the N k-space data matrices;

$$A_{k,n}=\begin{vmatrix} 1 & \left(e^{i2\pi\Delta f_m(t_1+\tau_{k,1})}-1\right) \\ 1 & \left(e^{i2\pi\Delta f_m(t_2+\tau_{k,2})}-1\right) \\ \cdots & \cdots \\ 1 & \left(e^{i2\pi\Delta f_m(t_n+\tau_{k,n})}-1\right) \end{vmatrix};$$

Δf_m is the frequency difference between the two species; and $\tau_{k,n}$ is an obtained time stamp.

28. The method of claim **20**, wherein after step d), the k-space species combination data set is corrected for field inhomogeneities in k-space and step e) is performed on one or more of the corrected combination data set.

29. The method of claim **20**, wherein the two spin species are hydrogen associated with water and hydrogen associated with fat.

30. The method of claim **20**, wherein k-space data sets are acquired using a pulse sequence with an rf excitation pulse tuned to the Larmor frequency of one of the spin species.

31. A method for producing images of a subject containing two spin species with a magnetic resonance imaging (MRI) system, the steps comprising:

a) acquiring a pair of k-space image data sets using a pulse sequence in which NMR signals (S_0') for one k-space image data set are acquired using a readout gradient of one polarity and NMR signals (S_1') for the other k-space image data set are acquired with a readout gradient of the opposite polarity;

b) reconstructing two images s_0 and s_1 from the respective k-space data sets S_0' and S_1';

c) removing phase shifts from one or both of the two images s_1 and s_0 to produce respective images s_0' and s_1'';

d) Fourier transforming the two images s_0' and s_1'' to k-space;