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(54) SYSTEM AND METHOD FOR METABOLIC MR IMAGING OF A HYPERPOLARIZED AGENT

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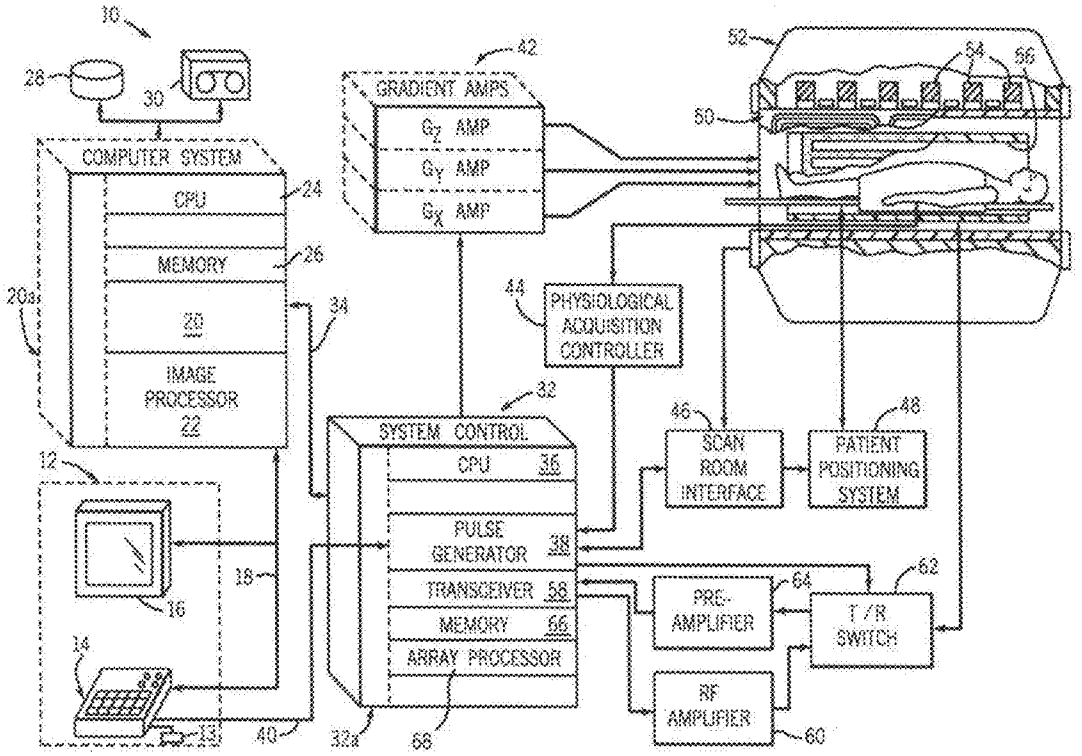
(57) **ABSTRACT**

A system and method for metabolic MR imaging of a hyperpolarized agent includes exciting a single metabolic species of a hyperpolarized agent injected into a subject of interest. MR signals are acquired from the excited single metabolic species and an image is reconstructed from the acquired MR signals.



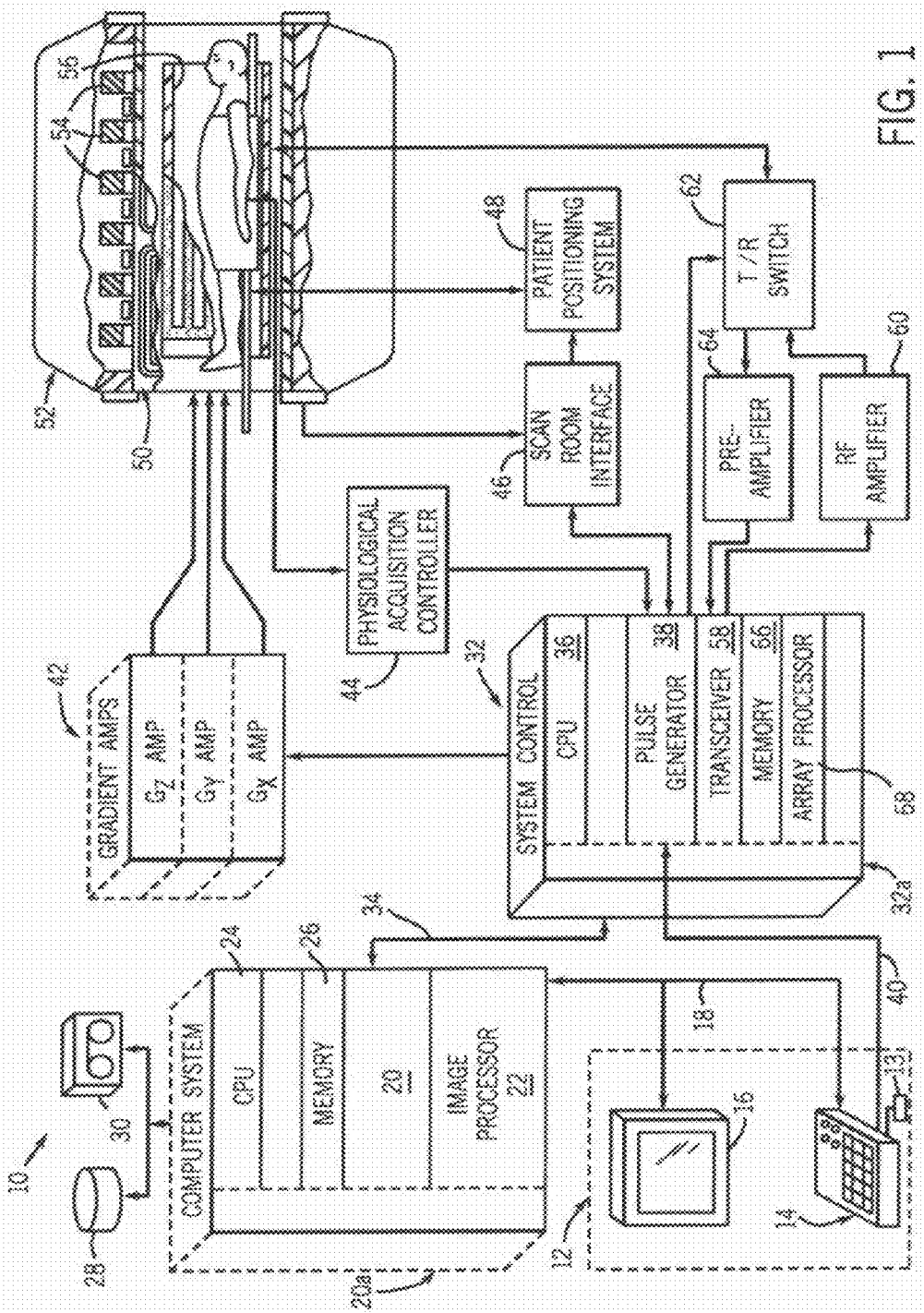

10
12
14
16
18
20
20a
22
24
26
28
30
32
32a
34
36
38
40
42
44
46
48
50
52
54
56
58
60
62
64
66
68
COMPUTER SYSTEM
CPU
MEMORY
IMAGE PROCESSOR
GRADIENT AMPS
G_Z AMP
G_Y AMP
G_X AMP
PHYSIOLOGICAL ACQUISITION CONTROLLER
SCAN ROOM INTERFACE
PATIENT POSITIONING SYSTEM
T/R SWITCH
PRE-AMPLIFIER
RF AMPLIFIER
SYSTEM CONTROL
CPU
PULSE GENERATOR
TRANSCEIVER
MEMORY
ARRAY PROCESSOR

FIG. 1

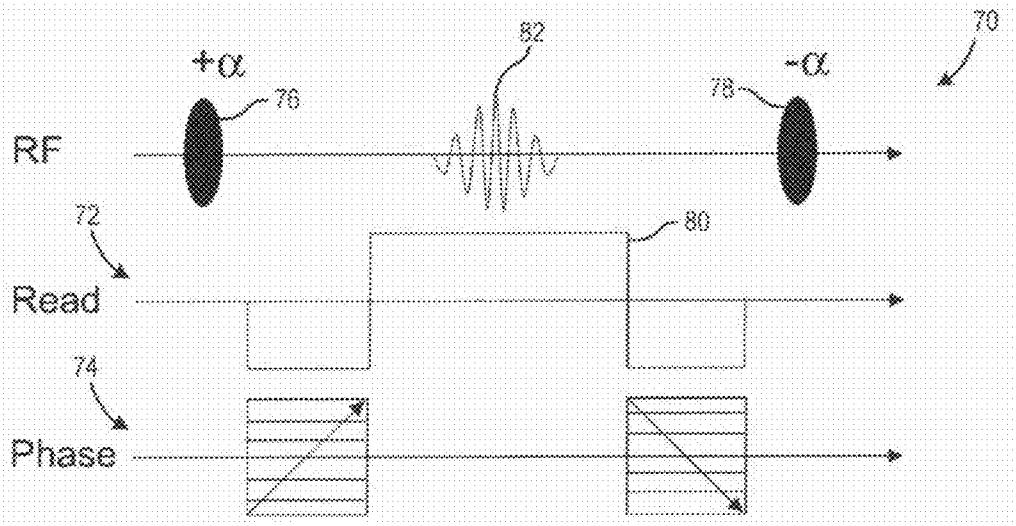

+α
82
-α
70
76
78
RF
72
80
Read
74
Phase

FIG. 2

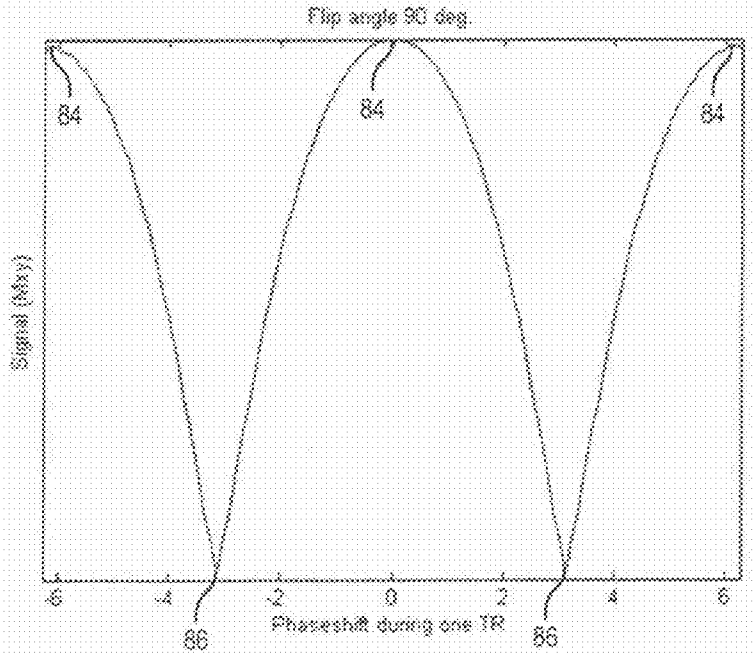

Flip angle 90 deg
84
84
84
Signal (M_xy)
-6
-4
-2
0
2
4
6
Phaseshift during one TR
86
86

FIG. 3

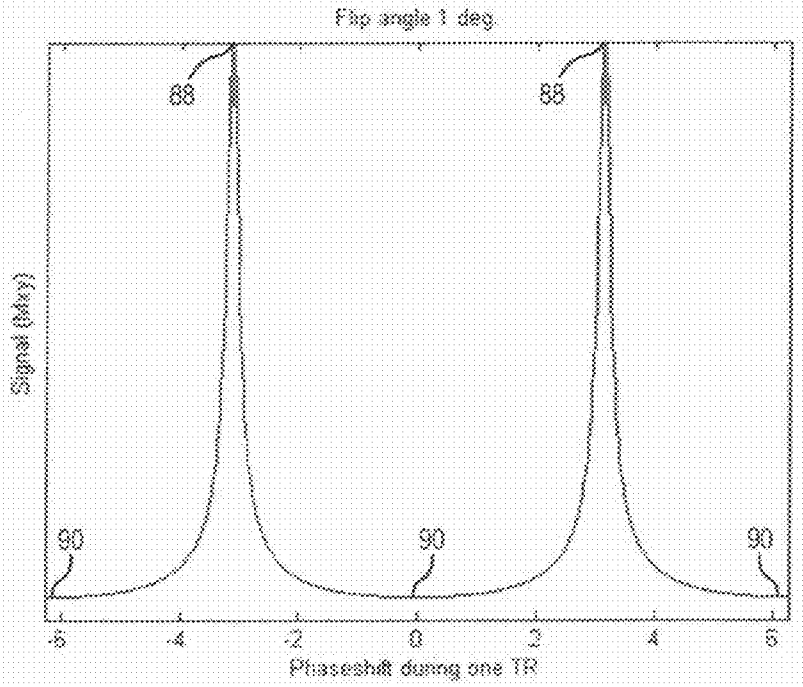

Flip angle 1 deg
88
88
90
90
90
Signal (Mxy)
-6
-4
-2
0
2
4
6
Phaseshift during one TR

FIG. 4

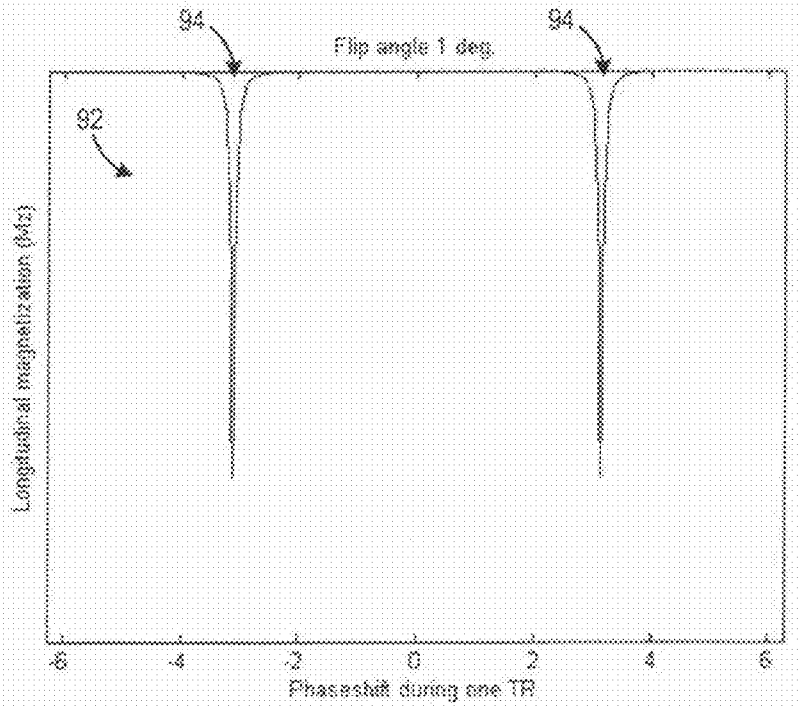

94
94
Flip angle 1 deg
92
Longitudinal magnetization (Mz)
-6
-4
-2
0
2
4
6
Phaseshift during one TR

FIG. 5

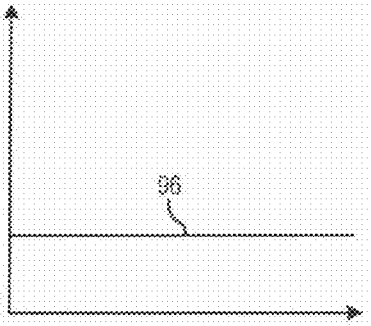

96

FIG. 6

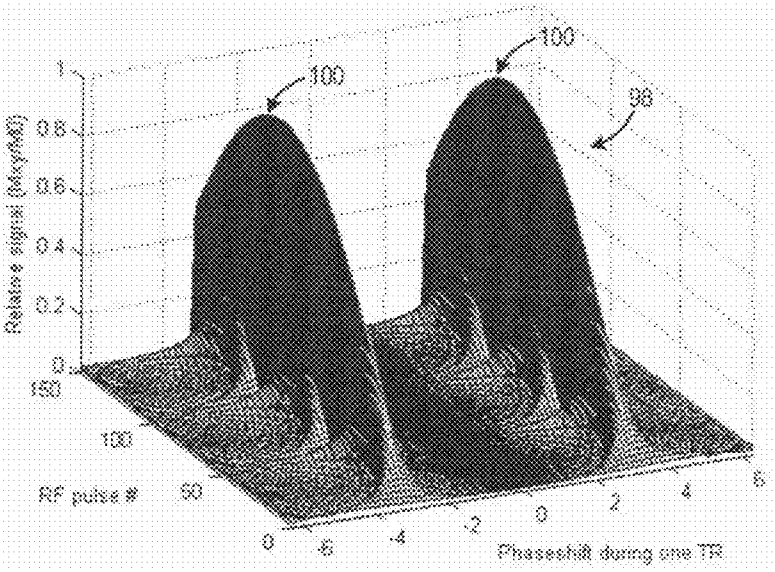

100
100
98
Relative signal (Mxy/M0)
1
0.8
0.6
0.4
0.2
0
150
100
50
0
RF pulse #
-6
-4
-2
0
2
4
6
Phaseshift during one TR

FIG. 7

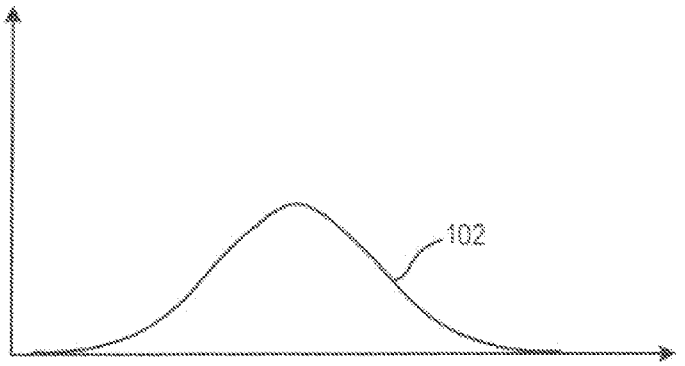


FIG. 8

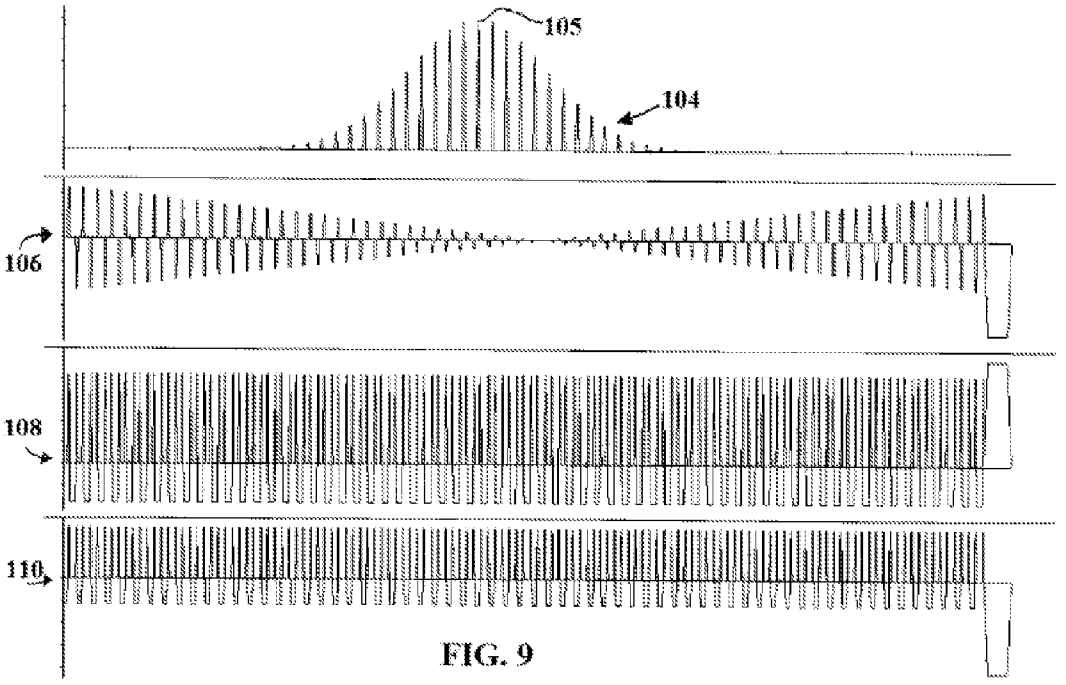


FIG. 9

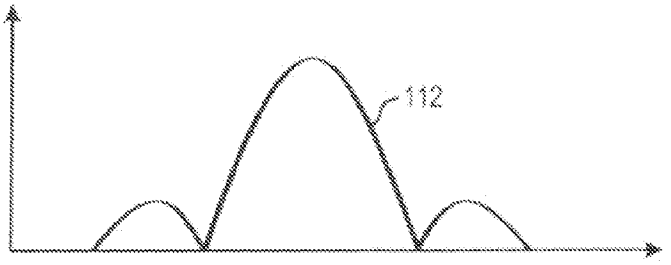


FIG. 10

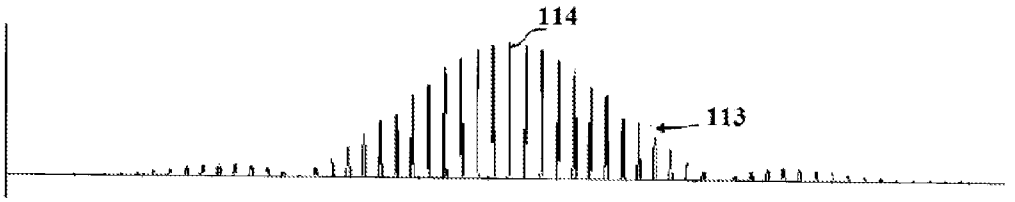


FIG. 11

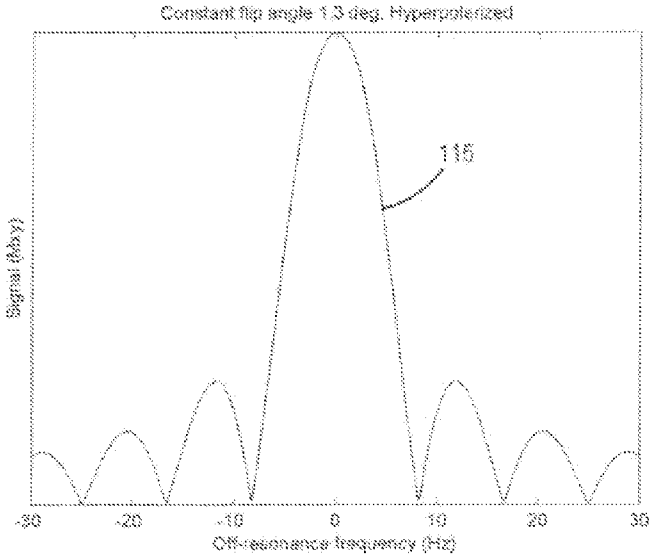


FIG. 12

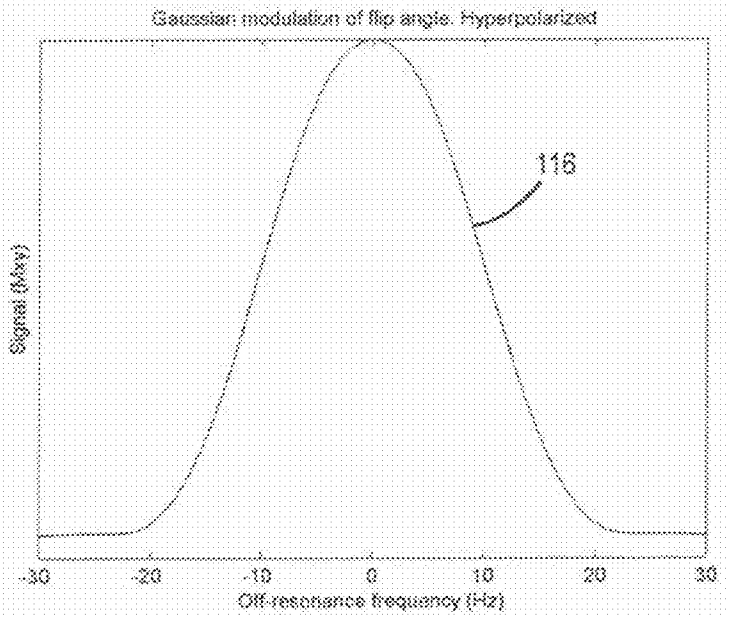

Gaussian modulation of flip angle. Hyperpolarized
116
Signal (Arb)
-30
-20
-10
0
10
20
30
Off-resonance frequency (Hz)

FIG. 13

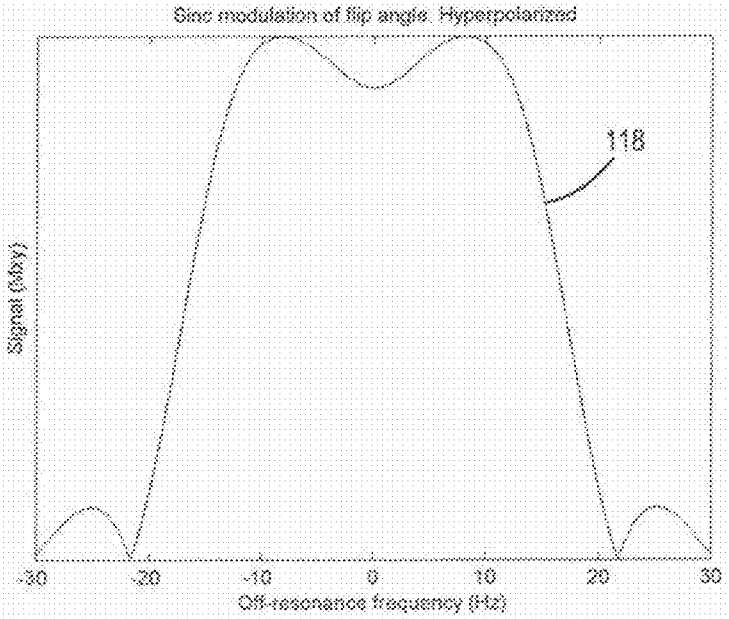

Sinc modulation of flip angle. Hyperpolarized
118
Signal (Arb)
-30
-20
-10
0
10
20
30
Off-resonance frequency (Hz)

FIG. 14

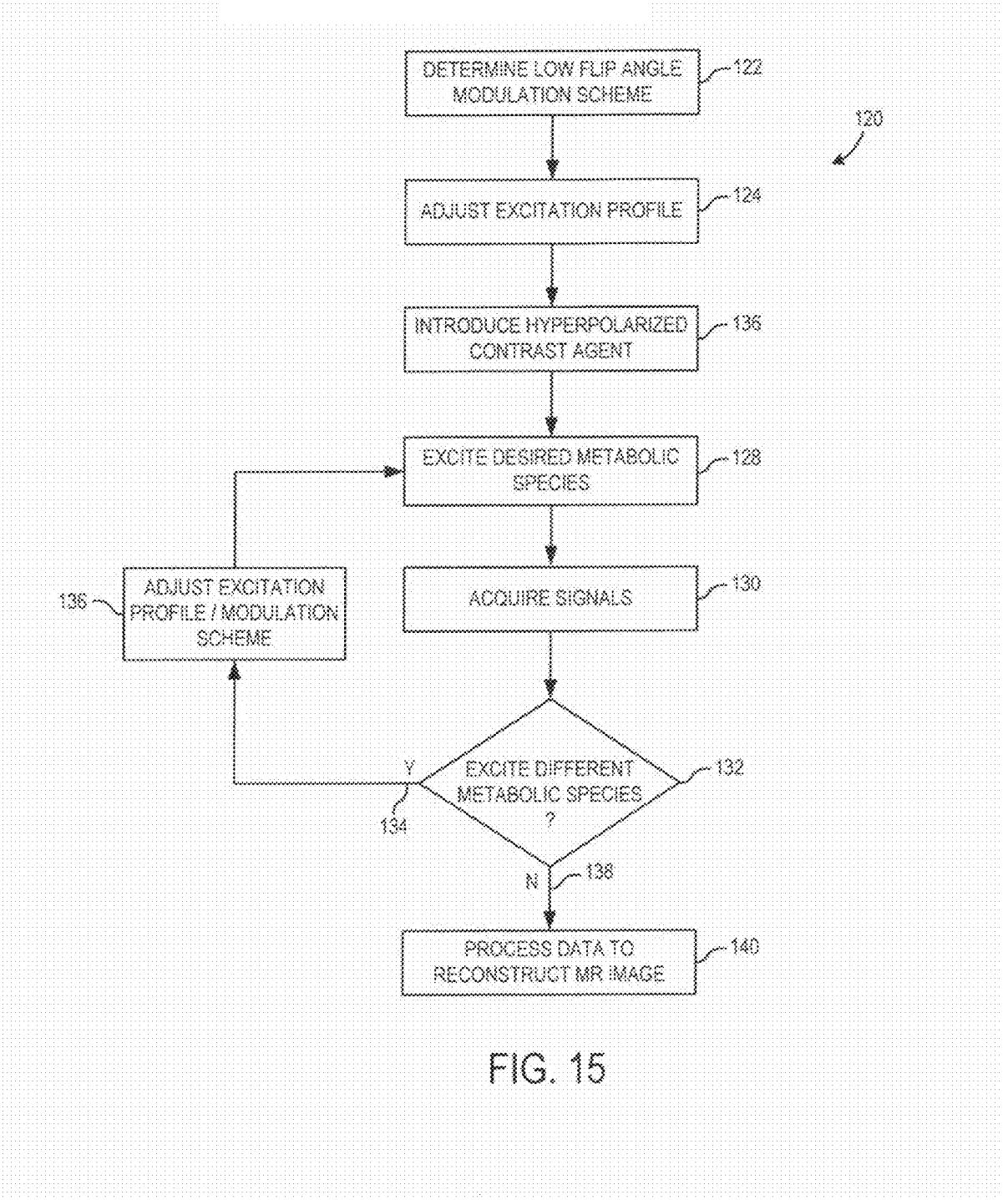

DETERMINE LOW FLIP ANGLE MODULATION SCHEME
122
120
ADJUST EXCITATION PROFILE
124
INTRODUCE HYPERPOLARIZED CONTRAST AGENT
126
EXCITE DESIRED METABOLIC SPECIES
128
ADJUST EXCITATION PROFILE / MODULATION SCHEME
136
ACQUIRE SIGNALS
130
EXCITE DIFFERENT METABOLIC SPECIES ?
132
Y
134
N
138
PROCESS DATA TO RECONSTRUCT MR IMAGE
140

FIG. 15

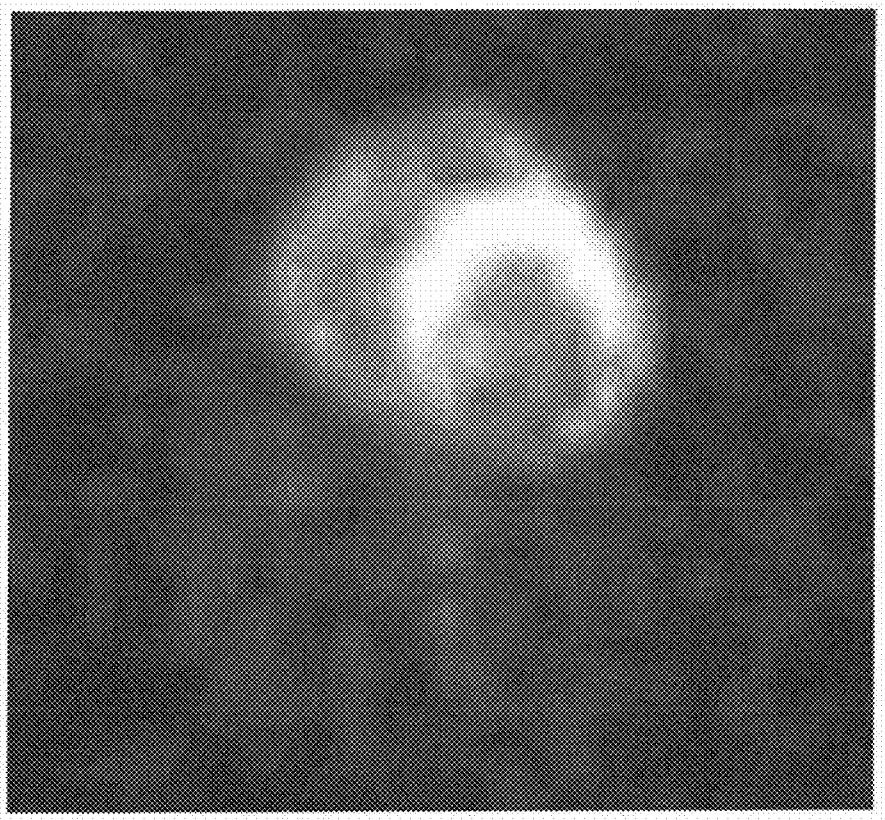


FIG. 16

SYSTEM AND METHOD FOR METABOLIC MR IMAGING OF A HYPERPOLARIZED AGENT

CROSS-REFERENCE TO RELATED APPLICATION

[0001] The present application is a continuation of and claims priority to U.S. patent application Ser. No. 11/623,277 filed Jan. 15, 2007, the disclosure of which is incorporated herein.

BACKGROUND OF THE INVENTION

[0002] The present invention relates generally to MR imaging and, more particularly, to metabolic MR imaging of a hyperpolarized agent.

[0003] When a substance such as human tissue is subjected to a uniform magnetic field (polarizing field B_0), the individual magnetic moments of the spins in the tissue attempt to align with this polarizing field, but precess about it in random order at their characteristic Larmor frequency. If the substance, or tissue, is subjected to a magnetic field (excitation field B_1) which is in the x-y plane and which frequency is near the Larmor frequency, the net aligned moment, or "longitudinal magnetization", M_Z, may be rotated, or "tipped", into the x-y plane to produce a net transverse magnetic moment M_t. A signal is generated by the excited spins after the excitation signal B_1 is terminated and this signal may be received and processed to form an image.

[0004] When utilizing these signals to produce images, magnetic field gradients (G_x, G_y, and G_z) are employed. Typically, the region to be imaged is scanned by a sequence of measurement cycles in which these gradients vary according to the particular localization method being used. The resulting set of received NMR signals are digitized and processed to reconstruct the image using one of many well known reconstruction techniques. It is desirable that the imaging process, from data acquisition to reconstruction, be performed as quickly as possible for improved patient comfort and throughput.

[0005] For some procedures and investigations, it is also desirable for MR images to display spectral information in addition to spatial information. One known method for acquiring MR signals and reconstructing MR images containing both spatial and spectral information is "chemical shift imaging" (CSI). CSI has been employed to monitor metabolic and other internal processes of patients, including imaging hyperpolarized substances such as ^{13}C labeled contrast agents and metabolites thereof. However, after injection of the hyperpolarized agent, imaging is a challenging task. The hyperpolarization of the agent has a limited lifetime, and imaging must be done rapidly. For example, typical T1 lifetimes of hyperpolarized agents are on the order of a few minutes in vivo. Furthermore, the RF excitations of the pulse sequence may destroy the hyperpolarization irreversibly.

[0006] The CSI method has some drawbacks which limit available signal-to-noise ratio, and thus image quality. For example, CSI tends to acquire data slowly, considering the short lifetimes of the increased magnetization of hyperpolarized substances. In addition, CSI typically exposes the imaging subject to a large number of RF excitations. These properties are especially unfavorable for a hyperpolarized agent because the hyperpolarized agent magnetization has a limited lifetime and is destroyed by the RF excitations of the CSI sequence. As a consequence, the available magnetization cannot be fully utilized by the CSI method, and the signal-to-noise ratio (SNR) is thus reduced.

[0007] Additionally, MR procedures which require very fast, or periodic data acquisition, such as cardiac imaging or metabolic imaging of the heart, are difficult to perform with CSI sequences because CSI can take more than 15 seconds for a 16×16 matrix, whereas cardiac and related metabolic imaging should be completed within a few heartbeats or a few seconds.

[0008] It would therefore be desirable to have a system and method capable of exciting and imaging a metabolic species of a hyperpolarized agent without affecting magnetization of metabolic species at other frequencies.

BRIEF DESCRIPTION OF THE INVENTION

[0009] Embodiments of the present invention provide a system and method of MR that overcome the aforementioned drawbacks. A single metabolic species of a hyperpolarized agent injected into a subject of interest is excited, and MR signals from the excited single metabolic species are acquired. An image is reconstructed from the acquired MR signals.

[0010] Therefore, in accordance with one aspect of the present invention, an MRI apparatus includes an MRI assembly having a plurality of gradient coils positioned about a bore of a magnet to impress a polarizing magnetic field. An RF transceiver system and an RF switch are controlled by a pulse module to transmit and receive RF signals to and from an RF coil assembly to acquire MR images. The MRI apparatus also includes a system controller coupled to the MRI assembly, the system controller configured to cause the RF coil assembly to excite a single metabolic species of a hyperpolarized agent injected into a subject of interest. The system controller further causes the RF transceiver system to acquire MR signals from the excited single metabolic species and reconstruct an image from the acquired MR signals.

[0011] In accordance with another aspect of the invention, a method of hyperpolarized agent MR imaging includes injecting a hyperpolarized agent into a subject of interest and exciting a first metabolic species of the hyperpolarized agent. The method also includes acquiring MR signals from the excited first metabolic species and reconstructing an image from the acquired MR signals.

[0012] According to a further embodiment of the invention, a computer readable storage medium includes a computer program stored thereon comprising instructions which when executed by a computer, causes the computer to modulate a plurality of flip angle train RF pulses of a pulse sequence. The instructions further cause the computer to acquire MR data from the plurality of molecules and generate an image from the MR data.

[0013] Various other features and advantages will be made apparent from the following detailed description and the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The drawings illustrate embodiments presently contemplated for carrying out the invention.

[0015] In the drawings:

[0016] FIG. **1** is a schematic block diagram of an MR imaging system for use with embodiments of the present invention.

[0017] FIG. **2** is a pulse sequence diagram of a trueFISP sequence with the slice gradient omitted.

[0018] FIG. **3** is a graph of the signal of the trueFISP sequence of FIG. **2** as a function of phase accumulation between two successive RF pulses with a constant flip angle of 90°.

[0019] FIG. **4** is a graph of the signal of the trueFISP sequence of FIG. **2** as a function of phase accumulation between two successive RF pulses with a constant flip angle of 1°.

[0020] FIG. **5** is a graph of the longitudinal magnetization of the trueFISP sequence of FIG. **2** as a function of phase accumulation between two successive RF pulses with a constant flip angle of 1°.

[0021] FIG. **6** is a modulation envelope of an RF pulse amplitude in accordance with an embodiment of the present invention.

[0022] FIG. **7** is a graph of trueFISP signals from hyperpolarized spins as function of phase shift per TR and RF pulse number.

[0023] FIG. **8** is another modulation envelope of the RF pulse amplitude in accordance with an embodiment of the present invention.

[0024] FIG. **9** is a pulse sequence diagram incorporating the pulse sequence modulation envelope of FIG. **8** in accordance with an embodiment of the present invention.

[0025] FIG. **10** is another modulation envelope of the RF pulse amplitude in accordance with an embodiment of the present invention.

[0026] FIG. **11** is a pulse sequence diagram incorporating the pulse sequence modulation envelope of FIG. **10** in accordance with an embodiment of the present invention.

[0027] FIG. **12** is a graph of frequency selectivity of a trueFISP sequence incorporating a constant amplitude of the RF pulses in accordance with an embodiment of the present invention.

[0028] FIG. **13** is a graph of frequency selectivity of a trueFISP sequence incorporating a Gaussian modulation envelope of the RF pulse amplitude in accordance with an embodiment of the present invention.

[0029] FIG. **14** is a graph of frequency selectivity of a trueFISP sequence incorporating a sinc modulation envelope of the RF pulse amplitude in accordance with an embodiment of the present invention.

[0030] FIG. **15** is a flowchart setting forth the steps of a technique in accordance with an embodiment of the present invention.

[0031] FIG. **16** is an exemplary image acquired in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0032] Referring to FIG. **1**, the major components of a preferred magnetic resonance imaging (MRI) system **10** that may incorporate embodiments of the present invention are shown. The operation of the system is controlled from an operator console **12** which includes a keyboard or other input device **13**, a control panel **14**, and a display screen **16**. The console **12** communicates through a link **18** with a separate computer system **20** that enables an operator to control the production and display of images on the display screen **16**. The computer system **20** includes a number of modules which communicate with each other through a backplane **20***a*. These include an image processor module **22**, a CPU module **24** and a memory module **26**, known in the art as a frame buffer for storing image data arrays. The computer system **20** is linked to disk storage **28** and removable storage **30** for storage of image data and programs, and communicates with a separate system control **32** through a high speed serial link **34**. The input device **13** can include a mouse, joystick, keyboard, track ball, touch activated screen, light wand, voice control, or any similar or equivalent input device, and may be used for interactive geometry prescription.

[0033] The system control **32** includes a set of modules connected together by a backplane **32***a*. These include a CPU module **36** and a pulse generator module **38** which connects to the operator console **12** through a serial link **40**. It is through link **40** that the system control **32** receives commands from the operator to indicate the scan sequence that is to be performed. The pulse generator module **38** operates the system components to carry out the desired scan sequence and produces data which indicates the timing, strength and shape of the RF pulses produced, and the timing and length of the data acquisition window. The pulse generator module **38** connects to a set of gradient amplifiers **42**, to indicate the timing and shape of the gradient pulses that are produced during the scan. The pulse generator module **38** can also receive patient data from a physiological acquisition controller **44** that receives signals from a number of different sensors connected to the patient, such as ECG signals from electrodes attached to the patient. And finally, the pulse generator module **38** connects to a scan room interface circuit **46** 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 **46** that a patient positioning system **48** receives commands to move the patient to the desired position for the scan.

[0034] The gradient waveforms produced by the pulse generator module **38** are applied to the gradient amplifier system **42** having Gx, Gy, and Gz amplifiers. Each gradient amplifier excites a corresponding physical gradient coil in a gradient coil assembly generally designated **50** to produce the magnetic field gradients used for spatially encoding acquired signals. The gradient coil assembly **50** forms part of a magnet assembly **52** which includes a polarizing magnet **54** and a whole-body RF coil **56**. A transceiver module **58** in the system control **32** produces pulses which are amplified by an RF amplifier **60** and coupled to the RF coil **56** by a transmit/receive switch **62**. The resulting signals emitted by the excited nuclei in the patient may be sensed by the same RF coil **56** and coupled through the transmit/receive switch **62** to a preamplifier **64**. The amplified MR signals are demodulated, filtered, and digitized in the receiver section of the transceiver **58**. The transmit/receive switch **62** is controlled by a signal from the pulse generator module **38** to electrically connect the RF amplifier **60** to the coil **56** during the transmit mode and to connect the preamplifier **64** to the coil **56** during the receive mode. The transmit/receive switch **62** can also enable a separate RF coil (for example, a surface coil) to be used in either transmit or receive mode.

[0035] The MR signals picked up by the RF coil **56** are digitized by the transceiver module **58** and transferred to a memory module **66** in the system control **32**. A scan is complete when an array of raw k-space data has been acquired in the memory module **66**. This raw k-space data is rearranged into separate k-space data arrays for each image to be reconstructed, and each of these is input to an array processor **68** which operates to Fourier transform the data into an array of image data. This image data is conveyed through the serial

link **34** to the computer system **20** where it is stored in memory, such as disk storage **28**. In response to commands received from the operator console **12**, this image data may be archived in long term storage, such as on the removable storage **30**, or it may be further processed by the image processor **22** and conveyed to the operator console **12** and presented on the display **16**.

[0036] A true fast imaging with steady presession (trueFISP) pulse sequence having low flip angles is described herein. As used herein, low flip angles are flip angles less than 15°. As described below, using low flip angles in conjunction with a trueFISP pulse sequence allows excitation and MR data acquisition of a single metabolite of a hyperpolarized agent, such as ^{13}C, while minimizing adverse effects on the magnetization of other metabolites. As such, the full magnetization of the hyperpolarized agent can be used for image generation. That is, in steady-state proton imaging, the relatively short relaxation times of protons make the signal to be approximately 25% of M_0. In contrast, the much longer relaxation times of ^{13}C makes it possible to reach a transient response with a maximum signal close to 100% of M_0 as shown below.

[0037] FIG. **2** shows a pulse sequence diagram of a trueFISP sequence **70** according to one embodiment of the present invention. The trueFISP sequence **70** is a fully balanced steady-state free precession (SSFP) sequence. TrueFISP sequence **70** includes balanced gradients **72** in the read or frequency direction and balanced gradients **74** in the phase direction applied between RF pulses **76**, **78**. During read gradient **80**, a signal **82** is acquired, filling one k-space line.

[0038] The trueFISP pulse sequence **70** is characterized by the signal **82** being dependent on a phase accumulation of the spins during the TR interval, i.e., the time between successive RF excitations. For spins perfectly on resonance, this phase accumulation is zero, but will be non-zero for off-resonance spins. As shown in FIG. **3**, for a trueFISP pulse sequence with 90° flip angles of thermal equilibrium spins at steady-state, maximum signals **84** are obtained when the phase accumulation is $\pm 2n\cdot\pi$ (n=0, 1, 2 . . .), and minimum signals **86** are obtained when the phase accumulation is $\pi \pm 2n\cdot\pi$ (n=0, 1, 2 . . .). In reconstructed trueFISP images, the signal minima are visible as dark stripes. The off-resonance may be caused by inhomogeneities of the B0 field, or chemical shift.

[0039] However, as shown in FIG. **4**, if the flip angles of the trueFISP sequence **70** (shown in FIG. **2**) are set to a low flip angle, e.g., 1°, an opposite result to that of FIG. **3** is obtained. Setting the flip angle to 1° results in obtaining maximum signals **88** when the phase accumulation is $\pi \pm 2n\cdot\pi$ (n=0, 1, 2 . . .), and obtaining minimum signals **90** when the phase accumulation is $\pm 2n\cdot\pi$ (n=0, 1, 2 . . .). Accordingly, signals **88** are obtained from a range of phase shifts at the same positions where signal minima were found for the signals shown in FIG. **3**.

[0040] FIG. **5** shows the longitudinal magnetization **92** (Mz) for the trueFISP sequence **70** (shown in FIG. **2**) set to a low flip angle of 1°. The longitudinal magnetization **92** is minimally affected outside excitation bands **94**. Consequently, magnetization from other metabolites will be preserved in an application with hyperpolarized substances. The position of the excitation bands **94** can be moved from phase=$\pm\pi$ to an arbitrary position by changing the phase cycling of the RF pulse. The width of the excitation profile is approximately 0.15° phase accumulation for a 1° flip angle. If TR=2 ms, a phase accumulation of 0.15° translates to a spectral width of approximately 12 Hz, or 0.75 ppm, for ^{13}C at 1.5 T. The width of the excitation profile may also be modified by changing the flip angle.

[0041] FIG. **6** shows an RF pulse amplitude modulation envelope **96** according to one embodiment of the present invention. RF pulse amplitude modulation envelope **96** is a constant modulation envelope to which flip angles of the trueFISP sequence **70** (shown in FIG. **2**) are set to acquire the signals of FIG. **4**. As discussed above with regard to FIG. **4** and as shown in FIG. **6**, the flip angles of the trueFISP sequence **70** (shown in FIG. **2**) may be set to a constant, low flip angle, such as 1°, with total flip angle ranging from 90° to 180°. However, it is contemplated that the low flip angle may be greater or lesser than 1°.

[0042] The behavior of hyperpolarized spins differs from that of spins at thermal equilibrium. After a transient phase, thermal equilibrium spins will reach a steady-state, where the signal (the transverse magnetization) levels out at typically 20%-50% of M_0. However, when the spins are hyperpolarized and the relaxation times are long compared with the duration of the scan, no steady-state is reached. Rather, the magnetization will gradually be tilted by the RF pulses from a starting position along the z-axis down to the xy-plane.

[0043] FIG. **7** shows trueFISP signals **98** from hyperpolarized spins as function of phase shift per TR and RF pulse number. The trueFISP signals **98** were acquired using a flip angle of 1°, and the magnetization is aligned with the z-axis before the first pulse. Further, the trueFISP signals **98** were acquired with TR=2.5 ms, T_1=30 s, and T_2=2 s. It can be seen that maximum signals **100**, i.e., after the 90th RF pulse, equals M_0. Thus, the full hyperpolarized signal can be utilized, despite the low flip angle.

[0044] FIG. **8** shows a pulse sequence modulation envelope **102** according to another embodiment of the present invention. Pulse sequence modulation envelope **102** is a Gaussian-shaped modulation envelope to which flip angles of the trueFISP sequence **70** (shown in FIG. **2**) may be set such that the total flip angle ranges from 90° to 180°. In a preferred embodiment, maximum pulse **105** has a flip angle between 5° and 15°.

[0045] FIG. **9** shows a pulse sequence according to the pulse sequence modulation envelope **102** of FIG. **8**. RF pulses **104** are modulated according to the Gaussian-shaped modulation envelope **102**, and phase gradient pulses **106**, read gradient pulses **108**, and slice encoding gradient pulses **110** are also determined.

[0046] In addition to the Gaussian-shaped modulation envelope **102** shown in FIG. **8**, it is contemplated that other modulation envelope shapes are possible. For example, FIG. **10** shows an RF pulse modulation envelope **112** having a shape of a sinc function. FIG. **11** shows a pulse sequence according to the pulse sequence modulation envelope **112** of FIG. **10**. RF pulses **113** are modulated according to the shape of the sinc function modulation envelope **112** such that the total flip angle ranges from 90° to 180°. In a preferred embodiment, maximum pulse **114** has a flip angle between 5° and 15°.

[0047] FIGS. **12-14** show frequency selectivity of trueFISP sequences having different amplitude modulations of the RF flip angle. The signals **115**, **116**, **118** shown in FIGS. **12-14**, respectively, have been calculated for a repetition time (TR) of 2.5 ms, which is assumed to represent about the shortest possible TR for ^{13}C imaging on a high-end clinical MR scanner. If the TR can be shortened further, the excitation for

FIGS. **12-14** will cover a broader frequency range. Furthermore, calculations were made for a sequence with 96 phase-encoding steps and a total flip angle of 120°. The signal responses shown in FIGS. **12-14** are shown after 48 RF pulses, i.e., at the center of the k-space, with a linear phase-encoding scheme.

[0048] FIG. **12** shows that, with constant RF amplitude at a flip angle of 1.3°, the usable frequency range for a reasonably uniform signal intensity is approximately 5 Hz, or approximately ⅓ ppm at 1.5 T. FIG. **13** shows that, with Gaussian amplitude modulation, the usable frequency range for a reasonable uniform signal intensity is approximately double the usable frequency range shown in FIG. **12**. FIG. **14** shows that, with a sinc function modulation, the usable frequency range for a reasonably uniform signal intensity is approximately 30 Hz, or approximately 2 ppm, at 1.5 T.

[0049] As shown in FIG. **14**, imaging of a single hyperpolarized agent metabolite should be possible without additional shimming actions given that other metabolites of interest are sufficiently far away from the excited frequency range. Further optimization of the excitation profiles shown in FIGS. **12-14** can be achieved by adjusting the modulation profile with the respect to the position in the k-space, e.g., adjusting the maximum of the modulation profile such that it does not coincide with the passage of the k-space center.

[0050] Referring now to FIG. **15**, a hyperpolarized agent imaging technique **120** in accordance with one embodiment of the present invention is shown. The technique **120** begins with determining, at block **122**, a low flip angle modulation scheme for the RF pulse sequence of a modified trueFISP pulse sequence. Determination of the low flip angle modulation scheme includes basing the determination on a desired frequency selectivity as described above as well as on the shimming, or the B_0 homogeneity. The low flip angle modulation scheme is based on a constant amplitude envelope, a Gaussian modulation envelope, a sinc modulation envelope, or the like. Additionally, determination of the low flip angle modulation scheme may include a consideration of the hyperpolarized contrast agent. In a preferred embodiment, the hyperpolarized contrast agent includes ^{13}C nuclei; however, it is contemplated that other hyperpolarized contrast agents may be used, such as ^{14}N, ^{31}P, ^{19}F, and ^{23}Na nuclei, other NMR relevant nuclei.

[0051] Following the determination at block **122** of the low flip angle modulation scheme, an excitation profile of the modified trueFISP pulse sequence is adjusted at block **124** for excitation of a single metabolic species of the hyperpolarized contrast agent. For example, a hyperpolarized ^{13}C-pyruvate may be injected into an imaging subject, and the excitation profile may be adjusted to excite ^{13}C-bicarbonate nuclei. The hyperpolarized contrast agent is then introduced into the imaging subject at block **126**. Next, the modified trueFISP pulse sequence excites the desired metabolic species at block **128**. This excitation may be delayed a specific time period after introduction of the agent to allow for perfusion into tissues, or for the agent to reach an organ of diagnostic interest. Alternatively, a period of delay may correspond to an amount of time for the contrast agent to be metabolized. Signals are then acquired from the excited metabolic species at block **130**.

[0052] Technique **120** then determines at block **132** whether to excite a different metabolic species for acquiring signals therefrom. If so **134**, then the excitation profile is adjusted at block **136** to excite the nuclei for another metabolite. The modulation scheme of the RF pulse sequence may also be adjusted, if desired, such that the modulation scheme for one metabolite is distinct from the modulation scheme for another metabolite. Technique **120** then excites and acquires signals from the other metabolite as described above in blocks **128** and **130**. If not **138**, MR images are reconstructed for the acquired signal data at block **140**. In a preferred embodiment, an image is reconstructed for each metabolite acquired. However, it is contemplated that a combined image may be reconstructed for all metabolites acquired.

[0053] FIG. **16** shows an exemplary in vivo trueFISP image of a pig heart, acquired with a constant flip angle of 2°. Hyperpolarized ^{13}C-pyruvate was injected intravenously, and images were acquired with the excitation profile adjusted to the resonance frequency of ^{13}C-bicarbonate, which is 160 Hz apart from the resonance frequency of pyruvate. FIG. **16** shows the sum of five consecutive images, acquired with 9-Hz frequency separation around the bicarbonate resonance.

[0054] Therefore, in accordance with one embodiment of the present invention, an MRI apparatus includes an MRI assembly having a plurality of gradient coils positioned about a bore of a magnet to impress a polarizing magnetic field. An RF transceiver system and an RF switch are controlled by a pulse module to transmit and receive RF signals to and from an RF coil assembly to acquire MR images. The MRI apparatus also includes a system controller coupled to the MRI assembly, the system controller configured to cause the RF coil assembly to excite a single metabolic species of a hyperpolarized agent injected into a subject of interest. The system controller further causes the RF transceiver system to acquire MR signals from the excited single metabolic species and reconstruct an image from the acquired MR signals.

[0055] In accordance with another embodiment of the invention, a method of hyperpolarized agent MR imaging includes injecting a hyperpolarized agent into a subject of interest and exciting a first metabolic species of the hyperpolarized agent. The method also includes acquiring MR signals from the excited first metabolic species and reconstructing an image from the acquired MR signals.

[0056] According to a further embodiment of the invention, a computer readable storage medium includes a computer program stored thereon comprising instructions which when executed by a computer, causes the computer to modulate a plurality of flip angle train RF pulses of a pulse sequence. The instructions further cause the computer to acquire MR data from the plurality of molecules and generate an image from the MR data.

[0057] The present invention has been described in terms of the preferred embodiment, and it is recognized that equivalents, alternatives, and modifications, aside from those expressly stated, are possible and within the scope of the appending claims.

What is claimed is:

1. An MRI apparatus comprising:

a magnetic resonance imaging (MRI) assembly having a plurality of gradient coils positioned about a bore of a magnet to impress a polarizing magnetic field and an RF transceiver system and an RF switch controlled by a pulse module to transmit RF signals to an RF coil assembly to acquire MR images; and

a system controller coupled to the MRI assembly, the system controller configured to:

cause the RF coil assembly to excite a single metabolic species of a hyperpolarized agent injected into a subject of interest;

cause the RF transceiver system to acquire MR signals from the excited single metabolic species; and

reconstruct an image from the acquired MR signals.

2. The MRI apparatus of claim **1** wherein the excitation of the single metabolic species excites the single metabolic species only.

3. The MRI apparatus of claim **1** wherein the excited single metabolic species comprises a metabolite of the hyperpolarized agent injected into the subject of interest.

4. The MRI apparatus of claim **1** wherein the system controller is further configured to repeat the excitation and the acquisition for each single metabolic species of the hyperpolarized agent.

5. The MRI apparatus of claim **1** wherein the single metabolic species comprises a single metabolic species of 13C.

6. A method of hyperpolarized agent MR imaging comprising the steps of:

injecting a hyperpolarized agent into a subject of interest;

exciting only a first metabolic species of the hyperpolarized agent;

acquiring MR signals from the excited first metabolic species; and

reconstructing an image from the acquired MR signals.

7. The method of claim **6** wherein the excitation of only the first metabolic species does not excite other metabolic species of the hyperpolarized agent.

8. The method of claim **6** wherein the excitation of the first metabolic species comprises a metabolite of the hyperpolarized agent injected into the subject of interest.

9. The method of claim **6** wherein the step of exciting comprises:

modifying a flip angle train according to a first low angle modulation pattern; and

applying a pulse sequence having the modified flip angle train to the first metabolic species.

10. The method of claim **9** wherein the step of modifying comprises modifying the flip angle train according to a constant amplitude low angle modulation pattern having amplitudes less than 2 degrees.

11. The method of claim **9** wherein the step of modifying comprises modifying the flip angle train according to a Gaussian modulated low angle modulation pattern.

12. The method of claim **9** wherein the step of modifying comprises modifying the flip angle train according to a sinc function modulated low angle modulation pattern.

13. The method of claim **9** further comprising the steps of:

exciting only a second metabolic species of the hyperpolarized agent; and

acquiring MR signals from the excited second metabolic species.

14. The method of claim **13** wherein the step of exciting the second metabolic species comprises:

modifying the flip angle train according to a second low angle modulation pattern distinct from the first low angle modulation pattern; and

applying a pulse sequence having the modified flip angle train according to the second low angle modulation pattern to the second metabolic species.

15. A non-transitory computer readable storage medium having stored thereon a computer program comprising instructions which when executed by a computer, causes the computer to:

modulate a plurality of flip angle train RF pulses of a pulse sequence;

excite, with the pulse sequence, a plurality of molecules of a single hyperpolarized metabolite within an object;

acquire MR data from the plurality of molecules; and

generate an image from the MR data.

16. The computer readable storage medium of claim **15** wherein the instructions, in exciting of the plurality of molecules of the single hyperpolarized metabolite with the pulse sequence, do not excite molecules of other hyperpolarized metabolites within the object.

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