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**Hurd**

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(54) **SYSTEM AND METHOD FOR TISSUE SPECIFIC MR IMAGING OF METABOLITES USING SPECTRAL-SPATIALLY FORMED STIMULATED ECHO**

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(57) **ABSTRACT**

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A system for magnetic resonance (MR) spectroscopy includes a plurality of gradient coils positioned about a bore of a magnet and an RF coil assembly coupled to a pulse generator to emit RF pulse sequences and arranged to receive resulting MR signals from a subject of interest. A system control is also included in the MR spectroscopy system and is coupled to the plurality of gradient coils and the RF coil assembly. The system control is programmed to cause the RF coil assembly to emit a first RF pulse and a second RF pulse, wherein at least one of the first and second RF pulses is spectrally selective and at least one of the first and second RF pulses is spatially selective. The system control is also programmed to cause the RF coil assembly to emit a third RF pulse after a pre-defined time delay to generate a stimulated echo and detect MR signals resulting from the stimulated echo.

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**G01V 3/00** (2006.01)

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

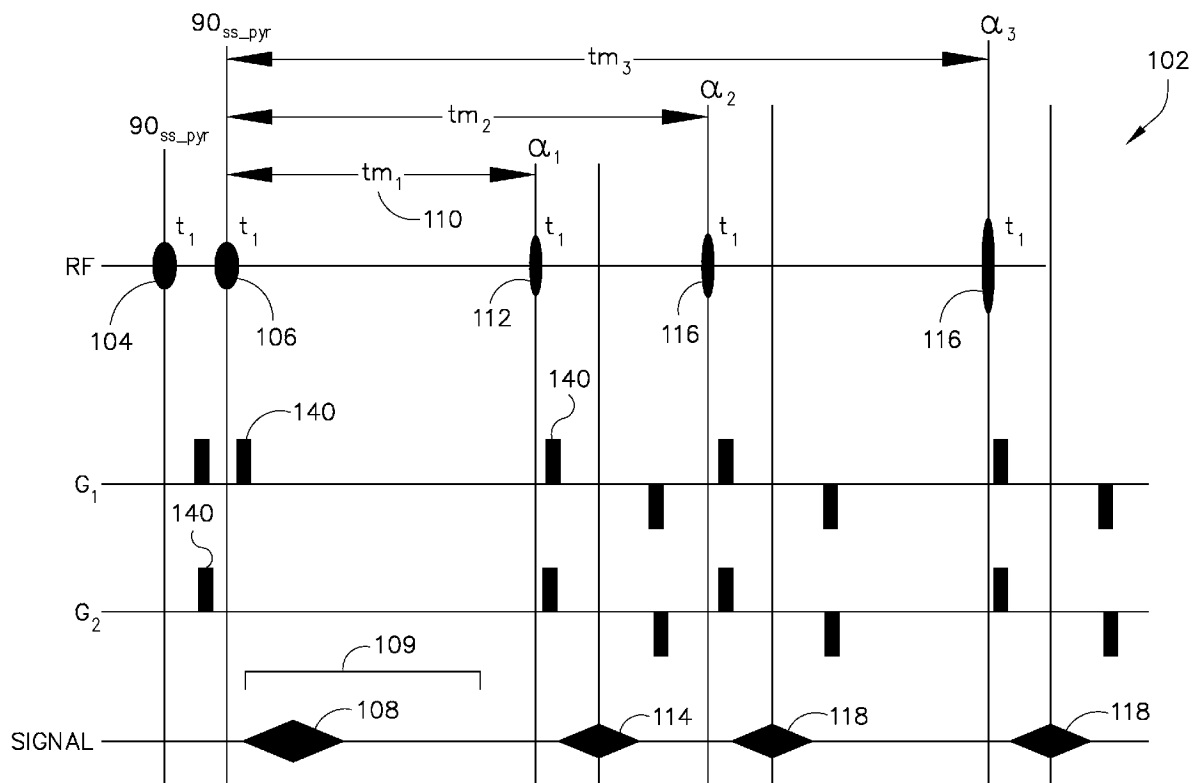
(58) **Field of Classification Search** ..... 324/300–322  
See application file for complete search history.

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**17 Claims, 8 Drawing Sheets**



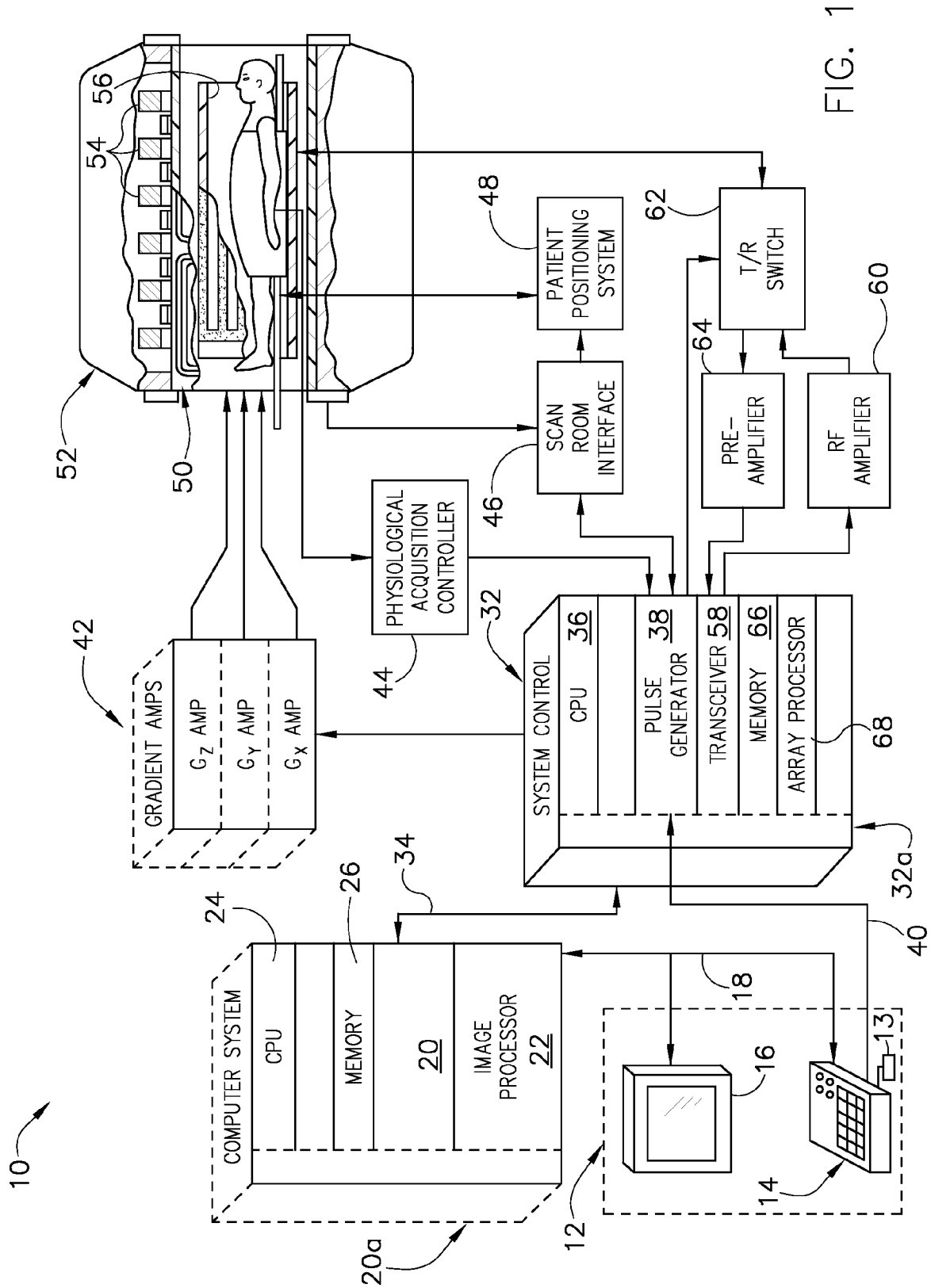


FIG. 1

FIG. 2

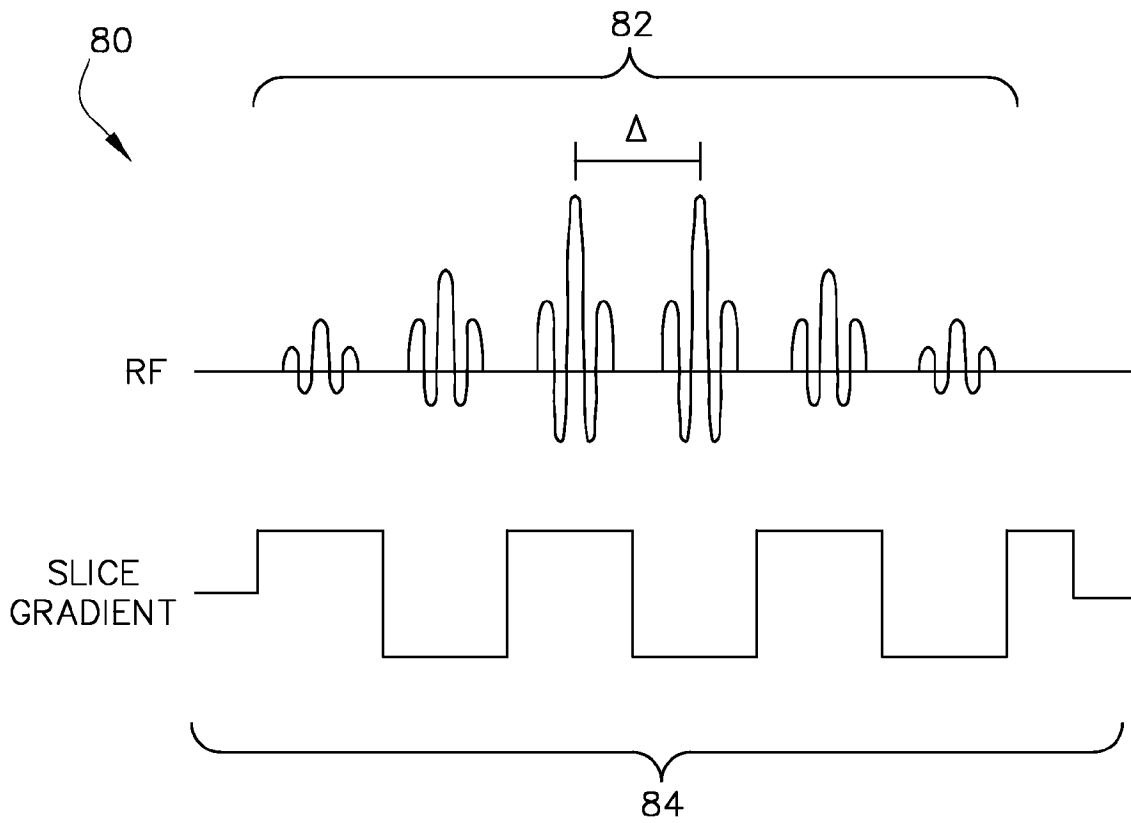
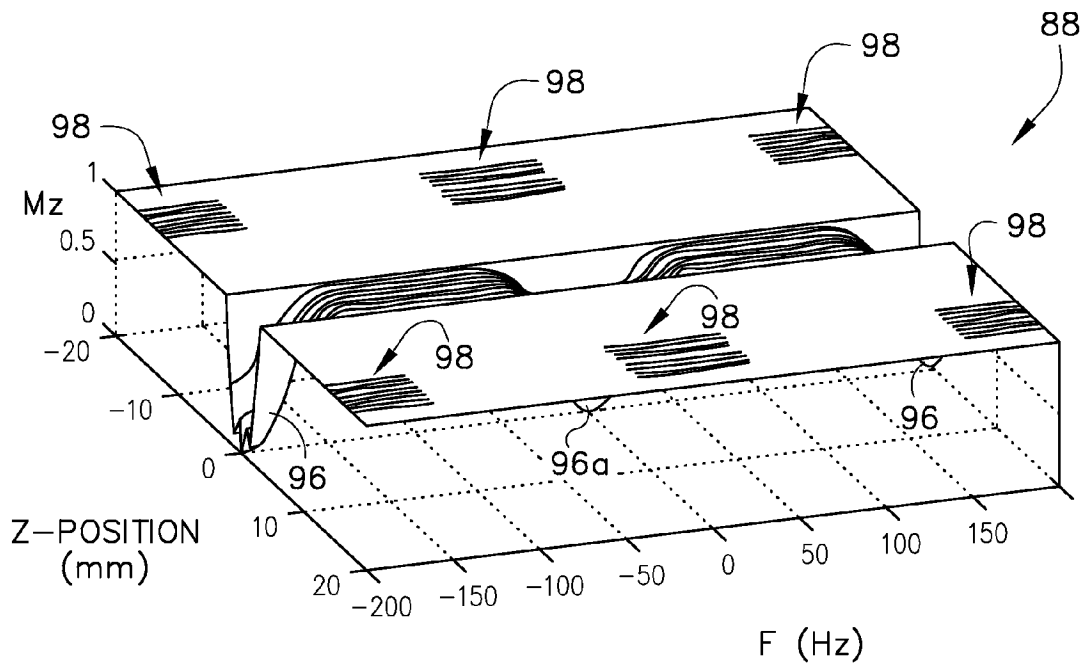
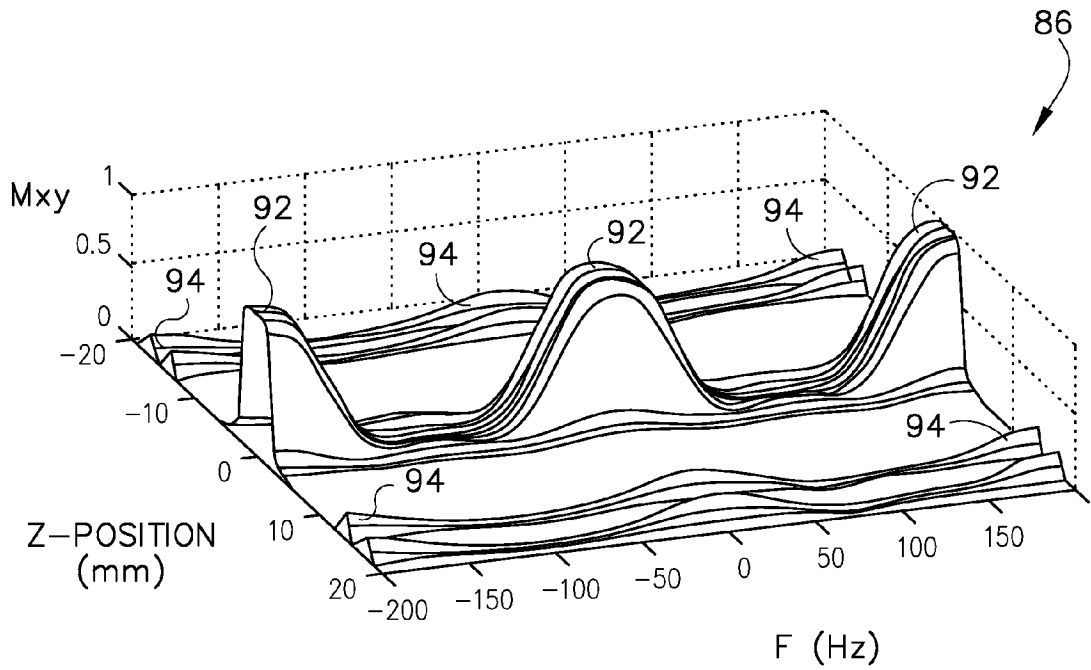


FIG. 3



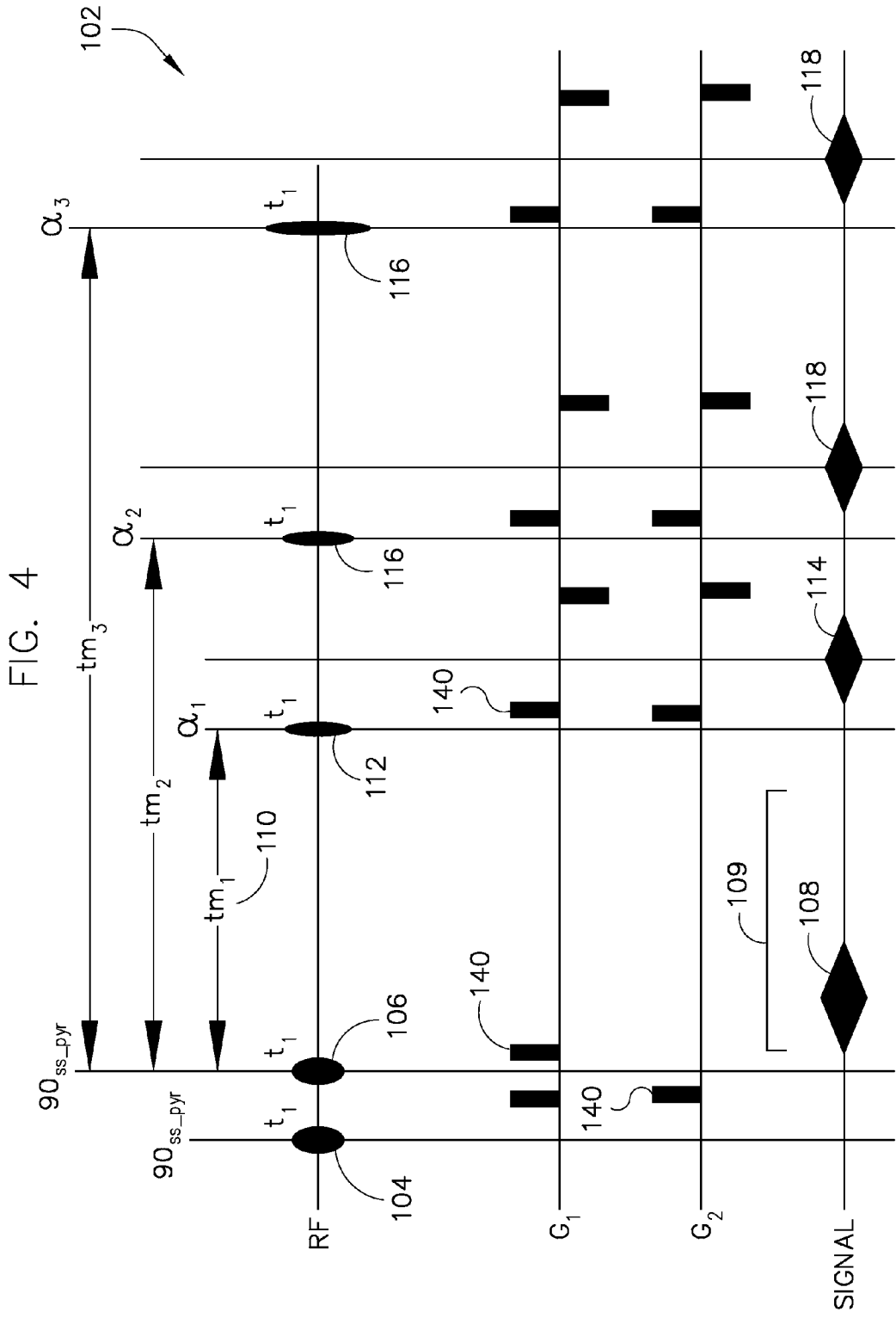
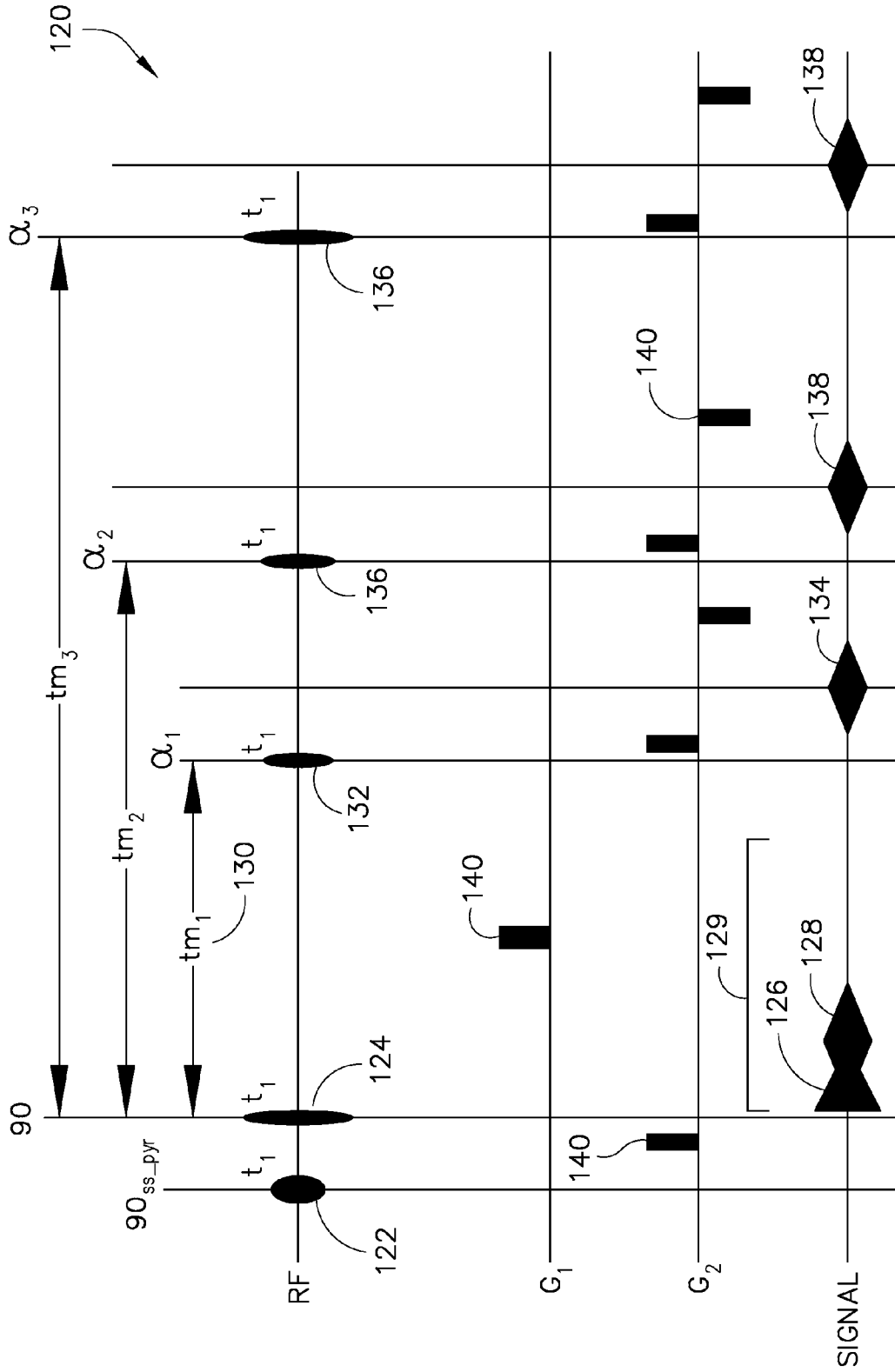


FIG. 5



142

FIG. 6

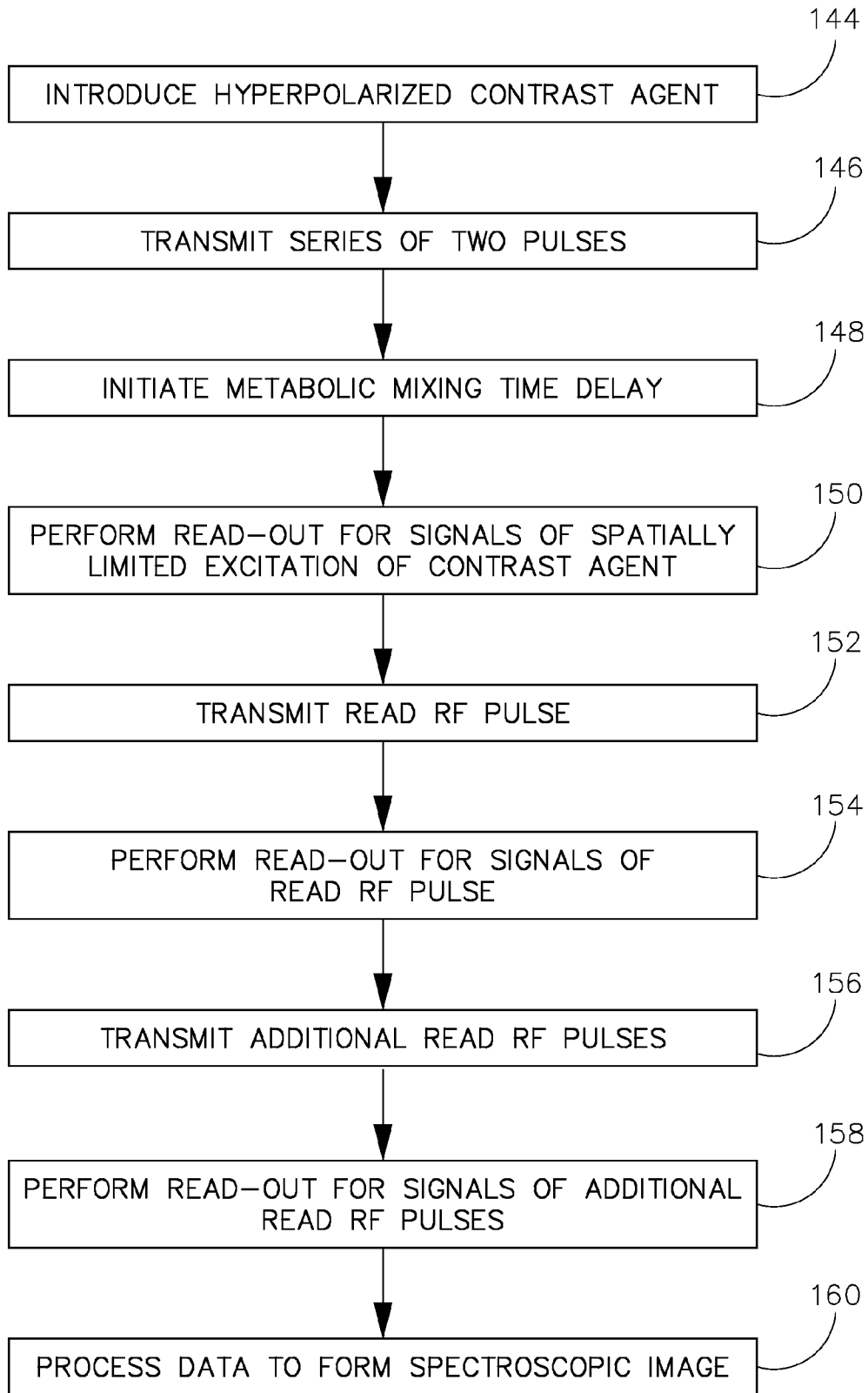


FIG. 7

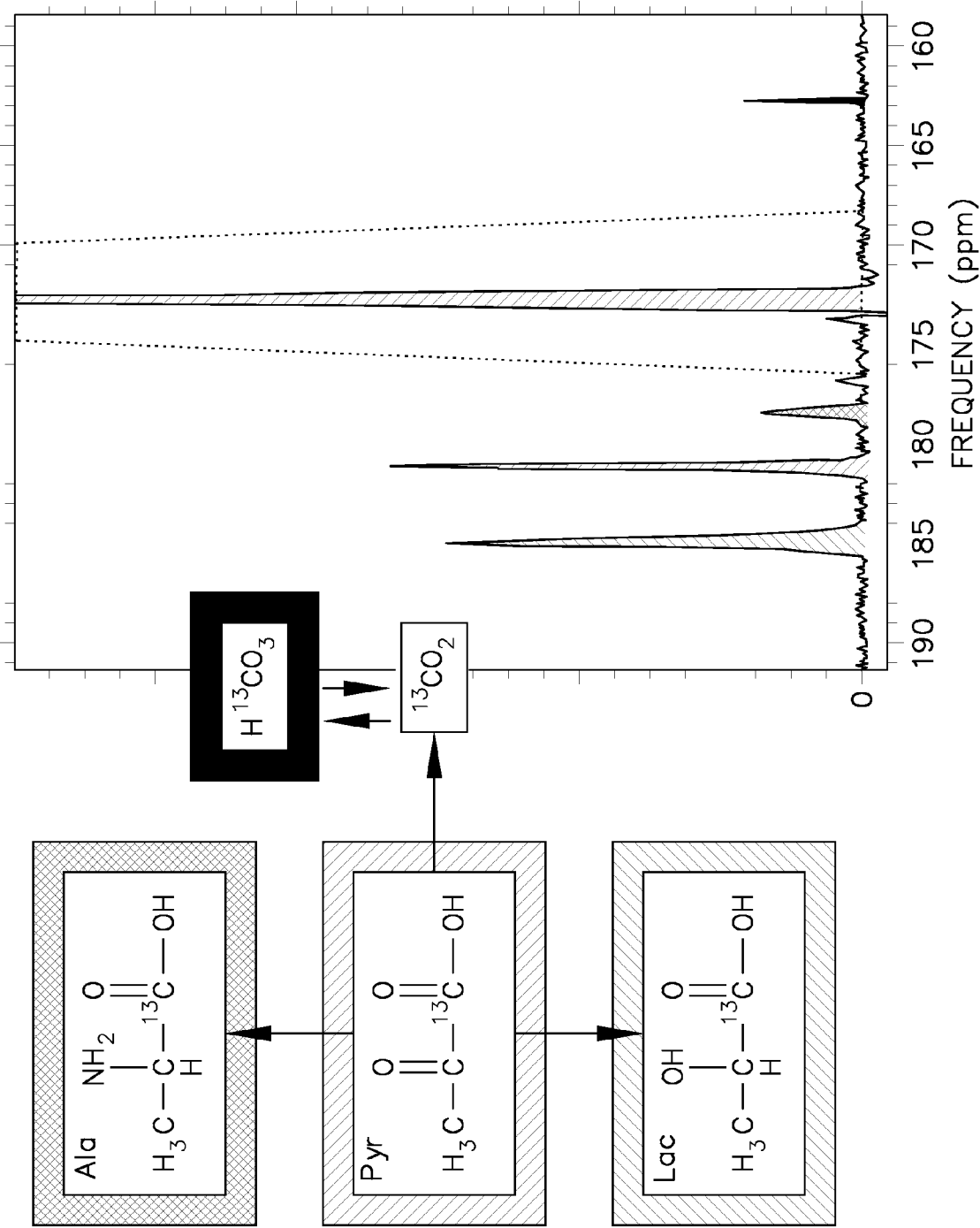
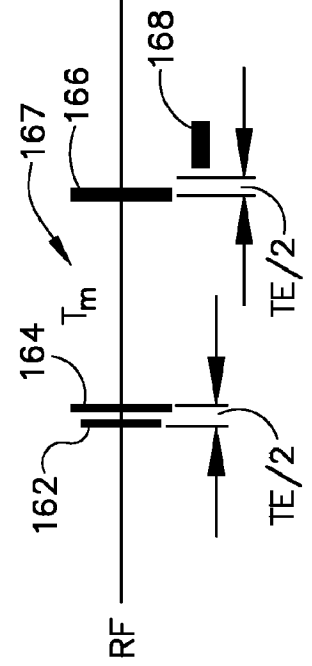
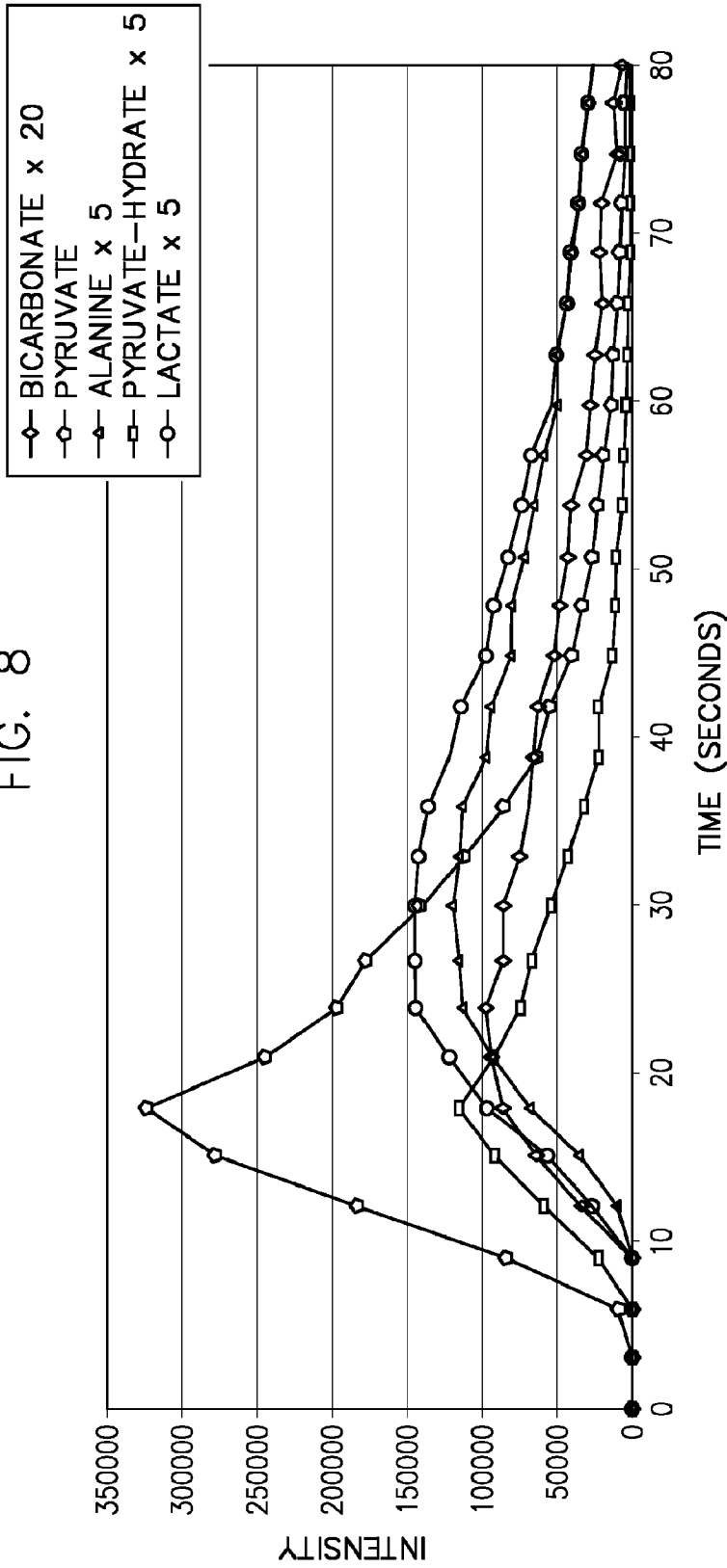




FIG. 8



1

**SYSTEM AND METHOD FOR TISSUE  
SPECIFIC MR IMAGING OF METABOLITES  
USING SPECTRAL-SPATIALLY FORMED  
STIMULATED ECHO**

BACKGROUND OF THE INVENTION

Embodiments of the invention relate generally to magnetic resonance (MR) imaging, and more particularly, to tissue-specific MR imaging of metabolites using spectral-spatially formed stimulated echoes.

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 has a frequency 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  $M_r$ . A signal is emitted by the excited spins after the excitation signal  $B_1$  is terminated and this signal may be received and processed to form an image.

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 set of received nuclear magnetic resonance (NMR) signals resulting from a scan sequence are digitized and sent to a data processing unit for image reconstruction 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.

For some procedures and investigations, it is also desirable for MR images to display spectral information in addition to spatial information. The traditional method for creating such images is known as "chemical shift imaging" (CSI). CSI has been employed to monitor metabolic and other internal processes of patients, including imaging hyperpolarized substances such as  $^{13}\text{C}$  labeled contrast agents and metabolites thereof. In such  $^{13}\text{C}$  imaging, spectral composition is dependent not only on tissue type and health of that tissue, but also on the time the image is acquired relative to the injection of the hyperpolarized  $^{13}\text{C}$  agent. The hyperpolarization of contrast agents tends to have a very limited lifetime; typical T1 lifetimes are on the order of a few minutes in vivo.

While CSI, as a sequence for imaging hyperpolarized substances, provides valuable information on tissue type and health of that tissue, prior art CSI does not distinguish where or when metabolic products are formed in a  $^{13}\text{C}$ -hyperpolarized metabolic imaging acquisition. That is, while hyperpolarized  $^{13}\text{C}$  imaging of  $^{13}\text{C}$ -1-pyruvate and its' metabolic products lactate, alanine and bicarbonate can provide tissue-specific metabolic fingerprints (spectra), these fingerprints can be confounded by the local uptake of metabolic products not formed in the tissue of interest. For example, lactate in the blood stream formed by the heart or by red blood cells may be taken up by the tissue of interest, confounding the measurement of locally formed lactate.

It would therefore be desirable to have a system and method of MR imaging with spectral information and hyperpolarization that is able to separate systemic from local metabolic activity. Specifically, it would be desirable to excite and image hyperpolarized agents and metabolites thereof for a

2

volume of interest, while effectively excluding metabolic products formed outside the volume of interest.

BRIEF DESCRIPTION OF THE INVENTION

In accordance with one aspect of the invention, a magnetic resonance (MR) spectroscopy system includes a plurality of gradient coils, an RF coil assembly, and a system control. The system control is programmed to cause the RF coil assembly to emit a first RF pulse and a second RF pulse, wherein at least one of the first and second RF pulses is spectrally selective and at least one of the first and second RF pulses is spatially selective. The system control is also programmed to cause the RF coil assembly to emit a third RF pulse after a pre-defined time delay to generate a stimulated echo and detect MR signals resulting from the stimulated echo.

In accordance with another aspect of the invention, a method for magnetic resonance (MR) imaging includes exciting a resonant frequency of a contrast agent, spatially limiting the excitation of the contrast agent to a slice or volume of interest, and detecting a first set of MR signals from the spatially limited excitation of the contrast agent. The method also includes, after a metabolic mixing time, exciting resonant frequencies for the contrast agent and at least one metabolic product formed from the contrast agent, detecting a second set of MR signals resulting from the excitation of the contrast agent and the at least one metabolic product after the metabolic mixing time, and generating a spectroscopic image from the detected first and second set of MR signals.

In accordance with yet another aspect of the invention, a computer readable storage medium includes a computer program stored thereon that represents a sequence of instructions that, when executed by a computer, causes the computer to request transmission of a spectral-spatial pulse at a first frequency and request transmission of a follow-up RF pulse, with the spectral-spatial pulse and the follow-up RF pulse generating a spin echo. The sequence of instructions also causes the computer to request transmission of at least one read RF pulse encompassing one or more frequencies, with the spectral-spatial pulse, the follow-up RF pulse, and the at least one read RF pulse generating a stimulated echo. The sequence of instructions further causes the computer to acquire magnetic resonance (MR) signals from the spin echo and the stimulated echo to generate a spectroscopic image and store the MR signals in computer memory.

These and other advantages and features will be more readily understood from the following detailed description of preferred embodiments of the invention that is provided in connection with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

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

In the drawings:

FIG. 1 is a schematic block diagram of an exemplary MR imaging system incorporating an embodiment of the invention.

FIG. 2 is a graph of an exemplary RF pulse train and slice gradient waveform of a spectral-spatial pulse in accordance with an embodiment of the invention.

FIG. 3 is a 3-D graph of an excitation profile for a spectral-spatial pulse in accordance with an embodiment of the invention.

FIG. 4 is a diagram of an imaging sequence in accordance with an embodiment of the invention.

FIG. 5 is a diagram of an imaging sequence in accordance with another embodiment of the invention.

FIG. 6 is a flowchart illustrating a technique for MR imaging of metabolites at selective excitation frequencies in accordance with an embodiment of the invention.

FIG. 7 is a 2-D graph of the spectral separation of 13C-1-pyruvate and its metabolic products, in accordance with an embodiment of the invention.

FIG. 8 is a graph of metabolic behavior of 13C-1-pyruvate relative to the timing of an exemplary spectral-spatial stimulated echo imaging sequence in accordance with an embodiment of the invention.

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

A system and method for slice-selectively exciting a resonant frequency for a metabolic reactant and for reading out a resulting metabolic process as a spectroscopic image is provided. In this regard, a pair of RF pulses may be emitted to spectral-spatially excite a frequency in a subject of interest for a specified metabolic reactant. Spectral-spatial radio frequency (RF) pulses may be used to create magnetization in a specific frequency profile without significantly affecting neighboring slices or nearby frequency ranges. A third RF pulse (either non-spectrally selective or spectrally selective) may then be emitted to generate a stimulated echo and excite a broad range of frequencies in the subject of interest for a plurality of metabolic products derived in vivo from the metabolic reactant. The signals resulting from these pulses are read in one or more of several well-known read out sequences.

Referring to FIG. 1, the major components of an exemplary magnetic resonance imaging (MRI) system 10 incorporating embodiments of the 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 20a. These include an image processor module 22, a CPU module 24 and a memory module 26 that may include a frame buffer for storing image data arrays. The computer system 20 is linked to archival media devices, permanent or back up memory or a network 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.

The system control 32 includes a set of modules connected together by a backplane 32a. 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.

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 the transmit or receive mode.

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. In response to commands received from the operator console 12, this image data may be archived in long term storage or it may be further processed by the image processor 22 and conveyed to the operator console 12 and presented on the display 16.

Referring now to FIG. 2, an exemplary spectral-spatial type excitation pulse 80 is depicted. As discussed above, spectral-spatial imaging is a type of imaging in which spectral data regarding the type of substance being imaged is combined with the typical slice selection of common MR imaging. Excitation pulse 80 includes a number of RF sub-elements 82. As shown, these RF sub-elements 82 represent periodic sinc functions of gradually increasing, then decreasing amplitudes. However, it is recognized that RF sub-elements 82 may take many forms other than merely sinc functions, such as Gaussian waveforms. The frequency of the RF sub-elements 82 may be selected to correspond to the resonant frequency of a particular substance of interest, for spectral encoding. For example, the resonant frequency of nuclei of a hyperpolarized substance may be targeted by pulse 80.

Along with the RF sub-elements 82, a slice encoding gradient 84 is applied. Slice encoding gradient 84 is a periodic gradient of alternating sign. In combination, RF sub-elements 82 and gradient 84 allow for slice-selective excitation within a specific frequency range. The spectral excitation profile of the pulse 80 (to be described below) is periodic with a peri-

5

odicity of  $1/\Delta$  Hz, where  $\Delta$  represents the time distance between the sub-elements **82** of the RF waveform **80**. In a preferred embodiment, excitation pulse **80** is applied to effect approximately a 90 degree total flip angle, though it is contemplated that other flip angles are also suitable. For example, the polarization and sensitivity to RF magnetization destruction of a contrast agent, the number of excitations desired, or the desired image resolution may affect the strength of the pulse to be applied.

Referring now to FIG. 3, the effects upon magnetization of an arbitrary spectral-spatial pulse (such as described with reference to FIG. 2) are shown. The upper plot **86** shows transverse magnetization  $M_{xy}$  and the lower plot **88** shows longitudinal magnetization  $M_z$ . The horizontal axes of the plots **86**, **88** represent spectral frequency, the front-to-back axes represent geometric position along the z axis, and the vertical axes show magnetization. As shown, the primary transverse magnetization **92** is centered along the position marked as 0 mm along the z-position axis. Along the spectral axis, the magnetization **92** is periodic, centered at 0 Hz. As discussed above, the periodicity of magnetization **92** is dependant upon the  $\Delta$  component of the spectral-spatial pulse applied. Thus, a desired period  $1/\Delta$  Hz may be attained by altering this characteristic of the spectral-spatial pulse. Magnetization **94** outside the primary slice is relatively weak in comparison. Likewise, magnetization at spectral positions 100 Hz on either side of primary magnetization **92** is nearly non-existent.

Lower plot **88** of FIG. 3 shows converse effects upon longitudinal magnetization. A corresponding primary decrease in longitudinal magnetization **96** is centered at the position marked as 0 mm along the z-position (front-to-back) axis. The primary reduction in magnetization **96** is periodic, centered at 0 Hz, as is the case with transverse magnetization. The period of the primary longitudinal magnetization reduction **96** is also  $1/\Delta$  Hz, dependant upon the spectral-spatial pulse applied. Magnetization at approximately 100 Hz on either side of primary magnetization reduction **96** remains at the initial strength (i.e. essentially unchanged by application of the spectral-spatial pulse). Likewise, magnetization **98** outside the primary slice along the z-position axis remains relatively unchanged.

Referring now to FIG. 4, one embodiment of a data acquisition sequence **102** incorporating spectral-spatial pulses **104**, **106**, as described above, is shown. In a preferred embodiment, sequence **102** is adapted for imaging a metabolic process. In this regard, the excitation frequency of the spectral-spatial pulses **104**, **106** may be keyed to the resonant frequency of a hyperpolarized contrast agent (i.e., metabolic reactant). For example, the excitation frequency of spectral spatial pulses **104**, **106** may be designed to excite the nuclei of hyperpolarized <sup>13</sup>C labeled pyruvate. However, it is recognized that other substances with other excitable nuclei are equally applicable (such as other <sup>13</sup>C-enriched compounds or substances having <sup>15</sup>-N, <sup>31</sup>-P, <sup>19</sup>-F, <sup>29</sup>-Si, <sup>129</sup>-Xe nuclei, and other NMR relevant nuclei).

Acquisition sequence **102** begins with emission of a first spectral-spatial pulse **104**, which causes excitation of a substance of corresponding resonant frequency. A second spectral-spatial pulse **106** (i.e., a follow-up RF pulse) is then transmitted at the same frequency as the first spectral-spatial pulse **104**. Second spectral-spatial pulse **106** is preferably applied at a time midway between the application of the first spectral-spatial pulse **104** and the peak of a spin echo **108**. (i.e., one-half the echo time (TE), TE/2) Preferably, spectral-spatial pulses **104**, **106** have flip angles of approximately 90 degrees. As shown in FIG. 4, the combination of the first and

6

second spectral-spatial pulses **104**, **106** produces a spin echo **108** (i.e., Hahn echo). A read-out or data sampling/acquisition stage **109** begins after application of second spectral-spatial pulse **106**, and signals from spin echo **108** are sampled or otherwise acquired (i.e., a first set of MR signals are acquired). Read-out may take the form of several well-known acquisition sequences, such as an echo planar imaging (EPI) readout (for example, spin echo EPI), a rapid acquisition with relaxation enhancement (RARE) readout, a true fast imaging with steady precession (trueFISP) readout, or variations thereof. The MR signals acquired from the spin echo comprises signals from the excited substance (e.g., <sup>13</sup>-C labeled pyruvate) and is limited to a slice or volume of interest.

Upon acquisition of the spectrally and spatially limited signals from the spin echo **108**, the acquisition sequence **102** delays for a remainder of a pre-defined delay period **110**, the length of which is measured from the application of the second spectral-spatial pulse **106**. While the pre-defined delay period **110** is shown in FIG. 4 as being measured from after the application of the second spectral-spatial pulse **106**, it is also recognized that the pre-defined delay period **110** could be a time period measured from introduction of the hyperpolarized contrast agent into the patient. The pre-defined delay period **110** comprises a metabolic mixing time  $T_{m1}$  that allows for sufficient metabolization of the hyperpolarized contrast agent to occur. That is, metabolic mixing time  $T_{m1}$  allows for metabolization of the hyperpolarized contrast agent into a plurality of metabolic products. These metabolic products can include, but are not limited to, lactate, alanine, and bicarbonate. The length of the metabolic mixing time  $T_{m1}$  can be selected by a system operator and can extend over several T1 decay periods (e.g., 3 T1 periods), being limited only by the length of time the contrast agent remains in a hyperpolarized state.

After the metabolic mixing time  $T_{m1}$  has passed, a third RF pulse **112** (i.e., a read pulse) is applied to excite a desired number of frequencies. In one embodiment, the third RF pulse **112** is a non-spectrally selective read RF pulse designed to cause the excitation of the resonant frequency for the hyperpolarized contrast agent as well as the resonant frequencies of each of the metabolic products. In another embodiment, however, third RF pulse **112** is a spectrally selective pulse designed to be spectrally selective for a specific metabolic product. Upon application of the third RF pulse **112**, a stimulated echo **114** is formed from which a second set of MR signals is sampled or otherwise acquired. More specifically, the combination of the first spectral spatial pulse **104**, the second spectral-spatial pulse **106**, and the third RF pulse **112** generates the stimulated echo **114**. Depending on the spectral selectivity (i.e., whether the third RF pulse is spectrally selective or non-spectrally selective) of the third RF pulse **112** that is applied, the signals contained in the stimulated echo **114** can include signals from the original hyperpolarized contrast agent, a specified metabolic product, or the hyperpolarized contrast agent and a plurality of the metabolic products formed during the metabolic mixing time  $T_{m1}$ .

As shown in FIG. 4, it is envisioned that additional spectrally selective or non-spectrally selective read RF pulses **116** can also be applied in the acquisition sequence **102**. That is, signals for the original hyperpolarized contrast agent and/or signals from one or more of the metabolic products can be acquired at additional, varied metabolic mixing times ( $T_{m2}$ ,  $T_{m3}$  . . .) by way of additional stimulated echoes **118**. Thus, the metabolization of the hyperpolarized contrast agent and the formation of metabolic products can be measured at varying points in the T1 decay periods of the excited hyperpolarized contrast agent (i.e., over the several T1 decay periods of

the excited hyperpolarized contrast agent). To maintain signal strength in each of the stimulated echoes **114**, **118** that are formed from the one or more read RF pulses **112**, **116**, the read RF pulses **112**, **116** can have low flip angles ( $\alpha$ ), such as, for example, 15 degrees. The low flip angle pulses allow for a plurality of stimulated echoes **114**, **118** to be generated and allow for signals to be acquired from each of those stimulated echoes **114**, **118**. The number of additional read RF pulses **116** that can be applied in the acquisition sequence **102** is limited only by the longitudinal relaxation time of the excited hyperpolarized contrast agent.

As shown in FIG. 4, gradient pulses **140** are also applied during the acquisition sequence **102**, **120** as G1 and G2 gradients. Gradients G1, G2 correspond to gradients applied along a pair of arbitrary axes (e.g., orthogonal axes) and the gradient pulses **140** are crusher gradients that function to spoil spin echo responses and rephase stimulated echo responses. It is envisioned that varying gradients G1, G2 can be applied to correspond with the data acquisition desired from a specified acquisition sequence and that gradient pulse patterns are not limited to those shown in FIG. 4.

Referring now to FIG. 5, another embodiment of a data acquisition sequence **120** incorporating a spectral-spatial pulse **122** is shown. In the embodiment of FIG. 5, acquisition sequence **120** begins with emission of a spectral-spatial pulse **122**, which causes excitation of a hyperpolarized contrast agent of corresponding resonant frequency. A follow-up RF pulse **124** is then transmitted in the form of a non-spectrally selective RF pulse. The follow-up RF pulse **124** causes excitation for a number of metabolic products that begin to form after in-vivo introduction of the hyperpolarized contrast agent. Preferably, spectral-spatial pulse **122** and follow-up RF pulse **124** have flip angles of approximately 90 degrees, and, preferably, follow-up RF pulse **124** is applied at a time of TE/2 after spectral-spatial pulse **122**. From the first spectral-spatial pulse **122** and the follow-up RF pulse **124**, free induction decay (FID) signals **126** and a spin echo signal **128** are generated. Specifically, the non-spectrally selective follow-up RF pulse **124** generates FID signals **126** for the hyperpolarized contrast agent as well as for each of the metabolic products that are formed from metabolization of the hyperpolarized contrast agent. The combination of the spectral-spatial pulse **122** and the follow-up RF pulse **124** generates spin echo (i.e., Hahn echo) signals **128** from only the hyperpolarized contrast agent. A read-out or data sampling/acquisition stage **129** begins after emission of the follow-up RF pulse **124** to acquire the FID signals **126** and the spin echo signals **128**, and the FID and spin echo signals **126**, **128** are sampled or otherwise acquired during the read-out or data sampling/acquisition stage **129**.

Referring still to FIG. 5, upon acquisition of the spectrally and spatially limited signals from the spin echo **128** and from the FID signals **126**, the acquisition sequence **120** allows for remainder of a pre-defined delay period **130** (i.e., metabolic mixing time  $T_{m1}$ ) to pass. The metabolic mixing time  $T_{m1}$  allows for sufficient metabolization of the hyperpolarized contrast agent to occur, such that a plurality of metabolic products are formed, such as lactate, alanine, and bicarbonate.

After the metabolic mixing time  $T_{m1}$  has passed, a spectrally selective or a non-spectrally selective read RF pulse **132** is applied to excite a plurality of frequencies. The read RF pulse **132** can be designed to cause excitation of the resonant frequency for a specified metabolic product or of the resonant frequency for the hyperpolarized contrast agent as well as each of the metabolic products. Upon application of the read RF pulse **132**, a stimulated echo **134** is formed. The signals

contained in the stimulated echo **134** can include signals for the original hyperpolarized contrast agent along with signals from one or more of the metabolic products formed during the metabolic mixing time  $T_{m1}$ .

As shown in FIG. 5, it is envisioned that additional read RF pulses **136** can also be applied in the acquisition sequence **120**. That is, signals for the original hyperpolarized contrast agent and/or signals from one or more of the metabolic products can be acquired at additional metabolic mixing times ( $T_{m2}$ ,  $T_{m3}$  . . . ) by way of additional stimulated echoes **138**. Thus, the metabolization of the hyperpolarized contrast agent, and the formation of metabolic products, can be measured at varying points in the T1 decay periods.

As shown in FIG. 5, gradient pulses **140** are applied during the acquisition sequence **102**, **120** as G1 and G2 gradients and correspond to gradients applied along a pair of arbitrary axes (e.g., orthogonal axes). The gradient pulses **140** are crusher gradients that function to spoil FID and/or spin echo responses and rephase stimulated echo responses. It is envisioned that varying gradients G1, G2 can be applied to correspond with the data acquisition desired from a specified acquisition sequence and that gradient pulse patterns are not limited to those shown in FIG. 5.

FIG. 6 is a flowchart illustrating a technique **142** for spectroscopic imaging of a hyperpolarized contrast agent and its metabolic products in accordance with an embodiment of the invention. A hyperpolarized contrast agent is introduced into an imaging subject at block **144**. Next, a series of two RF pulses are transmitted at block **146**. The series of two RF pulses 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. At least one of the two RF pulses is transmitted at the resonant frequency of the contrast agent to induce excitation of the contrast agent and at least one of the two RF pulses is transmitted along with a slice selective gradient to form a spectral-spatial pulse that limits the excitation to a slice or volume of interest. At block **148**, a metabolic mixing time delay is initiated upon the application of the second of the series of two RF pulses. Once excitation is complete, a signal read-out then begins at block **150** during which MR data is acquired from spin echo signals resulting from the series of two RF pulses, the signals being limited to the excited hyperpolarized contrast agent. Also, in one embodiment, the MR data additionally includes FID signals resulting from the series of two RF pulses when one of those pulses is non-spectrally selective.

Technique **142** continues by waiting a remainder of the metabolic mixing time delay that is initiated at block **148** during application of the second of the series of two RF pulses. The metabolic mixing time delay allows for the hyperpolarized contrast agent to metabolize in the patient and form metabolic products. Upon completion of the metabolic mixing time delay, a read RF pulse (spectrally or non-spectrally selective) is applied at block **152** to excite the resonant frequencies of the hyperpolarized contrast agent and/or one or more of the metabolic products. Once excitation is complete, a signal read-out then begins at block **154** during which MR data is acquired from a stimulated echo that is formed from the application of the read RF pulse (e.g., a spectrally or non-spectrally selective pulse). The MR data includes signals from the hyperpolarized contrast agent and/or one or more of the metabolic products. One or more additional read RF pulses can be applied at block **156** (spectrally or non-spectrally selective), with each pulse generating an additional stimulated echo signal that is read at block **158**. Once all MR data has been acquired, the data is processed to perform

spatial mapping or reconstruct a spectroscopic image, according to any of the known reconstruction techniques at block 160.

It is recognized that the application of technique 142 is not limited to a specific type of spatial mapping. For example, technique 142 could be used in a single voxel mode such as STEAM, where the sequence of three RF pulses (described in detail above) are used with orthogonal gradients to select a metabolic volume of interest, with no further spatial mapping. Technique 142, however, is also applicable to other spatially limited and non-spatially limited spectroscopic imaging techniques.

Referring now to FIG. 7, the spectral separation of 13C-1-pyruvate and its metabolic products at 3T is shown. As shown therein, selective excitation for the 13C-1-pyruvate is achieved by a spectrally limited RF excitation pulse. Signals from the 13C-1-pyruvate and the metabolic products can be acquired from the technique illustrated in FIG. 6.

FIG. 8 displays the dynamic and metabolic behavior of 13C-1-pyruvate, and its metabolization into metabolic products, relative to the timing of the application of a spectral-spatial stimulated echo sequence, such as the pulse sequences set forth in FIGS. 4 and 5. In the embodiment shown of an exemplary pulse sequence shown in FIG. 8, a series of two RF pulses 162, 164 are transmitted. At least one of the two RF pulses is transmitted at the resonant frequency of the contrast agent (i.e., 13C-1-pyruvate) to induce excitation of the contrast agent and at least one of the two RF pulses is transmitted along with a slice selective gradient to form a spectral-spatial pulse that limits the excitation to a slice or volume of interest. As shown, the series of two RF pulses 162, 164 are separated by a time  $TE/2$ , which is one-half the time between the application of the first RF pulse 162 and the peak of a spin echo (not shown) generated by the series of the two RF pulses 162, 164. As further illustrated in FIG. 8, application of a non-spectrally selective RF pulse 166 for generating a stimulated echo does not occur until after a pre-determined delay period 167 (i.e., a metabolic mixing time,  $T_m$ ) has passed during which the 13C-1-pyruvate is allowed to metabolize to a sufficient extent. Spectroscopic image acquisition 168 can then be achieved by way of readout of the stimulated echo generated by the third RF pulse 166.

A technical contribution for the disclosed method and apparatus is that it provides for a computer implemented tissue-specific MR imaging of metabolites using spectral-spatially formed stimulated echoes. Spectral-spatial radio frequency (RF) pulses are used to create magnetization in a specific frequency profile without significantly affecting neighboring slices or nearby frequency ranges. A spectrally or non-spectrally selective RF pulse is then used to generate a stimulated echo to create magnetization over a broad frequency profile, allowing for a metabolic process to be read out as a spectroscopic image.

Therefore, according to one embodiment of the invention, a magnetic resonance (MR) spectroscopy system includes a plurality of gradient coils, an RF coil assembly, and a system control. The system control is programmed to cause the RF coil assembly to emit a first RF pulse and a second RF pulse, wherein at least one of the first and second RF pulses is spectrally selective and at least one of the first and second RF pulses is spatially selective. The system control is also programmed to cause the RF coil assembly to emit a third RF pulse after a pre-defined time delay to generate a stimulated echo and detect MR signals resulting from the stimulated echo.

According to another embodiment of the invention, a method for magnetic resonance (MR) imaging includes excit-

ing a resonant frequency of a contrast agent, spatially limiting the excitation of the contrast agent to a slice or volume of interest, and detecting a first set of MR signals from the spatially limited excitation of the contrast agent. The method also includes, after a metabolic mixing time, exciting resonant frequencies for the contrast agent and at least one metabolic product formed from the contrast agent, detecting a second set of MR signals resulting from the excitation of the contrast agent and the at least one metabolic product after the metabolic mixing time, and generating a spectroscopic image from the detected first and second set of MR signals.

According to yet another embodiment of the invention, a computer readable storage medium includes a computer program stored thereon that represents a sequence of instructions that, when executed by a computer, causes the computer to request transmission of a spectral-spatial pulse at a first frequency and request transmission of a follow-up RF pulse, with the spectral-spatial pulse and the follow-up RF pulse generating a spin echo. The sequence of instructions also causes the computer to request transmission of at least one read RF pulse encompassing one or more frequencies, with the spectral-spatial pulse, the follow-up RF pulse, and the at least one read RF pulse generating a stimulated echo. The sequence of instructions further causes the computer to acquire magnetic resonance (MR) signals from the spin echo and the stimulated echo to generate a spectroscopic image and store the MR signals in computer memory.

The invention has been described in terms of the preferred embodiments, and it is recognized that equivalents, alternatives, and modifications, aside from those expressly stated, are possible and within the scope of the appending claims. The order and sequence of process or method steps may be varied or re-sequenced according to alternative embodiments.

What is claimed is:

1. A magnetic resonance (MR) spectroscopy system comprising:
  - a plurality of gradient coils positioned about a bore of a magnet;
  - an RF coil assembly coupled to a pulse generator to emit RF pulse sequences and arranged to receive resulting MR signals from a subject of interest; and
  - a system control coupled to the plurality of gradient coils and the RF coil assembly, the system control programmed to cause the RF coil assembly to:
    - emit a first RF pulse and a second RF pulse, wherein at least one of the first and second RF pulses is spectrally selective and at least one of the first and second RF pulses is spatially selective;
    - emit a third RF pulse after a pre-defined time delay to generate a stimulated echo; and
    - detect MR signals resulting from the stimulated echo.
2. The MR spectroscopy system of claim 1 wherein the system control is further programmed to detect spectral-spatially selective MR signals resulting from the first and second RF pulses.
3. The MR spectroscopy system of claim 2 wherein the spectral-spatially selective MR signals resulting from the first and second RF pulses comprise at least one of a free induction decay (FID) signal and a spin echo signal.
4. The MR spectroscopy system of claim 1 wherein the at least one of the first RF pulse and the second RF pulse that is spectrally selective is designed to excite a metabolic reactant at a specified frequency.
5. The MR spectroscopy system of claim 4 wherein the metabolic reactant comprises 13C-1-pyruvate.

## 11

6. The MR spectroscopy system of claim 4 wherein the pre-defined time delay comprises a mixing time measured from the emission of the second RF pulse, the mixing time designed to allow the metabolic reactant to metabolize into a plurality of metabolic products.

7. The MR spectroscopy system of claim 6 wherein the mixing time extends over a plurality of T1 time periods.

8. The MR spectroscopy system of claim 1 wherein the system control is further programmed to cause the RF coil assembly to emit additional RF pulses after additional time delays subsequent to the pre-defined time delay, the additional RF pulses generating additional stimulated echoes.

9. The MR spectroscopy system of claim 8 wherein at least one of the third RF pulse and the additional RF pulses is a non-spectrally selective pulse and the MR signals resulting from the stimulated echo contain signals from a metabolic product and contain signals from a plurality of metabolic products formed during the pre-defined time delay.

10. The MR spectroscopy system of claim 8 wherein at least one of the third RF pulse and the additional RF pulses is spectrally selective for a specific metabolic product.

11. The MR spectroscopy system of claim 8 wherein the third RF pulse and the additional RF pulses are low flip angle pulses.

12. A computer readable storage medium having a computer program stored thereon and representing a sequence of instructions that when executed by a computer causes the computer to:

request transmission of a first RF pulse and a follow-up RF pulse to generate a spin echo, wherein at least one of the first RF pulse and the follow-up RF pulse is spectrally selective and at least one of the first RF pulse and the follow-up RF pulse is spatially selective;

## 12

request transmission of at least one read RF pulse encompassing one or more frequencies, wherein the first RF pulse, the follow-up RF pulse, and the at least one read RF pulse generate a stimulated echo;

5 acquire magnetic resonance (MR) signals from the spin echo and the stimulated echo to generate a spectroscopic image; and

store the MR signals in computer memory.

13. The computer readable storage medium of claim 12 wherein the first RF pulse comprises a spectrally limited RF pulse and a slice selective gradient pulse, the spectrally limited RF pulse designed to excite a hyperpolarized contrast agent at a specified frequency.

14. The computer readable storage medium of claim 13 wherein the hyperpolarized contrast agent comprises <sup>13</sup>C-1-pyruvate.

15. The computer readable storage medium of claim 12 wherein the follow-up RF pulse is a non-spectrally selective pulse and the computer program further causes the computer to acquire free induction decay (FID) signals from the non-spectrally selective follow-up RF pulse.

16. The computer readable storage medium of claim 12 wherein the at least one read RF pulse is a non-spectrally selective read RF pulse designed to excite a hyperpolarized contrast agent and a plurality of metabolic products formed from the hyperpolarized contrast agent during a metabolic mixing time.

17. The computer readable storage medium of claim 12 wherein the at least one read RF pulse is a spectrally selective read RF pulse designed to excite a specific metabolic product from a plurality of metabolic products formed from a hyperpolarized contrast agent during a metabolic mixing time.

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