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(54) **METHOD AND APPARATUS FOR QUANTITATIVE MAGNETIC RESONANCE IMAGING USING SPIN-LOCK RADIO FREQUENCY TRAINS**

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G01R 33/56 (2006.01)

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CPC ***G01R 33/50*** (2013.01); ***G01R 33/5608*** (2013.01)

(58) **Field of Classification Search**
CPC G01R 33/50; G01R 33/5608
See application file for complete search history.

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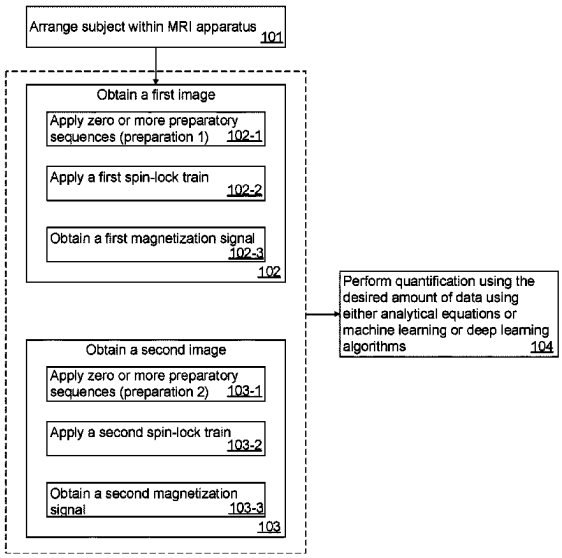
(57) **ABSTRACT**

A method for quantitative magnetic resonance imaging (MRI), an apparatus, and a non-transitory computer-readable storage medium are provided. In the method, a first magnetization signal is obtained based on a first train of spin-lock modules. Additionally, a second magnetization signal is obtained based on a second train of spin-lock modules. A final magnetization is obtained based on the first magnetization signal and the second magnetization signal. These processes are repeated to collect one or more final magnetization signals for quantification of tissue parameters.

20 Claims, 3 Drawing Sheets



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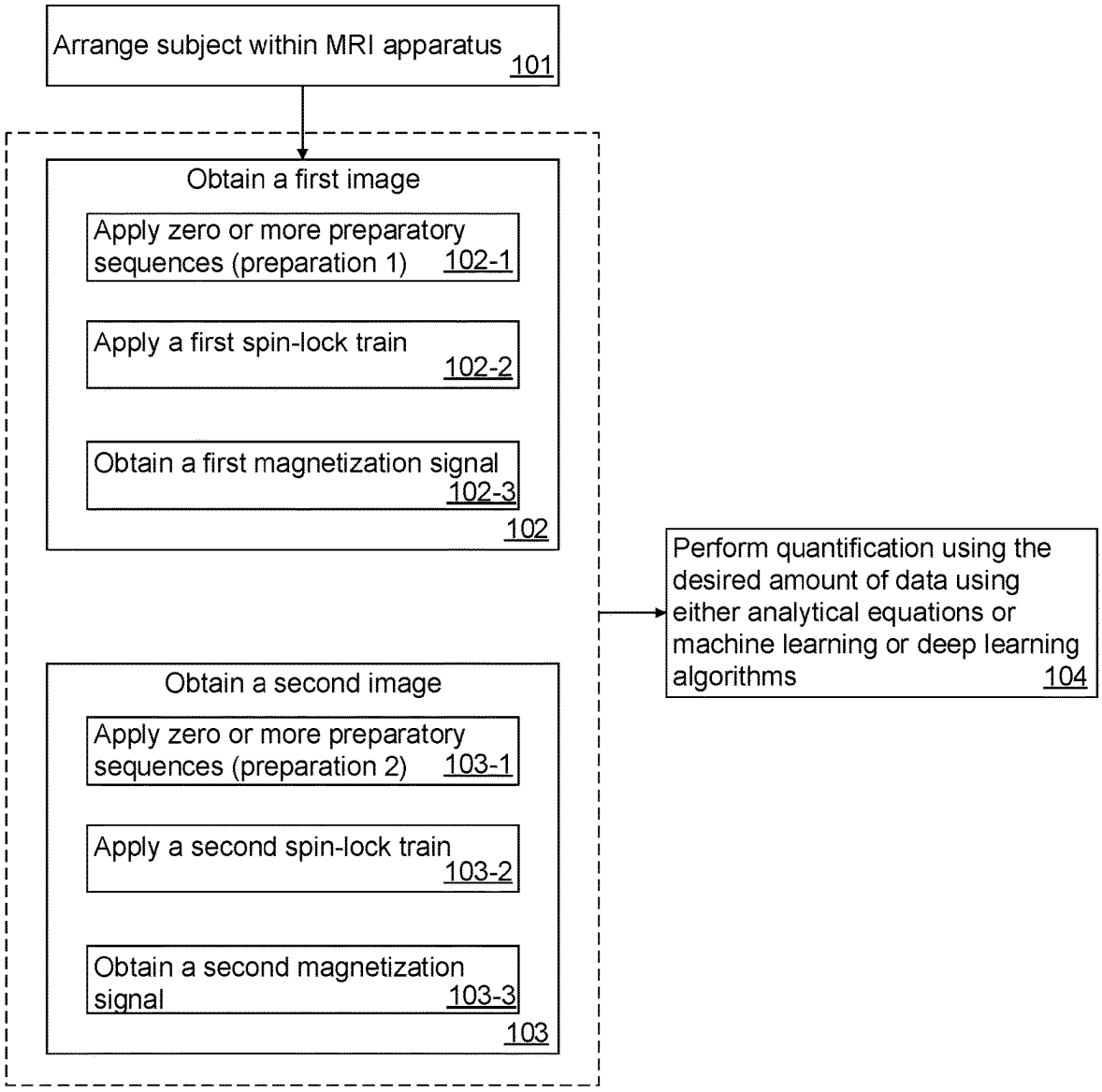
Arrange subject within MRI apparatus 101
Obtain a first image
Apply zero or more preparatory sequences (preparation 1) 102-1
Apply a first spin-lock train 102-2
Obtain a first magnetization signal 102-3
102
Obtain a second image
Apply zero or more preparatory sequences (preparation 2) 103-1
Apply a second spin-lock train 103-2
Obtain a second magnetization signal 103-3
103
Perform quantification using the desired amount of data using either analytical equations or machine learning or deep learning algorithms 104

FIG. 1

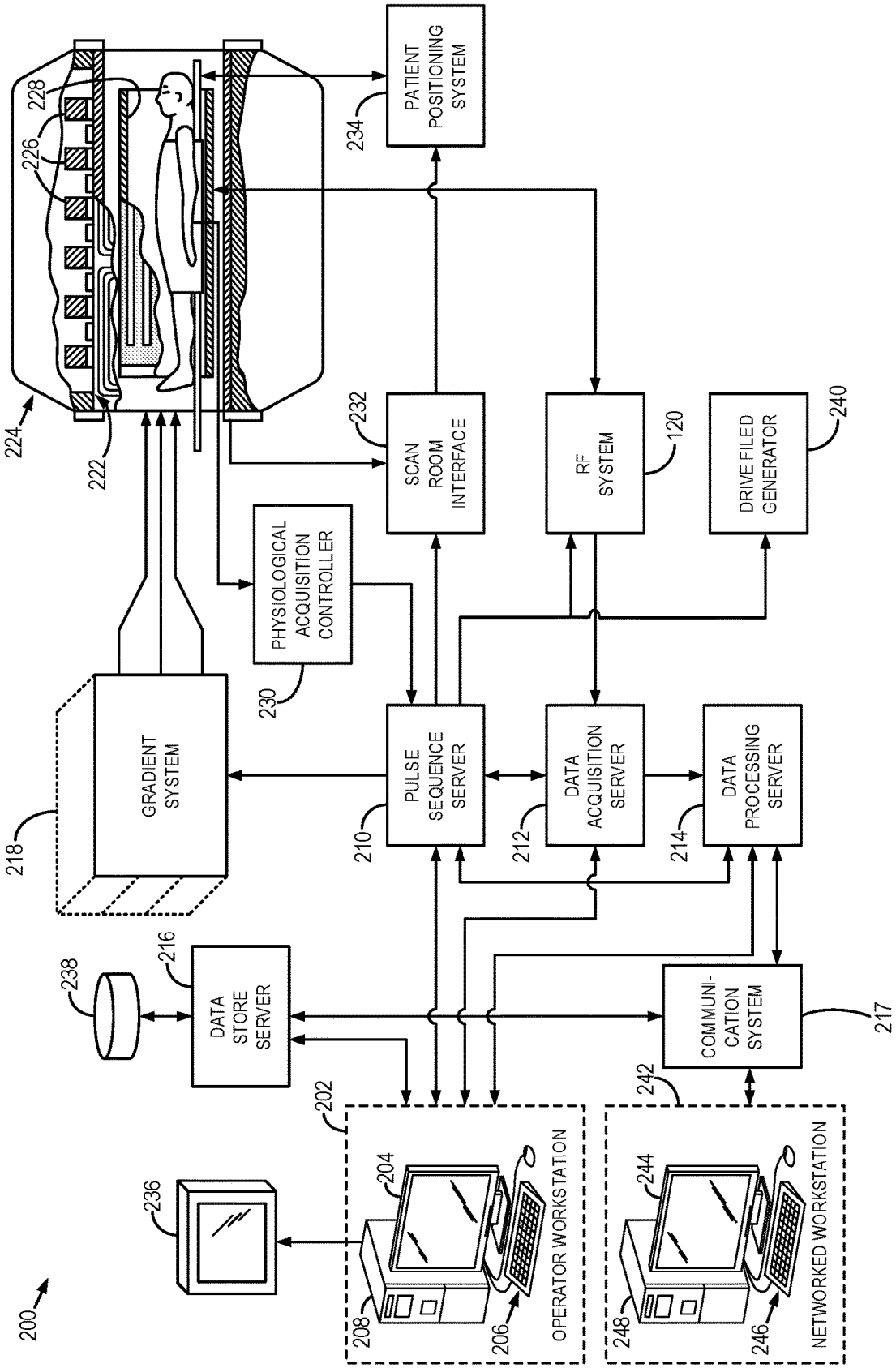
PATIENT POSITIONING SYSTEM
234
228
226
224
222
SCAN ROOM INTERFACE
232
RF SYSTEM
120
DRIVE FILED GENERATOR
240
PHYSIOLOGICAL ACQUISITION CONTROLLER
230
GRADIENT SYSTEM
218
PULSE SEQUENCE SERVER
210
DATA ACQUISITION SERVER
212
DATA PROCESSING SERVER
214
238
216
DATA STORE SERVER
COMMUNI-CATION SYSTEM
217
242
202
236
204
208
206
OPERATOR WORKSTATION
244
248
246
NETWORKED WORKSTATION
200

FIG. 2

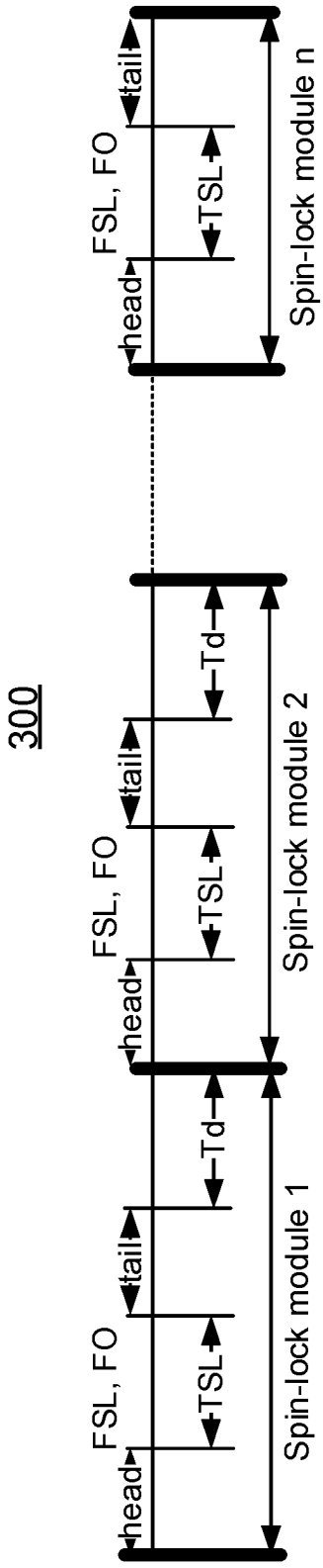
300
Spin-lock module 1
Spin-lock module 2
Spin-lock module n
FSL, FO
head
TSL
tail
Td

FIG. 3

METHOD AND APPARATUS FOR QUANTITATIVE MAGNETIC RESONANCE IMAGING USING SPIN-LOCK RADIO FREQUENCY TRAINS

CROSS-REFERENCE TO RELATED APPLICATION

This application is based upon and claims priority to Provisional Application No. 63/326,766, filed on Apr. 1, 2022, the entire content of which is incorporated herein by reference for all purposes.

TECHNICAL FIELD

The present disclosure is related to the field of Magnetic Resonance Imaging (MRI) system imaging, and more particularly, to a method and apparatus for quantitative magnetic resonance imaging using spin-lock radio frequency trains.

BACKGROUND

MRI is among the most widely used non-invasive imaging modalities in clinical diagnosis. In recent years, its ability to probe diseases at a molecular level has elicited increasing interest in both clinical and research settings. There are two types of molecular signal that are widely studied in MRI field, namely Chemical Exchange (CE) and Magnetization Transfer (MT).

Generally, it is popular of using off-resonance saturation radiofrequency (RF) pulses to study CE and MT based contrasts. Principally, it is based on the exchange or the transfer of saturated biological molecule protons or bond water protons of macromolecules with free water protons, which are saturated by applying a selective off-resonance RF pulse. This effect results in water signal attenuation, which allows indirect measurement of CE and MT signal.

Alternatively, spin-lock-based techniques can also be used to measure CE and MT signal. Spin-lock is achieved by applying a radiofrequency (RF) pulse to the magnetization to align the magnetization along an effective spin-lock field. The resulting MR signal decays with a time constant $T_{1\rho}$ that is related to an amplitude of the effective spin-lock field dependent on the amplitude of spin-lock pulse ($\gamma B_1/2\pi$) and the resonance frequency offset of spin-lock pulse.

Generally, the duration and amplitude of spin-lock RF pulses are crucial parameters for spin-lock-based techniques. They play an important role in assessment of biochemical properties of tissues. However, the maximum duration of the spin-lock RF pulse is limited by the hardware of MRI system and the Specific Absorption Rate (SAR). Employ a train of spin-lock pulse with a short duration of each individual RF pulse can be used to mitigate this problem. However, it is important to note that, unlike a single spin-lock pulse, the relaxation model of using a train of spin-lock RF pulses is highly complicated and a conventional mono-exponential model cannot be used for quantification in this case. This imposes great challenges in quantification when a train of spin-lock RF pulses is used.

SUMMARY

Examples of the present disclosure provide methods and apparatus for quantitative magnetic resonance imaging using spin-lock radio frequency trains.

According to a first aspect of the present disclosure, a method for quantitative magnetic resonance imaging (MRI) is provided. The method includes: obtaining a first magnetization signal based on a first train of spin-lock modules, obtaining a second magnetization based on a second train of spin-lock modules, and obtaining a final magnetization signal based on the first magnetization signal and the second magnetization signal.

According to a second aspect of the present disclosure, an apparatus for quantitative MRI is provided. The apparatus includes one or more processors and a memory configured to store instructions executable by the one or more processors. Further, the one or more processors, upon execution of the instructions, are configured to perform acts including: obtaining a first magnetization signal based on a first train of spin-lock modules, obtaining a second magnetization based on a second train of spin-lock modules, and obtaining a final magnetization signal based on the first magnetization signal and the second magnetization signal.

According to a third aspect of the present disclosure, a non-transitory computer-readable storage medium is provided. The medium stores computer-executable instructions that, when executed by one or more computer processors, cause the one or more computer processors to perform acts including: obtaining a first magnetization signal based on a first train of spin-lock modules, obtaining a second magnetization based on a second train of spin-lock modules, and obtaining a final magnetization signal based on the first magnetization signal and the second magnetization signal.

One or more final magnetizations are obtained by repeating the aforementioned processes and are used for quantification of ore or more tissue parameters.

It is to be understood that the above general descriptions and detailed descriptions below are only exemplary and explanatory and not intended to limit the present disclosure.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated in and constitute a part of this specification, illustrate examples consistent with the present disclosure and, together with the description, serve to explain the principles of the disclosure.

FIG. **1** is a flow chart illustrating a method for quantitative magnetic resonance imaging using spin-lock radio frequency trains in accordance with some examples of the present disclosure.

FIG. **2** illustrates an MRI system in accordance with some examples of the present disclosure.

FIG. **3** a pulse sequence including multiple repeating spin-lock modules in accordance with some examples according to the present disclosure.

DETAILED DESCRIPTION

Reference will now be made in detail to example embodiments, examples of which are illustrated in the accompanying drawings. The following description refers to the accompanying drawings in which the same numbers in different drawings represent the same or similar elements unless otherwise represented. The implementations set forth in the following description of example embodiments do not represent all implementations consistent with the disclosure. Instead, they are merely examples of apparatuses and methods consistent with aspects related to the disclosure as recited in the appended claims.

The terminology used in the present disclosure is for the purpose of describing particular embodiments only and is

not intended to limit the present disclosure. As used in the present disclosure and the appended claims, the singular forms "a," "an," and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It shall also be understood that the term "and/or" used herein is intended to signify and include any or all possible combinations of one or more of the associated listed items.

It shall be understood that, although the terms "first," "second," "third," etc., may be used herein to describe various information, the information should not be limited by these terms. These terms are only used to distinguish one category of information from another. For example, without departing from the scope of the present disclosure, first information may be termed as second information; and similarly, second information may also be termed as first information. As used herein, the term "if" may be understood to mean "when" or "upon" or "in response to a judgment" depending on the context.

Reference throughout this specification to "one embodiment," "an embodiment," "an example," "some embodiments," "some examples," or similar language means that a particular feature, structure, or characteristic described is included in at least one embodiment or example. Features, structures, elements, or characteristics described in connection with one or some embodiments are also applicable to other embodiments, unless expressly specified otherwise.

For making it convenient for those skilled in the art to understand, multiple implementation modes are listed in the embodiments of the disclosure to describe the technical solutions of the embodiments of the disclosure clearly. Of course, those skilled in the art can understood that multiple embodiments provided in the embodiments of the disclosure can be executed independently, or can be combined with methods of the other embodiments in the embodiments of the disclosure for execution together, or may be executed independently or after combined with some methods in other related technologies. No limits are made thereto in the embodiments of the disclosure.

The present disclosure provides methods and apparatuses for simplifying the quantification of $T_{1\rho}$ using spin-lock radiofrequency trains. Additionally, the present disclosure provides methods and devices to quantify tissue parameters related to magnetization transfer using spin-lock radiofrequency trains based on off-resonance spin-lock. Spin-lock radiofrequency (RF) trains are a type of MRI pulse sequence that is used to manipulate the magnetization of protons in the body. Spin-lock RF trains may be composed of a series of spin-lock modules that are applied at a specified frequency and duration.

In some examples according to the present disclosure, a pulse sequence of trains of spin-lock modules may contain multiple spin-lock modules. In a spin-lock RF train, a spin-lock module may include a set of RF pulses that are applied to the tissue in a specific pattern to create a spin-lock field. Spin-lock is a specialized MRI technique used to manipulate spins by using RF pulses. This technique is particularly useful for investigating various molecular-scale interactions, measuring relaxation rates, and studying tissue properties.

For example, a spin-lock module may consist of a spin-lock RF cluster followed by an idle time without RF irradiation with a duration of Td. The spin-lock RF cluster includes a spin-lock RF pulse with duration time-of-spin-lock (TSL) sandwiched by a head RF pulse and a tail RF pulse, where the head RF pulse may be a RF pulse before the spin-lock RF pulse and the tail RF pulse may be a RF pulse after the spin-lock RF pulse. Crusher gradients may be added after each spin-lock RF cluster to de-phase transverse magnetizations. The parameters of each spin-lock module, including but not limited to TSL, Td, phase of RF pulses, the orientation of spin-lock field, and the area of crusher can vary for different spin-lock modules.

FIG. **3** illustrates a pulse sequence including multiple spin-lock modules in accordance with some examples according to the present disclosure. As shown in FIG. **3**, the pulse sequence **300** includes a plurality of spin-lock modules **1**-*n*, where n is the number of spin-lock modules. At least one spin-lock module except the last spin-lock module n includes a spin lock RF cluster followed by an idle time without RF irradiation with a duration of Td. The spin lock RF cluster includes the spin-lock RF pulse with a duration of the TSL, the head RF pulse, and the tail RF pulse, where the spin-lock RF pulse is sandwiched between the head and the tail RF pulse. As shown in FIG. **3**, the amplitude of the spin lock RF pulse is represented by Frequency of Spin-lock (FSL), and the resonance frequency offset of the spin-lock RF pulse is represented by frequency offset (FO). The last spin-lock module, the spin-lock module n as shown in FIG. **3**, includes the head RF pulse, the spin-lock RF pulse with the duration of the TSL, and the tail RF pulse, where the spin-lock RF pulse is sandwiched between the head and the tail RF pulse.

For a spin-lock module with a spin-lock RF pulse with the duration TSL and a constant RF amplitude, the magnetization M at the end of a spin-lock module can be expressed by following equation (1):

$$M = M_{ini}e^{-R_{1\rho}TSL} + M_{ss}\left(1 - e^{-R_{1\rho}TSL}\right), \tag{1}$$

where M_{ini} is the initial magnetization after the head RF pulse and before the spin-lock RF pulse in the first spin-lock module in a spin-lock radiofrequency train; $R_{1\rho(=1/T_1\rho)}$ is the spin-lattice relaxation rate in the rotating frame; M_{ss} is the steady state magnetization. A train with multiple spin-lock modules can achieve a much longer total TSL compared to a single spin-lock module. In the presence of a train of 2 or more spin-lock modules, the magnetization at the end of the train of spin-lock modules denoted as $M_{sl\_train\_1}$ can be derived using the equation (2) and T**1** relaxation during the idle time Td:

$$M_{sl\_train\_1} = (M_{ini} - M_{ss})e^{-R_{1\rho}TSL\cdot n}e^{-R_1Td\cdot(n-1)} + (M_{ss} - M_0)\left[\left(e^{-R_1Td}\cdot e^{-R_{1\rho}TSL} - e^{-R_{1\rho}TSL}\right)\cdot a_{n-1}\right] + M_{ss}, \tag{2}$$

where $R_1(=1/T1)$ is the tissue spin-lattice relaxation rate; n is the number of spin-lock modules in the spin-lock train; and M_0 is the equilibrium magnetization. The a_{n-1} is a recursive formula and is defined as

$$\begin{cases} a_1 = 1, \\ a_n = e^{-R_1Td}\cdot e^{-R_{1\rho}TSL}\cdot a_{n-1} + 1, \end{cases}$$

for n≥2.

In some examples of the present disclosure, a second magnetization signal is acquired with different initial magnetization M_{ini2} but the same stead-state magnetization M_{ss}.

The magnetization at the end of spin-lock train in second acquisition as $M_{sl\_train\_2}$ may be obtained based on the equation (3) as follows:

$$M_{sl\_train\_2} = (M_{ini2} - M_{ss})e^{-R_1\rho TSL\cdot n}e^{-R_1 Td\cdot(n-1)} + (M_{ss} - M_0)\left[\left(e^{-R_1 Td}\cdot e^{-R_1\rho TSL} - e^{-R_1\rho TSL}\right)\cdot a_{n-1}\right] + M_{ss}, \quad (3)$$

M_{ini} may be modified by, but not limited to, following approaches. In some examples, the spin-lock radio frequency trains are performed after different time durations of relaxation (T1 and/or T2). Thus, different degree of magnetization relaxation can result in different M_{ini}.

In some other examples, the attributes of the head RF pulse of the first spin-lock module in the train are manipulated to alter M_{ini}. The attributes may include the phase, the frequency modulation, duration, amplitude, etc.

In some other examples, one or more RF pulses may be used in front of the spin-lock radiofrequency trains to alter M_{ini}. This RF pulse can have arbitrary flip angle, phase, frequency modulation, duration, amplitude, etc. Spoiling gradient may be applied after each of these RF pulses.

By subtracting the equation (2) from the equation (3) or vice versa, the magnetization equation may be essentially simplified into a simple mono-exponential model that allows convenient quantification of $R_{1\rho}$ ($=1/T_{1\rho}$):

$$M_{fin} = M_{sl\_train\_2} - M_{sl\_train} = (M_{ini2} - M_{ini})e^{-R_1\rho TSL\cdot n}e^{-R_1 Td\cdot(n-1)}. \quad (4)$$

In some examples, the term $(M_{ini2}-M_{ini})e^{-R_1 Td\cdot(n-1)}$ is independent of TSL. Thus, by collecting M_{fin} with different TSL, M_{fin} may be fit to a mono-exponential model to obtain $R_{1\rho}$.

In some examples, the spin-lock RF pulse clusters may be applied either on-resonance or off-resonance. For on-resonance, the spin-lock RF pulse is tuned to on-resonance Larmor frequency, and the magnetization is spin-locked in the transverse plane. For off-resonance spin-lock, the spin-lock RF pulse is tuned to at a resonance frequency offset $\Delta\omega$ from the on-resonance Larmor frequency, and the magnetization is spin-locked at an angle from the transverse plane, which is determined by $\Delta\omega$ and the spin-lock RF amplitude ω_1. The present disclosure may be used for quantification of $R_{1\rho}$ both at on-resonance and off-resonance spin-lock.

According to the present disclosure, using trains of spin-lock RF pulses for quantitative MRI may also be used to quantify tissue parameters related to magnetization transfer by employing a train of off-resonance spin-lock RF modules. By using a train of off-resonance spin-lock modules and follow the aforementioned steps to acquire data at different M_{ini}, M_{fin} may be obtained as shown in equation (4).

In some examples, by adjusting MRI pulse sequence parameters of trains of spin-lock RF pulse, the acquired signal will be more sensitive to specific tissue parameter related to magnetization transfer, such as macromolecule proton fraction (MPF, also known as bound pool fraction (BPF), or other terms), compared to the other tissue parameters related to magnetization transfer.

In some examples, the pulse sequence parameters of each individual spin-lock module in a train of spin-lock modules may vary when collecting magnetization signal. These pulse sequence parameters include but not limited to TSL, Td, area of crusher gradient, orientation of spin-lock field etc. Machine learning or deep learning can be used to quantify data acquired using trains of spin-lock RF pulse with varying parameters.

In some examples, datasets may be collected at various $\Delta\omega$ and ω_1 as follows. Here $\Delta\omega$ is the resonance frequency offset of spin-lock, and ω_1 is the amplitude of spin-lock RF pulse. For example, a first image of M_{fin} as shown in equation (4) is acquired by using a train of spin-lock pulses with characteristics ($\Delta\omega=\Delta\omega^{(1)}$, $\omega_1=\omega_1{}^{(1)}$).

Similarly, a second image of M_{fin} as shown equation (4) is acquired in the same manner as the first image of M_{fin} by using a train of spin-lock pulses with characteristics (($\Delta\omega=\Delta\omega^{(2)}$, $\omega_1=\omega_1{}^{(2)}$).

Moreover, the third or more image images of M_{fin} as shown in equation (4) may be further acquired. By using the spin-lock pulse trains with ($\Delta\omega=\Delta\omega^{(i)}$), $\omega_1=\omega_1{}^{(i)}$), where i=3, 4 . . . . N and N is the total number of images of M_{fin} as shown equation (4).

Under the condition that

$$\frac{\Delta\omega}{\omega_1}$$

is unchanged, a parameter R_{mpfsl} can be calculated from a pair of M_{fin} as following:

$$R_{mpfsl} = \frac{\mathrm{abs}\left(\log\left(\frac{M_{fin,1}}{M_{fin,2}}\right)\right)}{TSL\cdot n} \quad (5)$$

Here $M_{fin,1}$ and $M_{fin,2}$ are the first and the second images of M_{fin}, respectively. R_{mpfsl} is insensitive to the tissue parameters of the water pool. Under the condition that R_{mpfsl} is much more sensitive to macromolecule proton fraction (MPF) than the other tissue parameters related to magnetization transfer or under the assumption that the other tissue parameter is nearly a constant, MPF may be calculated from R_{mpfsl} using Bloch-McConnell equation, or by machine learning or deep learning methods. R_{mpfsl} may be obtained under different values of $\Delta\omega$, ω_1, and/or

$$\frac{\Delta\omega}{\omega_1},$$

and may be used to calculate one or more tissue parameters related to magnetization transfer.

Furthermore, the magnetizations obtained by spin-lock RF trains may be inputted into machine learning or deep learning algorithms to obtain tissue parameters directly. These tissue parameters may carry important information for tissue characterization.

FIG. **1** is a flow chart illustrating a method for quantitative magnetic resonance imaging using spin-lock radio frequency trains in accordance with some examples of the present disclosure.

At step **101**, a target subject is arranged within an MRI system or apparatus. For example, as shown in FIG. **2** discussed below, a patient is arranged within the MRI system **200**.

At step **102**, a first MR image is obtained. For example, step **102** may include multiple steps **102-1**, **102-2**, and **102-3**. At step **102-1**, preparation **1** including zero, one or more preparatory sequences is applied. In **102-1**, first a

magnetization reset module is applied. This module is used to reset the magnetization to zero or a non-zero value under controlled condition. Suppression of blood signal, fluid signal, or fat signal may also be included in step **102-1**.

At step **102-2**, a first spin-lock RF train is applied. In step **102-2**, a module of fat suppression may also be included and applied after the spin-lock RF train.

At step **102-3**, a first magnetization signal is obtained.

After step **102**, a second MR image is obtained at step **103**.

At step **103**, a second magnetization corresponding the second MR image is obtained based on a second initial magnetization different than the first initial magnetization that is used in obtaining the first magnetization and a same steady state magnetization as used in obtaining the first magnetization. In some examples, an initial magnetization may be modified by, but not limited to, at least one of following steps: using different time durations of relaxation before a spin-lock RF train, changing a phase, frequency modulation, a duration, or an amplitude of the head RF pulse in a first spin-lock module of the spin-lock RF train; changing the orientation of the effective spin-lock field; or applying one or more RF pulses with an arbitrary flip angle, a phase, frequency modulation, a duration, or an amplitude in front of the spin-lock RF train.

For example, step **103** may include multiple steps **103-1**, **103-2**, and **103-3**. At step **103-1**, preparation **2** including zero, one or more preparatory sequences is applied. At **103-1**, first a magnetization reset module is applied. This module is used to reset the magnetization to zero or a non-zero value under controlled condition. Suppression of blood signal, fluid signal, or fat signal can also be included int **103-1**.

At step **103-2**, a second spin-lock RF train module is applied. In step **103-2**, a module of fat suppression can also be included and applied after the spin-lock module. In step **103-3**, a second magnetization signal is obtained. As discussed above, the second magnetization is obtained with an initial magnetization different than in obtaining the first image but the same steady state magnetization as in obtaining the first image.

In some examples, step **102** and step **103** are interchangeable. For example, the order to perform steps **102** and **103** can be changed and step **102** may be performed before or after step **103**.

At step **104**, a final magnetization is obtained based on the first magnetization obtained at step **102** and the second magnetization obtained at step **103**.

In some examples, step **102**, step **103**, and step **104** may be repeatedly performed after a final magnetization is obtained at step **104** using different acquisition parameters including but not limited to TSL, Td, amplitude of spin-lock, and resonance frequency offset of spin-lock. A desired number of final magnetizations Mfin may be obtained after repeatedly performing steps **102**, **103**, and **104**. Further, quantification may be performed based on the desired number of final magnetizations M_{fin} obtained. In some examples, one final magnetizations M_{fin} may be calculated based on one $M_{sl\_train\_1}$ and one $M_{sl\_train\_2}$ as obtained above. Two or more final magnetizations M_{fin} may be obtained at different acquisition parameters used in **102** and **103**. The desired number of final magnetizations M_{fin} and quantification methods are flexible.

According to the examples of the present disclosure, a spin relaxation rate,

$$R_{1\rho}\left(=\frac{1}{T_{1\rho}}\right),$$

may be calculated from an exponential relaxation model when using a train of spin-lock modules by fixing Td as a constant. It is also possible to calculate $R_{1\rho}$ and R1 simultaneously by varying TSL and Td, where R1 indicates a longitudinal relaxation rate. The present disclosure is applicable for quantification of single $R_{1\rho}$ in a mono-exponential relaxation model, two $R_{1\rho}$ in bi-exponential relaxation model, or more than two $R_{1\rho}$ in multiexponential relaxation model.

The $R_{1\rho}$ values may also be calculated directly by machine learning or deep learning using the first magnetization from **102**, the second magnetization from **103**, and their repetitions acquired at different acquisition parameters without calculating M_{fin}.

In some examples, step **102** and **103** may be repeated to obtain magnetizations at different resonance frequency offset ($\Delta\omega$) and spin-lock RF amplitude (ω_1) used in the spin-lock RF trains. Magnetization obtained at step **102** and **103** can be used to calculate M_{fin} according to tissue parameters related to magnetization transfer. Moreover, one or more R_{mpfsl} may be used to obtain one or more tissue parameters related to magnetization transfer.

In some examples, various magnetizations obtained at step **102** and **103** at different resonance frequency offset ($\Delta\omega$) and spin-lock RF amplitude ($@_1$) used in the spin-lock RF trains may be directly fed into machine learning and deep learning algorithm, and output one or more tissue parameters related to magnetization transfer.

In some examples, sensitivity of signals to tissue parameters related to magnetization transfer may be adjusted by adjusting the pulse sequence parameters of the first and second trains of spin-lock modules.

The method for the quantification using spin-lock RF train in accordance with the examples above of the present disclosure may be performed using an MRI system **200** as illustrated in FIG. **2**. The MRI system **200** includes an operator workstation **202**, which will typically include a display **204**, one or more input devices **206**, such as a keyboard and mouse, and a processor **208**. The processor **208** may include a commercially available programmable machine running a commercially available operating system. The operator workstation **202** provides the operator interface that enables scan prescriptions to be entered into the MRI system **200**. In general, the operator workstation **202** may be coupled to four servers: a pulse sequence server **110**; a data acquisition server **212**; a data processing server **214**; and a data store server **216**. The operator workstation **202** and each server **210**, **212**, **214**, and **216** are connected to communicate with each other. For example, the servers **210**, **212**, **214**, and **216** may be connected via a communication system **217**, which may include any suitable network connection, whether wired, wireless, or a combination of both. As an example, the communication system **217** may include both proprietary or dedicated networks, as well as open networks, such as the internet.

The pulse sequence server **210** functions in response to instructions downloaded from the operator workstation **202** to operate a gradient system **218** and a RF system **120**. Gradient waveforms necessary to perform the prescribed scan are produced and applied to the gradient system **218**, which excites gradient coils in an assembly **122** to produce the magnetic field gradients, and used for position encoding

magnetic resonance signals. The gradient coil assembly **122** forms part of a magnet assembly **224** that includes a polarizing magnet **226** and a whole-body RF coil **228**.

RF waveforms are applied by the RF system **220** to the RF coil **228**, or a separate local coil (not shown in FIG. **2**), in order to perform the prescribed magnetic resonance pulse sequence. Responsive magnetic resonance signals detected by the RF coil **228**, or a separate local coil (not shown in FIG. **2**), are received by the RF system **220**, where they are amplified, demodulated, filtered, and digitized under direction of commands produced by the pulse sequence server **210**. The RF system **220** includes an RF transmitter for producing a wide variety of RF pulses used in MRI pulse sequences. The RF transmitter is responsive to the scan prescription and direction from the pulse sequence server **210** to produce RF pulses of the desired frequency, phase, and pulse amplitude waveform. The generated RF pulses may be applied to the whole-body RF coil **228** or to one or more local coils or coil arrays (not shown in FIG. **2**). A drive field generator **240** is used to generate the desired electromagnetic drive field. For example, the drive field generator may include an external Solenoid, or a shielded solenoid, that is driven by a large amplifier at a low frequency. In some examples, an additional gradient amplifier can be utilized to drive the drive field generator.

The RF system **220** also includes one or more RF receiver channels. Each RF receiver channel includes an RF preamplifier that amplifies the magnetic resonance signal received by the coil **228** to which it is connected, and a detector that detects and digitizes the I and Q quadrature components of the received magnetic resonance signal. The magnitude of the received magnetic resonance signal may, therefore, be determined at any sampled point by the square root of the sum of the squares of the/and Q components:

$$M = \sqrt{I^2 + Q^2} \tag{6}$$

and the phase of the received magnetic resonance signal may also be determined according to the following relationship:

$$\varphi = \tan^{-1}\left(\frac{Q}{I}\right) \tag{7}$$

The pulse sequence server **210** also alternatively receives patient data from a physiological acquisition controller **230**. In some examples, the physiological acquisition controller **230** may receive signals from a number of different sensors connected to the patient, such as electrocardiograph ("ECG") signals from electrodes, or respiratory signals from a respiratory bellows or other respiratory monitoring device. Such signals are typically used by the pulse sequence server **210** to synchronize, or "gate," the performance of the scan with the subject's heart beat or respiration.

The pulse sequence server **210** also connects to a scan room interface circuit **132** that 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 **232** that a patient positioning system **234** receives commands to move the patient to desired positions during the scan.

The digitized magnetic resonance signal samples produced by the RF system **220** are received by the data acquisition server **212**. The data acquisition server **212** operates in response to instructions downloaded from the operator workstation **202** to receive the real-time magnetic resonance data and provide buffer storage, such that no data is lost by data overrun. In some scans, the data acquisition server **212** does little more than passing the acquired magnetic resonance data to the data processor server **214**. However, in scans that require information derived from acquired magnetic resonance data to control the further performance of the scan, the data acquisition server **212** is programmed to produce such information and convey it to the pulse sequence server **210**. For example, during prescans, magnetic resonance data is acquired and used to calibrate the pulse sequence performed by the pulse sequence server **210**. As another example, navigator signals may be acquired and used to adjust the operating parameters of the RF system **220** or the gradient system **218**, or to control the view order in which k-space is sampled. In still another example, the data acquisition server **212** may also be employed to process magnetic resonance signals used to detect the arrival of a contrast agent in a magnetic resonance angiography (MRA) scan. In all these examples, the data acquisition server **212** acquires magnetic resonance data and processes it in real-time to produce information that is used to control the scan.

The data processing server **214** receives magnetic resonance data from the data acquisition server **212** and processes it in accordance with instructions downloaded from the operator workstation **202**. Such processing may, for example, include one or more of the following: reconstructing two-dimensional or three-dimensional images by performing a Fourier transformation of raw k-space data; performing other image reconstruction algorithms, such as iterative or back projection reconstruction algorithms; applying filters to raw k-space data or to reconstructed images; generating functional magnetic resonance images; calculating motion or flow images; and so on.

Images reconstructed by the data processing server **214** are conveyed back to the operator workstation **202** where they are stored. Real-time images are stored in a data base memory cache (not shown in FIG. **2**), from which they may be output to operator display **212** or a display **136** that is located near the magnet assembly **224** for use by attending physicians. Batch mode images or selected real time images are stored in a host database on disc storage **138**. When such images have been reconstructed and transferred to storage, the data processing server **214** notifies the data store server **216** on the operator workstation **202**. The operator workstation **202** 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 **200** may also include one or more networked workstations **142**. By way of example, a networked workstation **242** may include a display **244**; one or more input devices **246**, such as a keyboard and mouse; and a processor **248**. The networked workstation **242** may be located within the same facility as the operator workstation **202**, or in a different facility, such as a different healthcare institution or clinic.

The networked workstation **242**, whether within the same facility or in a different facility as the operator workstation **202**, may gain remote access to the data processing server **214** or data store server **216** via the communication system **217**. Accordingly, multiple networked workstations **242** may have access to the data processing server **214** and the data store server **216**. In this manner, magnetic resonance data, reconstructed images, or other data may exchange between the data processing server **214** or the data store server **216**

and the networked workstations **142**, such that the data or images may be remotely processed by a networked workstation **242**. This data may be exchanged in any suitable format, such as in accordance with the transmission control protocol (TCP), the internet protocol (IP), or other known or suitable protocols.

In some examples, there is also provided an apparatus for quantitative MRI, such as the MRI system **200**. The apparatus may include one or more processors and a memory configured to store instructions executable by the one or more processors. Further, the one or more processors, upon execution of the instructions, are configured to perform acts including: obtaining a first magnetization signal based on a first spin-lock train, obtaining a second magnetization based on a second spin-lock train, and obtaining a final magnetization signal based on the first magnetization signal and the second magnetization signal.

In some examples, each of the first spin-lock train and the second spin-lock train include a trains of spin lock RF clusters with each spin-lock RF pulse cluster followed by an idle time without RF irradiation with a duration of Td, where the spin lock RF cluster may include a spin lock RF pulse with a duration of time-of-spin-lock (TSL), a head RF pulse, and a tail RF pulse, where the spin lock RF pulse is sandwiched between the head and the tail RF pulses. For example, the first spin-lock train and the second spin-lock train may be respectively illustrated in FIG. **3**.

In some examples, the duration of TSL, the duration of Td, the orientation of spin-lock field may be different in each spin-lock module.

In some examples, one or more processors may further repeat steps of obtaining the first magnetization signal and the second magnetization signal to obtain one or more final magnetization signals. As shown in FIG. **1**, step **102**, step **103**, and step **104** may repeated at the desired numbers to obtain multiple final magnetization signals.

In some examples, one or more processors may further perform quantification based on all final magnetization signals obtained after repeating the steps of obtaining the first magnetization signal and the second magnetization signal.

In some examples, one or more processors may further obtain one or more final magnetization signals at different resonance frequency offset and spin-lock RF amplitude used in the train of spin-lock modules. The magnetization signals can be used to calculate tissue parameters related to magnetization transfer based on Bloch-McConnell equations. In some examples, one or more processors may further feed the all final magnetization signals into an artificial intelligence system, e.g., machine learning or deep learning system, and outputting one or more tissue parameters related to magnetization transfer.

The above methods may be implemented using an apparatus that includes one or more circuitries, which include application specific integrated circuits (ASICs), digital signal processors (DSPs), digital signal processing devices (DSPDs), programmable logic devices (PLDs), field programmable gate arrays (FPGAs), controllers, micro-controllers, microprocessors, or other electronic components. The apparatus may use the circuitries in combination with the other hardware or software components for performing the above described methods. Each module, sub-module, unit, or sub-unit disclosed above may be implemented at least partially using the one or more circuitries.

Other examples of the disclosure will be apparent to those skilled in the art from consideration of the specification and practice of the disclosure disclosed here. This application is intended to cover any variations, uses, or adaptations of the disclosure following the general principles thereof and including such departures from the present disclosure as come within known or customary practice in the art. It is intended that the specification and examples be considered as exemplary only.

It will be appreciated that the present disclosure is not limited to the exact examples described above and illustrated in the accompanying drawings, and that various modifications and changes can be made without departing from the scope thereof.

What is claimed is:

1. A method for quantitative magnetic resonance imaging (MRI), comprising:

obtaining a first magnetization signal based on a first train of spin-lock modules, wherein the first train of spin-lock modules is performed on a first initial magnetization;

obtaining a second magnetization signal based on a second train of spin-lock modules, wherein the second train of spin-lock modules is performed on a second initial magnetization different from the first initial magnetization; and

obtaining a final magnetization signal based on the first magnetization signal and the second magnetization signal.

2. The method of claim **1**, wherein at least one spin-lock module in the first train of spin-lock modules and the second train of spin-lock modules comprises a spin lock radiofrequency (RF) cluster and an idle time without RF irradiation with a duration of Td following the spin lock RF cluster.

3. The method of claim **2**, wherein the spin lock RF cluster comprises a head RF pulse, a tail RF pulse, and a spin lock RF pulse with a duration of time-of-spin-lock (TSL), an amplitude of spin lock RF pulse, and a resonance frequency offset, and the spin lock RF pulse is sandwiched between the head and the tail RF pulses, and a crusher gradient follows the tail RF pulse.

4. The method of claim **1**, further comprising:

modifying an initial magnetization by at least one of following steps:

using different time durations of relaxation before a spin-lock RF train;

changing a phase, frequency modulation, a duration, or an amplitude of the head RF pulse in a first spin-lock module of the spin-lock RF train; or

applying one or more RF pulses with an arbitrary flip angle, a phase, frequency modulation, a duration, or an amplitude in front of the spin-lock RF train.

5. The method of claim **3**, wherein pulse sequence parameters in each spin-lock module in the first train of spin-lock modules and the second train of spin-lock modules are same or different, wherein the pulse sequence parameters comprise at least one of following parameters: the duration of TSL, the amplitude of spin-lock RF pulse, the resonance frequency offset of the spin-lock RF pulse, the duration of Td, area of crusher gradient, or orientation of spin-lock field.

6. The method of claim **3**, further comprising:

obtaining one or more final magnetization signals by repeating steps of obtaining the first magnetization signal and the second magnetization signal, wherein a duration of TSL or a duration of Td in repeating is different from the duration of TSL or the duration of Td used in obtaining the first magnetization signal or the second magnetization signal.

7. The method of claim 6, further comprising:

performing qualification based on all final magnetization signals obtained after repeating the steps of obtaining the first magnetization signal and the second magnetization signal.

8. The method of claim 3, further comprising:

obtaining all final magnetization signals at different resonance frequency offset and amplitude of spin lock RF pulse in the first and second train of spin-lock modules, wherein the all final magnetization signals comprise the final magnetization signal obtained based on the first magnetization signal and the second magnetization signal and the one or more final magnetization signals obtained in repeating the steps of obtaining the first magnetization signal and the second magnetization signal.

9. The method of claim 8, further comprising:

feeding the all final magnetization signals into a machine learning or artificial intelligence system and outputting one or more tissue parameters, or

using Bloch-McConnell equations to calculate one or more tissue parameters from the all final magnetization signals.

10. The method of claim 8, further comprising:

adjusting sensitivity of signals to tissue parameters related to magnetization transfer by adjusting the pulse sequence parameters of the first and second trains of spin-lock modules.

11. The method of claim 1, wherein the first train of spin-lock modules is performed after a first duration of relaxation, and the second train of spin-lock modules is performed after a second duration of relaxation different from the first duration of relaxation.

12. An apparatus for quantitative magnetic resonance imaging (MRI), comprising: one or more processors; and

a memory configured to store instructions executable by the one or more processors; wherein the one or more processors, upon execution of the instructions, are configured to perform a method for quantitative MRI, comprising:

obtaining a first magnetization signal based on a first train of spin-lock modules, wherein the first train of spin-lock modules is performed on a first initial magnetization;

obtaining a second magnetization signal based on a second train of spin-lock modules, wherein the second train of spin-lock modules is performed on a second initial magnetization different from the first initial magnetization; and

obtaining a final magnetization signal based on the first magnetization signal and the second magnetization signal.

13. The apparatus of claim 12, wherein at least one spin-lock module in the first train of spin-lock modules and the second train of spin-lock modules comprises a spin lock radiofrequency (RF) cluster and an idle time without RF irradiation with a duration of Td following the spin lock RF cluster.

14. The apparatus of claim 13, wherein the spin lock RF cluster comprises a head RF pulse, a tail RF pulse, and a spin lock RF pulse with a duration of time-of-spin-lock (TSL), an amplitude of spin lock RF pulse, and a resonance frequency offset, and the spin lock RF pulse is sandwiched between the head and the tail RF pulses, and a crusher gradient follows the tail RF pulse.

15. The apparatus of claim 12, wherein the method further comprises:

modifying an initial magnetization by at least one of following steps:

using different time durations of relaxation before a spin-lock RF train;

changing a phase, frequency modulation, a duration, or an amplitude of the head RF pulse in a first spin-lock module of the spin-lock RF train; or

applying one or more RF pulses with an arbitrary flip angle, a phase, frequency modulation, a duration, or an amplitude in front of the spin-lock RF train.

16. The apparatus of claim 14, wherein pulse sequence parameters in each spin-lock module in the first train of spin-lock modules and the second train of spin-lock modules are same or different, wherein the pulse sequence parameters comprise at least one of following parameters: the duration of TSL, the amplitude of spin-lock RF pulse, the resonance frequency offset of the spin-lock RF pulse, the duration of Td, area of crusher gradient, or orientation of spin-lock field.

17. The apparatus of claim 14, wherein the method further comprises:

obtaining one or more final magnetization signals by repeating steps of obtaining the first magnetization signal and the second magnetization signal, wherein a duration of TSL or a duration of Td in repeating is different from the duration of TSL or the duration of Td used in obtaining the first magnetization signal or the second magnetization signal.

18. The apparatus of claim 17, wherein the method further comprises:

performing qualification based on all final magnetization signals obtained after repeating the steps of obtaining the first magnetization signal and the second magnetization signal.

19. The apparatus of claim 12, wherein the first train of spin-lock modules is performed after a first duration of relaxation, and the second train of spin-lock modules is performed after a second duration of relaxation different from the first duration of relaxation.

20. A non-transitory computer-readable storage medium for storing computer-executable instructions that, when executed by one or more computer processors, cause the one or more computer processors to perform a method for quantitative MRI, comprising:

obtaining a first magnetization signal based on a first train of spin-lock modules, wherein the first train of spin-lock modules is performed on a first initial magnetization;

obtaining a second magnetization signal based on a second train of spin-lock modules, wherein the second train of spin-lock modules is performed on a second initial magnetization different from the first initial magnetization; and

obtaining a final magnetization signal based on the first magnetization signal and the second magnetization signal.

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