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(54) SYSTEM AND METHOD FOR MAGNETIC RESONANCE I MAGING WITH PROSPECTIVE MOTION CONTROL

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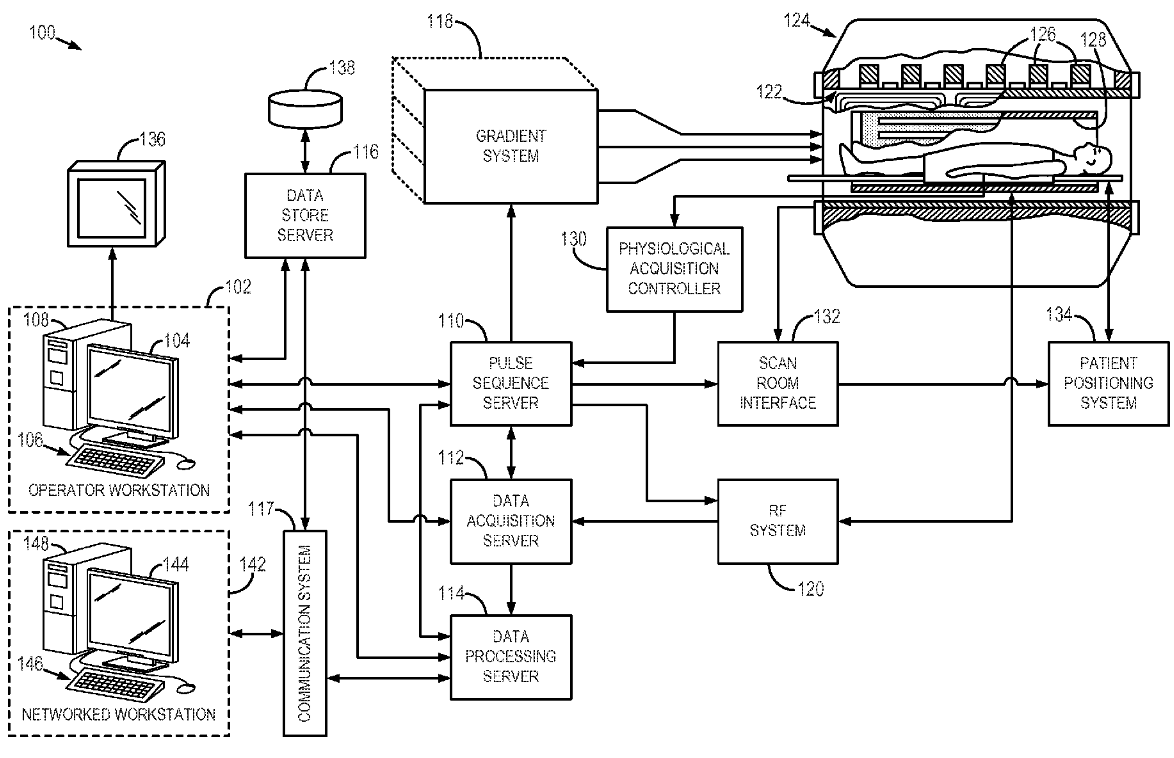
(57) ABSTRACT

A system and method for reconstructing an image of a subject, in which motion has been prospectively corrected, using a magnetic resonance imaging (MRI] system are provided. An imaging pulse sequence is used to acquire image data in addition to navigator data using an ultra-fast navigator, such as a cloverleaf navigator. When motion is detected in the navigator data, a volume navigator (vNav] sequence is performed, from which motion estimates are generated and used to update the imaging pulse sequence to prospectively correct for the motion in subsequent repetition times.



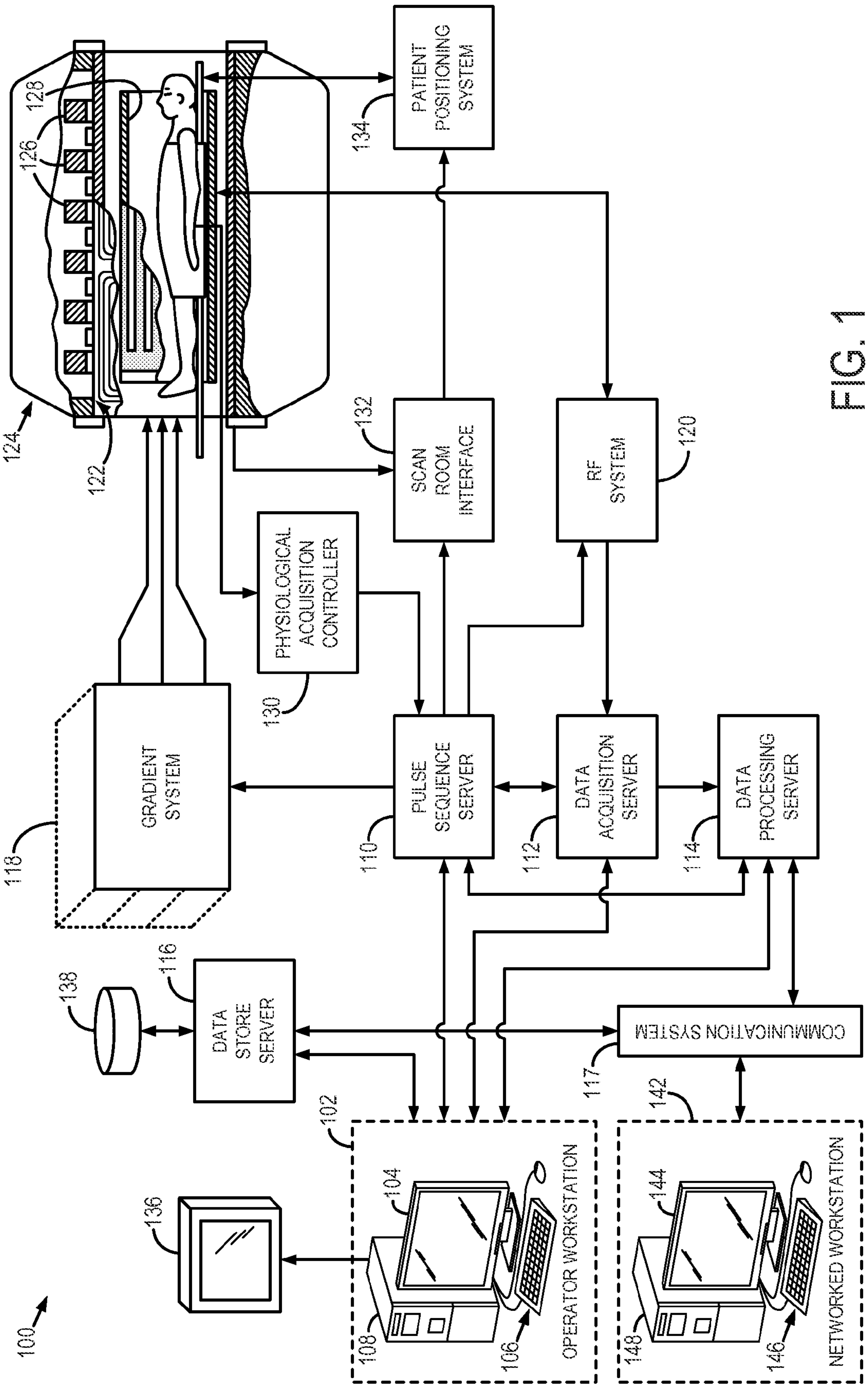

100
102
104
106
108
110
112
114
116
117
118
120
122
124
126
128
130
132
134
136
138
142
144
146
148
PATIENT POSITIONING SYSTEM
SCAN ROOM INTERFACE
RF SYSTEM
PHYSIOLOGICAL ACQUISITION CONTROLLER
GRADIENT SYSTEM
PULSE SEQUENCE SERVER
DATA ACQUISITION SERVER
DATA PROCESSING SERVER
DATA STORE SERVER
COMMUNICATION SYSTEM
OPERATOR WORKSTATION
NETWORKED WORKSTATION

FIG. 1

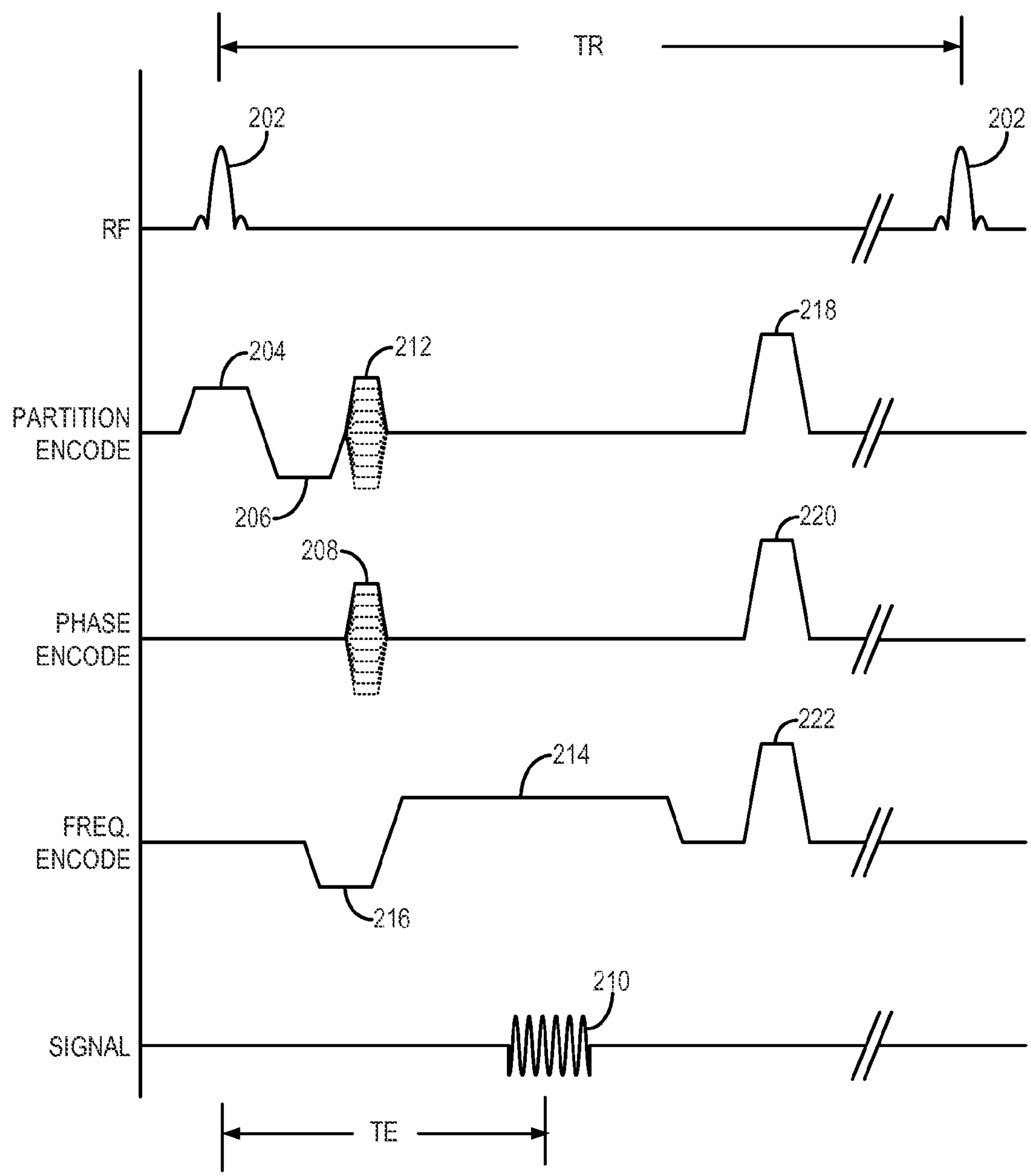

TR
202
202
RF
204
212
218
PARTITION ENCODE
206
208
220
PHASE ENCODE
214
222
FREQ. ENCODE
216
210
SIGNAL
TE

FIG. 2

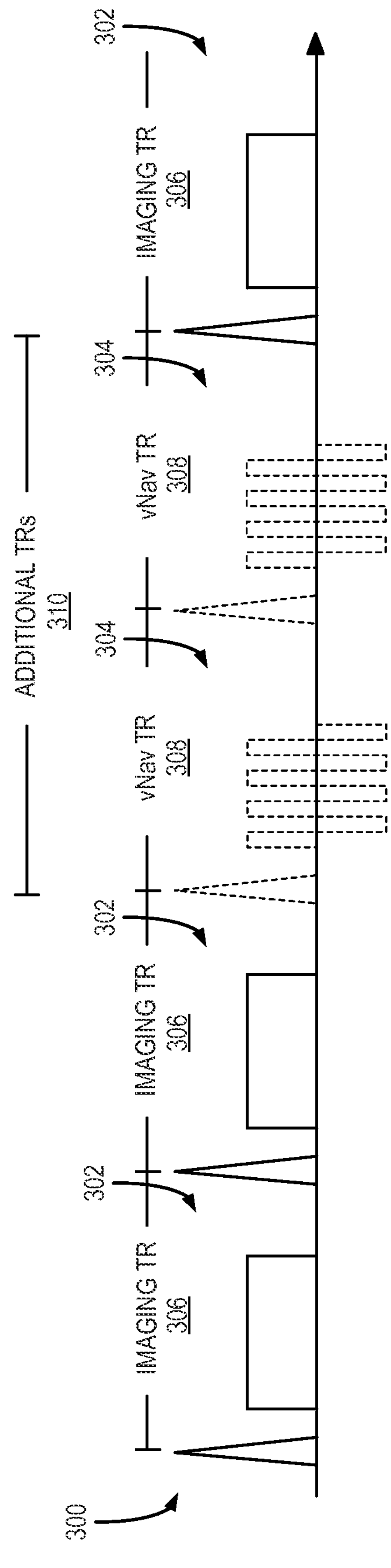

300
IMAGING TR
306
302
IMAGING TR
306
302
vNav TR
308
ADDITIONAL TRs
310
304
vNav TR
308
304
IMAGING TR
306
302

FIG. 3

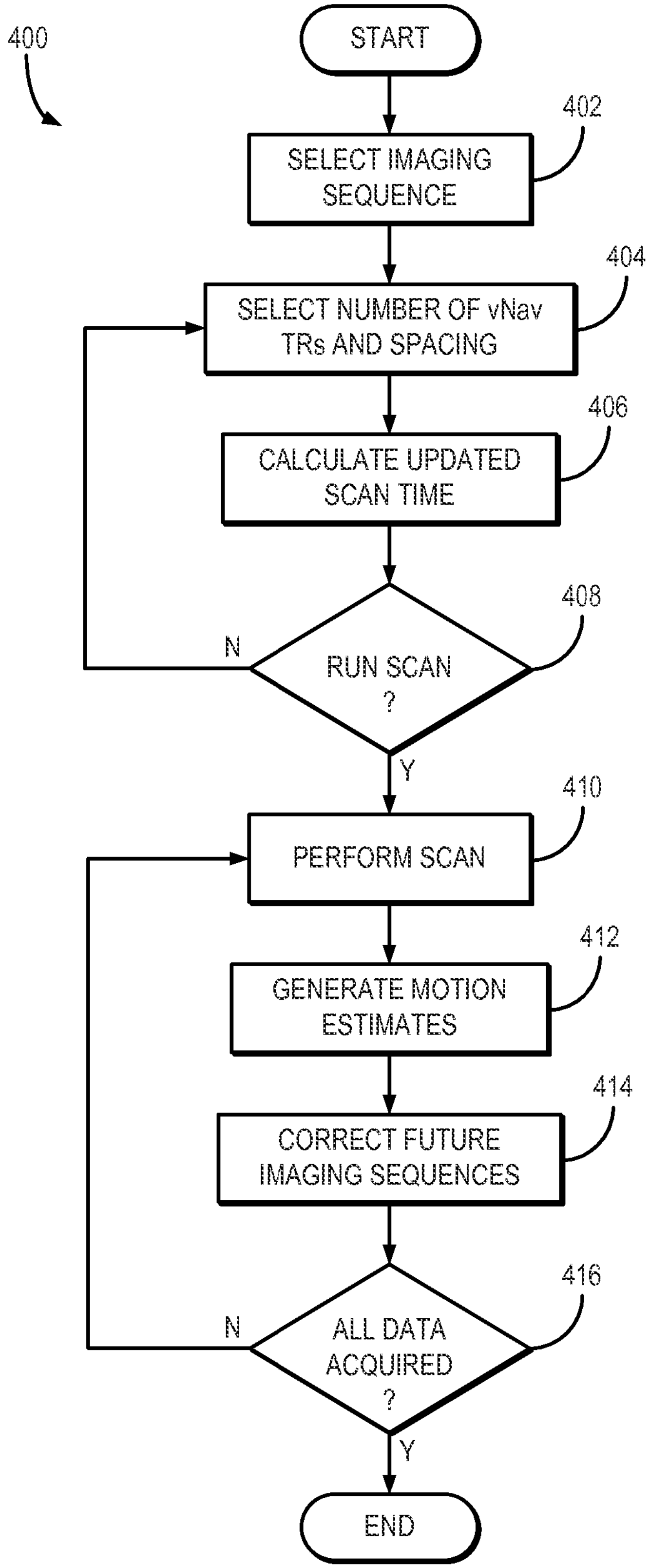

400
START
SELECT IMAGING SEQUENCE
402
SELECT NUMBER OF vNav TRs AND SPACING
404
CALCULATE UPDATED SCAN TIME
406
RUN SCAN ?
408
N
Y
PERFORM SCAN
410
GENERATE MOTION ESTIMATES
412
CORRECT FUTURE IMAGING SEQUENCES
414
ALL DATA ACQUIRED ?
416
N
Y
END

FIG. 4

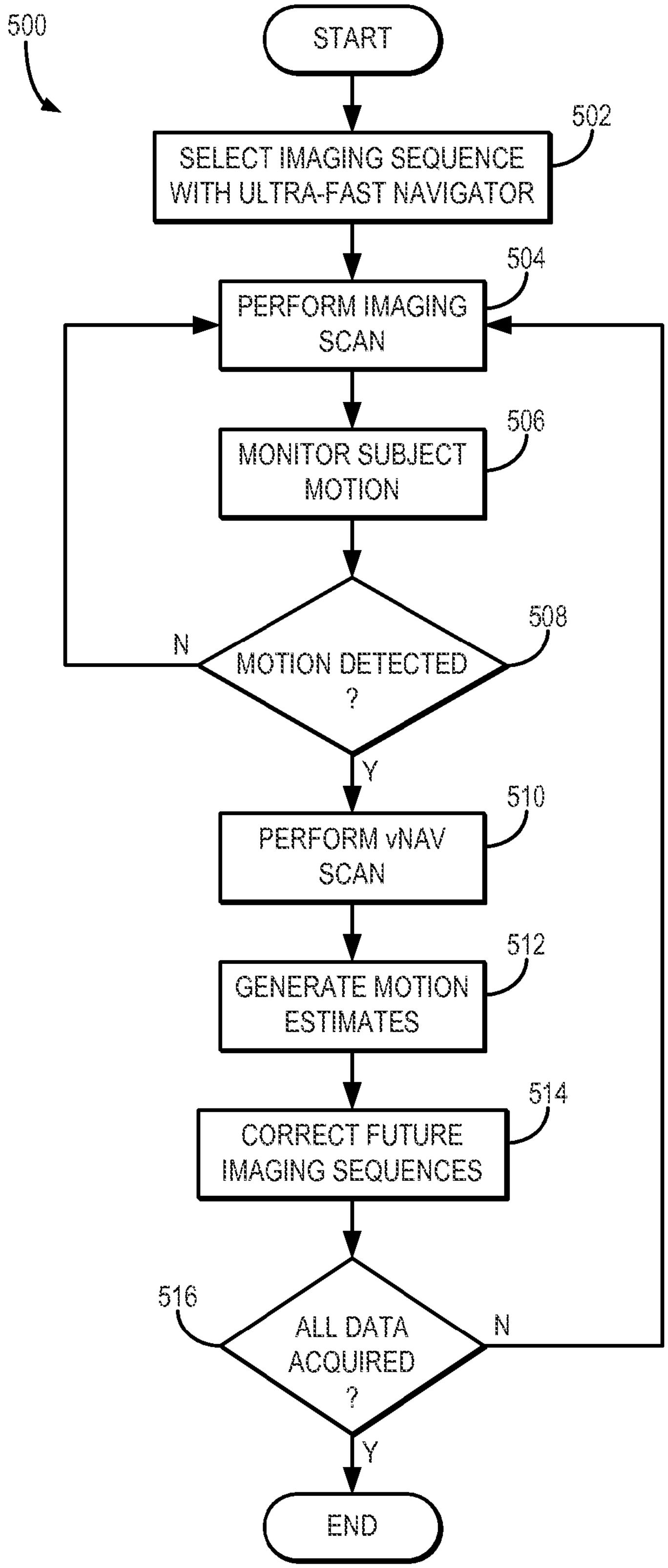

500
START
SELECT IMAGING SEQUENCE WITH ULTRA-FAST NAVIGATOR
502
PERFORM IMAGING SCAN
504
MONITOR SUBJECT MOTION
506
MOTION DETECTED ?
508
N
Y
PERFORM vNAV SCAN
510
GENERATE MOTION ESTIMATES
512
CORRECT FUTURE IMAGING SEQUENCES
514
ALL DATA ACQUIRED ?
516
N
Y
END

FIG. 5

SYSTEM AND METHOD FOR MAGNETIC RESONANCE I MAGING WITH PROSPECTIVE MOTION CONTROL

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is based on, claims priority to, and incorporates herein by reference in its entirety, U.S. Provisional Application Ser. No. 61/981,452, filed Apr. 18, 2014, and entitled "SYSTEM AND METHOD FOR MAGNETIC RESONANCE IMAGING WITH PROSPECTIVE MOTION CONTROL" and is based on, claims priority to, and incorporates herein by reference in its entirety, U.S. Provisional Application Ser. No. 62/005,165, filed May 30, 2014, and entitled "SYSTEM AND METHOD FOR MAGNETIC RESONANCE IMAGING WITH PROSPECTIVE MOTION CONTROL."

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

[0002] This invention was made with government support under HD074649 awarded by the National Institutes of Health. The government has certain rights in the invention.

BACKGROUND

[0003] The present disclosure relates to systems and methods for magnetic resonance imaging ("MRI"). More particularly, the disclosure relates to systems and methods for tracking and controlling artifacts caused by motion during a MRI procedure.

[0004] MRI uses the nuclear magnetic resonance ("NMR") phenomenon to produce images. When a substance such as human tissue is subjected to a uniform magnetic field ("main magnetic field"), B_0, the individual magnetic moments of the nuclei in the tissue attempt to align with this magnetic field, but precess about it in random order at their characteristic Larmor frequency, ω. If the substance, or tissue, is subjected to an excitation magnetic field, B_1, that is in the plane transverse to the main magnetic field, B_0, and that is near the Larmor frequency, ω, the net aligned magnetic moment of the nuclei may be rotated, or "tipped," into the transverse plane to produce a net transverse magnetic moment. A signal is emitted by the excited nuclei, or "spins," after the excitation magnetic field, B_1, is terminated. The emitted signal may be received and processed to form an image.

[0005] When utilizing these emitted "MR" signals to produce images, magnetic field gradients (G_x, G_y, and G_z) are employed. Typically, the region to be imaged is scanned by a sequence of measurement cycles in which these gradients vary according to the particular localization method being used. The resulting set of received MR signals are digitized and processed to reconstruct the image using one of many well known reconstruction techniques.

[0006] The measurement cycle used to acquire each MR signal is performed under the direction of a pulse sequence produced by a pulse sequencer. Clinically available MRI systems store a library of such pulse sequences that can be prescribed to meet the needs of many different clinical applications. Research MRI systems include a library of clinically-proven pulse sequences and they also enable the development of new pulse sequences.

[0007] Depending on the technique used, many MR scans currently require many minutes to acquire the necessary data used to produce medical images. The reduction of this scan time is an important consideration, since reduced scan time increases patient throughout, improves patient comfort, and improves image quality by reducing motion artifacts. Many different strategies have been developed to shorten the scan time.

[0008] For example, one popular category of pulse sequences are so-called gradient echo sequences. Within this category, the spoiled gradient echo and three-dimensional spoiled gradient-recalled echo (SPGR) or fast low angle shoot (FLASH) pulse sequences are often used in neuroimaging applications. Specifically, the SPGR or FLASH sequence forms the basis of many 3D neuroimaging sequences, but acquisition times often stretch to several minutes. Lengthy acquisitions in neuroimaging applications can be particularly troublesome because it is imperative that the subject remain motionless during the duration of the sequence. That is, in neuroimaging applications, motion can be particularly damaging to the resulting images because of the complexity of the structures being imaged and studied in neuroimaging applications.

[0009] Motion-correction systems in MRI can be grouped into two general methods: prospective and retrospective. Retrospective methods use information about the subject's motion to estimate what k-space data would have been measured if the subject had not moved during scanning. Prospective methods use motion-tracking data acquired during the scan to follow the subject with the gradient axes of the sequence, measuring the desired k-space data directly. Additionally, it is possible to combine the two methods so that retrospective processing corrects residual errors in the prospective system. A retrospective system can access all of the k-space data while performing reconstruction; a prospective system must necessarily rely only on previous measurements to estimate the current position of the patient. However, a prospective system avoids the need to estimate missing k-space data, allowing for direct reconstruction while avoiding possible sources of estimation error in the k-space data.

[0010] Also, one can differentiate between two types of motion correction problems that arise in MRI: between-scan motion and within-scan motion. For between-scan motion, several retrospective motion correction methods are available that register either slice-by-slice or volume-by-volume to estimate the data that would have been acquired in each volume if the subject had not moved. Prospective motion correction can also be employed for this problem, such as the orbital navigator system that inserts 3-plane circular k-space navigators, or the PACE system that registers each completed EPI volume back to the first time-point and so requires no navigators.

[0011] For in-scan motion, several methods are available, such as PROPELLER and the like that use redundant sampling of the center of k-space during each repetition time (TR) and estimate motion-free k-space data retrospectively. Also, prospective motion correction is available, such as by using cloverleaf navigators. The use of cloverleaf navigators is useful with SPGR/FLASH sequences.

[0012] However, in order to maximize SNR/time efficiency, short TR protocols are often used in neuroimaging applications. Such short-TR protocols, by definition, have very-little dead time and, thus, force navigators to be very short and provide limited k-space coverage. That is, as the TR is reduced, the effectiveness of the navigator is reduced because there is less information gathered by the navigator to use to form an estimate of the subject's head motion.

[0013] It would therefore be desirable to provide a system and method for controlling the competing constraints of neuroimaging applications that desire extended acquisition times and the need to control or compensate or correct for patient motion during such acquisitions.

SUMMARY

[0014] The present disclosure overcomes the aforementioned drawbacks by providing a system and method for directing a magnetic resonance imaging (MRI) system to reconstruct an image of a subject, in which motion has been prospectively corrected. The method includes acquiring image data and navigator data from a subject by directing the MRI system to perform an imaging pulse sequence that includes a navigator portion. The navigator data is processed to determine whether motion occurred while the image data was acquired. The imaging pulse sequence is updated when processing the navigator data determines motion occurred. The imaging pulse sequence is updated by first acquiring volume navigator data by directing the MRI system to perform a volume navigator pulse sequence that uses an echo-planar imaging (EPI) technique to acquire volume navigator data from a volume-of-interest in the subject. The volume navigator data is then processed to generate motion estimates of motion in the VOI. The imaging pulse sequence is then updated based on the motion estimates, wherein the updated imaging pulse sequence prospectively corrects for the motion in the VOI using the motion estimates. The imaging pulse sequence, whether updated or not, is then repeated and navigator data processed to determine whether motion occurred and whether the imaging pulse sequence should be further updated until a desired amount of image data is acquired. An image of the subject is then reconstructed from the acquired image data.

[0015] In accordance with yet another aspect of the disclosure, a magnetic resonance imaging (MRI) system is disclosed that includes a magnet system configured to generate a polarizing magnetic field about at least a portion of a subject arranged in the MRI system, a magnetic gradient system including a plurality of magnetic gradient coils configured to apply at least one magnetic gradient field to the polarizing magnetic field, and radio frequency (RF) system configured to apply an RF field to the subject and to receive magnetic resonance signals from the subject using a coil array. The system also includes a computer system programmed to control the gradient system and the RF system to perform an imaging pulse sequence that includes a navigator portion to acquire image data and navigator data from a subject. The computer system is further programmed to process the navigator data to determine whether the subject moved while the image data was acquired. Upon determining that the subject moved, the computer system is configured to control the gradient system and the RF system to perform a volume navigator pulse sequence that uses an echo-planar imaging (EPI) technique to acquire volume navigator data from a volume-of-interest in the subject, process the volume navigator data to generate motion estimates of motion in the VOI, and update the imaging pulse sequence based on the motion estimates, wherein the updated imaging pulse sequence prospectively corrects for the motion in the VOI using the motion estimates. The computer system is further configured to reconstruct an image of the subject from the acquired image data.

[0016] The foregoing and other aspects and advantages of the invention will appear from the following description. In the description, reference is made to the accompanying drawings which form a part hereof, and in which there is shown by way of illustration a preferred embodiment of the invention. Such embodiment does not necessarily represent the full scope of the invention, however, and reference is made therefore to the claims and herein for interpreting the scope of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] FIG. **1** is a block diagram of an example of a magnetic resonance imaging ("MRI") system.

[0018] FIG. **2** is an example of a three-dimensional spoiled gradient-recalled echo ("3D SPGR") pulse sequence.

[0019] FIG. **3** is an illustrative example of an integrated pulse sequence that includes both imaging sequences, each played out during an imaging repetition time ("TR"), and volumetric navigator sequences, each played out during a volumetric navigator TR;

[0020] FIG. **4** is a flowchart setting forth the steps of an example method for performing prospective motion correction using a pulse sequence such as the one described with respect to FIG. **3**; and

[0021] FIG. **5** is a flowchart setting forth the steps of an example method for performing prospective motion correction based on an integrated pulse sequence that uses an ultra-fast navigator in an imaging pulse sequence to detect motion and trigger the performance of one or more vNav sequences.

DETAILED DESCRIPTION OF THE INVENTION

[0022] Referring particularly now to FIG. **1**, an example of a magnetic resonance imaging ("MRI") system **100** is illustrated. The MRI system **100** includes an operator workstation **102**, which will typically include a display **104**; one or more input devices **106**, such as a keyboard and mouse; and a processor **108**. The processor **108** may include a commercially available programmable machine running a commercially available operating system. The operator workstation **102** provides the operator interface that enables scan prescriptions to be entered into the MRI system **100**. In general, the operator workstation **102** may be coupled to four servers: a pulse sequence server **110**; a data acquisition server **112**; a data processing server **114**; and a data store server **116**. The operator workstation **102** and each server **110**, **112**, **114**, and **116** are connected to communicate with each other. For example, the servers **110**, **112**, **114**, and **116** may be connected via a communication system **140**, which may include any suitable network connection, whether wired, wireless, or a combination of both. As an example, the communication system **140** may include both proprietary or dedicated networks, as well as open networks, such as the internet.

[0023] The pulse sequence server **110** functions in response to instructions downloaded from the operator workstation **102** to operate a gradient system **118** and a radiofrequency ("RF") system **120**. Gradient waveforms necessary to perform the prescribed scan are produced and applied to the gradient system **118**, which excites gradient coils in an assembly **122** to produce the magnetic field gradients G_x, G_y, and G_z used for position encoding magnetic resonance signals. The gradient coil assembly **122** forms part of a magnet assembly **124** that includes a polarizing magnet **126** and a whole-body RF coil **128**.

[0024] RF waveforms are applied by the RF system **120** to the RF coil **128**, or a separate local coil (not shown in FIG. **1**), in order to perform the prescribed magnetic resonance pulse sequence. Responsive magnetic resonance signals detected by the RF coil **128**, or a separate local coil (not shown in FIG. **1**), are received by the RF system **120**, where they are amplified, demodulated, filtered, and digitized under direction of commands produced by the pulse sequence server **110**. The RF system **120** 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 **110** 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 **128** or to one or more local coils or coil arrays (not shown in FIG. **1**).

[0025] The RF system **120** 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 **128** 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 I and Q components:

$$M=\sqrt{I^2+Q^2} \qquad (1);$$

[0026] and the phase of the received magnetic resonance signal may also be determined according to the following relationship:

$$\varphi = \tan^1\left(\frac{Q}{I}\right). \qquad (2)$$

[0027] The pulse sequence server **110** also optionally receives patient data from a physiological acquisition controller **130**. By way of example, the physiological acquisition controller **130** 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 **110** to synchronize, or "gate," the performance of the scan with the subject's heart beat or respiration.

[0028] The pulse sequence server **110** 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 **132** that a patient positioning system **134** receives commands to move the patient to desired positions during the scan.

[0029] The digitized magnetic resonance signal samples produced by the RF system **120** are received by the data acquisition server **112**. The data acquisition server **112** operates in response to instructions downloaded from the operator workstation **102** 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 **112** does little more than pass the acquired magnetic resonance data to the data processor server **114**. However, in scans that require information derived from acquired magnetic resonance data to control the further performance of the scan, the data acquisition server **112** is programmed to produce such information and convey it to the pulse sequence server **110**. For example, during prescans, magnetic resonance data is acquired and used to calibrate the pulse sequence performed by the pulse sequence server **110**. As another example, navigator signals may be acquired and used to adjust the operating parameters of the RF system **120** or the gradient system **118**, or to control the view order in which k-space is sampled. In still another example, the data acquisition server **112** 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. By way of example, the data acquisition server **112** acquires magnetic resonance data and processes it in real-time to produce information that is used to control the scan.

[0030] The data processing server **114** receives magnetic resonance data from the data acquisition server **112** and processes it in accordance with instructions downloaded from the operator workstation **102**. 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 backprojection 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.

[0031] Images reconstructed by the data processing server **114** are conveyed back to the operator workstation **102** where they are stored. Real-time images are stored in a data base memory cache (not shown in FIG. **1**), from which they may be output to operator display **112** or a display **136** that is located near the magnet assembly **124** 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 **114** notifies the data store server **116** on the operator workstation **102**. The operator workstation **102** may be used by an operator to archive the images, produce films, or send the images via a network to other facilities.

[0032] The MRI system **100** may also include one or more networked workstations **142**. By way of example, a networked workstation **142** may include a display **144**; one or more input devices **146**, such as a keyboard and mouse; and a processor **148**. The networked workstation **142** may be located within the same facility as the operator workstation **102**, or in a different facility, such as a different healthcare institution or clinic.

[0033] The networked workstation **142**, whether within the same facility or in a different facility as the operator workstation **102**, may gain remote access to the data processing server **114** or data store server **116** via the communication system **140**. Accordingly, multiple networked workstations **142** may have access to the data processing server **114** and the data store server **116**. In this manner, magnetic resonance data, reconstructed images, or other data may be exchanged between the data processing server **114** or the data store server **116** and the networked workstations **142**, such that the data or images may be remotely processed by a networked workstation **142**. 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.

[0034] As described, systems such as described above with respect to FIG. **1** have been used to perform neuroimaging acquisitions with short repetition times ("TRs"), which force navigators to be very short and, therefore, provide limited k-space coverage. These navigators are often referred to as "ultra-fast navigators." The effectiveness of the navigators at providing an estimate of the subject's head motion is, therefore, also limited.

[0035] In contrast to these ultra-fast navigators, echo-planar imaging (EPI)-based navigators, or volume navigators ("vNays"), have been used to acquire a whole-head volume in roughly 275 ms and, thereby, allow high-accuracy motion tracking. However, vNays have previously only been used in sequences with significant dead time provided by inflow times ("TI") or TR gaps in which the entire vNav could be inserted. As will be described, however, the present disclosure provides a way to insert a vNav into a 3D FLASH/SPGR sequence with only marginal impact on SNR or time. By doing so, the present disclosure provides a system and method for prospective motion correction of in-scan motion using a 3D FLASH/SPGR pulse sequence with vNays that does not substantially extend acquisition times.

[0036] An example of a pulse sequence employed to direct an MRI system to acquire image data in accordance with some configurations of the present invention is illustrated in FIG. **2**. The pulse sequence includes an RF excitation pulse **202** that is played out in the presence of a slab-selective gradient **204** in order to produce transverse magnetization in a volume-of-interest. The slab-selective gradient **204** includes a rephasing lobe **206** that acts to rephase unwanted phase dispersions introduced by the slab-selective gradient **204** such that signal losses resultant from these phase dispersions are mitigated.

[0037] Following excitation of the nuclear spins in the volume-of-interest, a phase-encoding gradient **208** is applied to spatially encode a nuclear magnetic resonance echo signal **210** at a given echo time (TE) representative of a gradient-recalled echo along one direction in the volume-of-interest. At the same time, a partition-encoding gradient **212** is applied to spatially encode the echo signal **210** along a second, orthogonal direction in the volume-of-interest. By way of example, the phase-encoding gradient **208** may spatially encode the echo signal **210** along the y-direction, while the partition-encoding gradient **212** may spatially encode the echo signal **210** along the z-direction. A readout gradient **214** is also applied after a dephasing gradient lobe **216** to spatially encode the echo signal **210** along a third, orthogonal direction in the volume-of-interest. By way of example, the readout gradient **214** may spatially encode the echo signal along the x-direction. The echo signal **210** is sampled during a data acquisition window.

[0038] Spoiler gradients **218**, **220**, **222** may be played out along the partition-encoding, phase-encoding, and frequency-encoding directions to dephase any residual transverse magnetization in the volume-of-interest to prevent signal contamination from one repetition time (TR) period to the next.

[0039] Referring now to FIG. **3**, the pulse sequence descried above with respect to FIG. **2** can, in accordance with the present disclosure, be combined with vNav sequences to yield a pulse sequence for performing prospective motion correction in SPGR/FLASH without extended TI or TR gaps. Specifically, FIG. **3** provides a timing diagram of an integrated vNav and a SPGR/FLASH sequence **300**, showing common pulses and TRs, but varied gradients, for interleaved imaging and vNav sequences. In particular, a plurality of imaging sequences **302**, such as described above with respect to FIG. **2** are illustrated. Integrated therewith are a plurality of vNav sequences **304**. As will be described, the scan time of the imaging sequence **302** is selected such that an imaging TR **306** allows vNav sequences **304**, each having a vNav TR **308**, to be inserted at any desired point. Furthermore, the RF pulses used in the vNav sequences **304** and the imaging sequences **302** may be the same. To this end, the steady-state of the imaging sequences **302** is maintained, even when vNav sequences **304** are inserted in the integrated sequence **300**.

[0040] As an example, the vNav sequence **304** may be a 3D-encoded echo-planar imaging (EPI) pulse sequence with a 32^3 matrix and may be acquired with ¾ partial Fourier encoding in the partition direction. As such, in this example, the vNav sequence **304** may have 25 three-dimensional excitation pulses. In this example, the vNav TR **308** is assumed to be 11 ms and the TR **306** for each imaging sequence **302** is assumed to match the vNav TR **308**. If the pulses of both sequences **302**, **304** are matched, a train of 25 vNav TRs (i.e., one vNav) can be played instead of a TR **306** of an imaging sequence **302** without disturbing the steady state of the imaging sequence **302**. Expanding on this example, as long as the TR **306** of the imaging sequence **302** is 11 ms or longer, matching the vNav TR **308** to the imaging TR **306** can be readily achieved by adding TRs **310** to the vNav sequence **304** after its readouts and not simply attempting to fit the vNav TR **308** within dead time. Again, as long as the scan time of the imaging sequence **302** meets the minimum TR requirement, vNav TRs **308** can be inserted at any desired point while maintaining the steady-state of the imaging sequence.

[0041] Inserting the vNav sequences **304** as separate TRs **308** at any time allows a great deal of flexibility, but also increases overall scan time. In previous acquisitions using vNav sequences, the navigators were inserted in TR or TI gaps and, thus, did not increase scan time. However, continuing with the non-limiting example provided above, 25 additional TRs are added to the total scan time with every vNav sequence while not gaining any additional imaging signal. To allow grater flexibility, as will be described, the user may set how many imaging TRs will be played between each vNav sequence, and the overall scan time is updated to inform users of the trade-off between tracking accuracy and scan time.

[0042] In some embodiments, however, an additional time savings can be realized by selectively performing a limited number of vNav sequences **304** such that the vNav sequences **304** are performed only when a predetermined amount of motion is occurring. In these instances, motion detection can be provided by inserting an ultra-fast navigator, such as a cloverleaf navigator, into each imaging sequence **302**. Examples of cloverleaf navigators are described in U.S. Pat. Nos. 6,771,068 and 6,958,605, both of which are herein incorporated by reference in their entirety. The ultrafast-navigator can be used as a high-sensitivity motion detector that can be relied on to determine when motion occurs without a significant scan time cost. When motion is detected, one or more vNav sequences **304** can be performed to provide a more accurate measurement of the motion, as described above in detail. In this manner, the more time consuming vNav sequences **304** can be performed only when a predetermined amount of motion is detected by an ultra-fast navigator, thereby reducing overall scan time by eliminating the performance of unnecessary vNav sequences **304**. Integrating an ultra-fast navigator into the imaging sequences **302** also has the added benefit of enabling resonance frequency correction.

[0043] Specifically, referring to FIG. **4**, a flowchart is provided that sets forth an example of a process for performing prospective motion correction using the pulse sequence described with respect to FIG. **3**. The prospective motion-corrected process **400** begins with user selection of the imaging pulse sequences and parameters for the sequence at process block **402**. As described above, the imaging pulse sequence may be a FLASH or SPGR or other name for such gradient-echo sequences. Once the imaging sequence and parameters are selected, at process block **404**, the user is prompted to select how many imaging TRs will be played between each vNav TR. Using this information, at process block **406**, the overall scan time is updated to inform users of the trade-off between tracking accuracy and scan time. As indicated by decision block **408**, the user may adjust the number and spacing of the vNav sequences to reach a desired overall scan time until the user has developed an overall integrated pulse sequence that is desired to be run.

[0044] At process block **410**, scanning begins using the overall integrated pulse sequence built by the user as described above. Using the data acquired from each performance of the vNav pulse sequence, motion estimates are generated at process block **412**. Specifically, the motion estimates are sent back to the scanner as they are generated on the image reconstruction computer, and are immediately applied at process block **414** to the coordinates of the next imaging sequence to provide real-time and prospective correction of subject motion that is identified. This process is repeated until, at decision block **416**, all data has been acquired. This method is applicable both to three-dimensional acquisitions and to simultaneous multi-slice acquisitions, including when such acquisitions include in-place acceleration.

[0045] To test the efficacy of the above-described process, a human volunteer was scanned in a 3T TIM Trio (Siemens Healthcare, Erlangen, Germany) using a 32-channel head matrix. The imaging sequence was a FLASH pulse sequence that used a 15 degree flip angle, 11 ms TR, 3.43 ms TE, 200 Hz/px bandwidth, 256 mm×256 mm×176 mm FOV, and 1 mm isotropic resolution, and 2×GRAPPA acceleration for a total scan time of 4:48. One volume was acquired with this protocol while the subject remained still. Thereafter, a vNav sequence was inserted after every 136 FLASH TRs (approximately 1.5 seconds), increasing the scan time to 5:38, and acquired another volume while the subject remained still. Then, two more volumes were acquired with the vNays sequences inserted, during both of which the subject was prompted to change their head position every minute, repeating the same motion pattern in both scans. In the first of these with-motion scans, correction was applied, using the process described above, for the subject's motion in real time, while in the second with-motion scan not apply the update.

[0046] Referring now to FIG. **5**, a flowchart is illustrated as setting forth the steps of an example method for performing prospective motion correction based on an integrated pulse sequence that uses an ultra-fast navigator in an imaging pulse sequence to detect motion and trigger the performance of one or more vNav sequences. The method begins with user selection of the imaging pulse sequences and parameters for the sequence at process block **502**. As described above, the imaging pulse sequence may be a FLASH, SPGR, or other such gradient-echo pulse sequence. Selecting the imaging pulse sequences also includes selecting an ultra-fast navigator to be included in each imaging pulse sequence. For example, the ultra-fast navigator may include a cloverleaf navigator.

[0047] At process block **504**, scanning begins using the selected imaging pulse sequences. Motion of the subject is monitored using the data acquired from the ultra-fast navigators acquired in each performance of the imaging pulse sequence, as indicated at step **506**. A determination is made at decision block **508** whether a predetermined amount of motion has occurred and been detected in the acquired navigator data. If not, imaging continues at step **504** and motion is monitored again at step **506**.

[0048] If, however, a predetermined amount of motion is detected, then one or more vNav sequences are performed, as indicated at step **510**, as described above. Using data acquired from the vNav pulse sequences, motion estimates are generated at process block **512**. Specifically, the motion estimates are sent back to the scanner as they are generated on the image reconstruction computer, and are immediately applied at process block **514** to the coordinates of the next imaging sequence to provide real-time and prospective correction of subject motion that is identified. This process is repeated until, at decision block **516**, all data has been acquired. This method is applicable for both three-dimensional acquisitions and simultaneous multi-slice acquisitions, including when such acquisitions include in-place acceleration.

[0049] Thus, a system and method is provided for performing prospective motion correction in FLASH, SPGR, or FLASH/SPGR-like pulse sequences. Unlike previous navigator methods that attempted to insert ultra-fast navigators into the imaging (FLASH/SPGR) TR, the present disclosure provides a way to insert multiple matched vNav TRs into the overall pulse sequence train and, thus, preserves the steady state. The present disclosure recognizes that a navigator of substantial length, including vNays, can be inserted or interleaved in a dense sequence imaging sequence (like FLASH), by substituting FLASH TRs for vNav TRs, while preserving the magnetization steady state. For example, to preserve the magnetization steady state, it is advantageous to match the vNav and FLASH TR times. Also, it is advantageous to ensure that the waveform of the excitation pulses match between the vNav and FLASH TRs. Further, if any gradients are used during the excitation pulse, it is advantageous to match these gradients. In addition, any RF spoiling between the vNav and FLASH TRs may be advantageously synchronized.

[0050] Unlike in previous applications of vNays, where there was no scan-time increase, the additional TRs to accommodate the vNav sequence in the integrated FLASH-vNav pulse sequence does increase overall scan time. However, this drawback is overcome by the high registration accuracy enabled by whole-head navigators readily achieved with the vNav sequence. Furthermore, the additional scan time is still significantly less than what would be required for an MR technologist to request patient compliance and rescan. Additionally, the provided, integrated vNav-FLASH/SPGR sequence allows users the flexibility to trade-off scan time for tracking accuracy based on the needs of their application and the subject population involved.

[0051] In some configurations, the additional scan time introduced by the vNav sequences is reduced by incorporating an ultra-fast navigator, such as a cloverleaf navigator, into each imaging pulse sequence. The navigator data is then relied upon to monitor motion, such that vNav sequences are performed only when a significant amount of subject motion is detected. In this manner, the benefits of the vNav sequences can be realized without adding unnecessary amounts of additional scan time.

[0052] The present invention has been described in terms of one or more preferred embodiments, and it should be appreciated that many equivalents, alternatives, variations, and modifications, aside from those expressly stated, are possible and within the scope of the invention.

1. A method for reconstructing an image of a subject, in which motion has been prospectively corrected, using a magnetic resonance imaging (MRI) system, the steps of the method comprising:
- (a) acquiring image data and navigator data from a subject by directing the MRI system to perform an imaging pulse sequence that includes a navigator portion;
- (b) processing the navigator data to determine whether motion occurred while the image data was acquired;
- (c) upon determining motion occurred in step (b), updating the imaging pulse sequence by:
  - (i) directing the MRI system to perform a volume navigator pulse sequence that uses an echo-planar imaging (EPI) technique to acquire volume navigator data from a volume-of-interest in the subject;
  - (ii) processing the volume navigator data to generate motion estimates of motion in the VOI;
  - (iii) updating the imaging pulse sequence based on the motion estimates, wherein the updated imaging pulse sequence prospectively corrects for the motion in the VOI using the motion estimates;
- (d) repeating steps (a) through (c) until a desired amount of image data is acquired; and
- (e) reconstructing an image of the subject from the acquired image data.

2. The method as recited in claim **1**, wherein the imaging pulse sequence includes a gradient echo pulse sequence.

3. The method as recited in claim **1**, wherein the navigator portion of the imaging pulse sequence includes performing a cloverleaf navigator.

4. The method as recited in claim **1**, wherein the image data is acquired during an imaging repetition time (TR) and the volume navigator data is acquired during a volume navigator TR that is coordinated with the imaging TR to preserve a steady-state of magnetization in the VOI associated with the imaging pulse sequence.

5. The method as recited in claim **4**, wherein the volume navigator TR is selected to match the imaging TR.

6. The method as recited in claim **1**, wherein the VOI includes a head of the subject, and the volume navigator pulse sequence is configured to acquire the volume navigator data from the head.

7. A magnetic resonance imaging (MRI) system, comprising:
- a magnet system configured to generate a polarizing magnetic field about at least a portion of a subject arranged in the MRI system;
- a magnetic gradient system including a plurality of magnetic gradient coils configured to apply at least one magnetic gradient field to the polarizing magnetic field;
- a radio frequency (RF) system configured to apply an RF field to the subject and to receive magnetic resonance signals from the subject using a coil array;
- a computer system programmed to:
  - control the gradient system and the RF system to perform an imaging pulse sequence that includes a navigator portion to acquire image data and navigator data from a subject;
  - process the navigator data to determine whether the subject moved while the image data was acquired;
  - upon determining that the subject moved, control the gradient system and the RF system to:
    - perform a volume navigator pulse sequence that uses an echo-planar imaging (EPI) technique to acquire volume navigator data from a volume-of-interest in the subject;
    - process the volume navigator data to generate motion estimates of motion in the VOI;
    - update the imaging pulse sequence based on the motion estimates, wherein the updated imaging pulse sequence prospectively corrects for the motion in the VOI using the motion estimates; and
- reconstruct an image of the subject from the acquired image data.

8. The system as recited in claim **7**, wherein the imaging pulse sequence includes a gradient echo pulse sequence.

9. The system as recited in claim **7**, wherein the navigator portion of the imaging pulse sequence includes performing a cloverleaf navigator.

10. The system as recited in claim **7**, wherein the image data is acquired during an imaging repetition time (TR) and the volume navigator data is acquired during a volume navigator TR that is coordinated with the imaging TR to preserve a steady-state of magnetization in the VOI associated with the imaging pulse sequence.

11. The method as recited in claim **10**, wherein the volume navigator TR is selected to match the imaging TR.

12. The method as recited in claim **7**, wherein the VOI includes a head of the subject, and the volume navigator pulse sequence is configured to acquire the volume navigator data from the head.

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