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METHOD FOR RETROSPECTIVELY CALIBRATING AN EXTERNAL MOTION SIGNAL ACQUIRED IN PARALLEL TO AN MRI EXAMINATION

Abstract

Systems and methods for retrospectively calibrating an external motion signal in parallel to a magnetic resonance imaging examination of a subject, wherein the magnetic resonance imaging examination includes several magnetic resonance imaging scans. The method includes acquiring a plurality of motion calibration k-space data packets using a magnetic resonance imaging protocol in between the magnetic resonance imaging scans, combining the k-space data packets acquired across the magnetic resonance imaging examination (and applying an optimization algorithm to the combined k-space data packets in order to estimate motion states of the subject during acquisition of the k-space data packets. The method further includes estimating a calibration motion model from the motion states and the external motion signal acquired simultaneously with the data packets, wherein the calibration motion model maps the external motion signal to a corresponding motion state.

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Background/Summary

CROSS REFERENCE TO RELATED APPLICATIONS
[0001] This application claims the benefit EP 24157550.5 filed on Feb. 14, 2024, which is hereby incorporated by reference in its entirety.
FIELD
[0002] Embodiments relate to a method for retrospectively calibrating an external motion signal acquired in parallel to a magnetic resonance imaging examination, a magnetic resonance imaging apparatus and a computer program.
BACKGROUND
[0003] Patient motion may degrade the diagnostic quality of magnetic resonance (MR) exams.
[0004] Some magnetic resonance imaging (MRI) motion correction techniques involve measuring the subject motion by external motion sensors or tracking devices. Such external motion measurements may be used for prospective or retrospective motion-correction of MRI data.
[0005] In prospective motion correction, the patient motion is detected in real time and the MRI scanner acquisition geometry is updated during the acquisition to keep the patient at the same position in the imaging coordinate system.
[0006] By contrast, retrospective motion correction methods correct for motion artefacts after the data acquisition. This may be done be using data from an external motion measurement during the image reconstruction, or the image data itself may be used to infer both a motion trace of the subject and an estimate of a motion-corrected reconstructed image. Mathematically, this is often done by including a motion operator into the MR forward model. In other words, these so-called data-driven retrospective techniques account for the patient's motion in the final image reconstruction and therefore reduce motion artefacts through improved model agreement. Examples of data-driven retrospective correction techniques using an MR forward model are described in L. Cordero-Grande, E. J. Hughes, J. Hutter, A. N. Price, and J. V Hajnal, "*Three-dimensional motion corrected sensitivity encoding reconstruction for multi-shot multi-slice MRI: Application to neonatal brain imaging*," Magn. Reson. Med., vol. 79, no. 3, pp. 1365-1376, 2018. For volumetric encoding using array receiver coils and Cartesian sampling, the so-called "aligned SENSE framework" described in J. Cordero-Grande, L., Teixeira, R., Hughes, E., Hutter, J., Price, A., & Hajnal, "*Sensitivity Encoding for Aligned Multishot Magnetic Resonance Reconstruction*," IEEE Trans. Comput. Imaging, vol. 2, no. 3, pp. 266-280, 2016, achieves motion correction by dividing k-space readouts into temporal segments (shots) and allowing each segment to have a distinct motion state correction that may be estimated.
[0007] It has been found that the robustness of retrospective motion estimation may be further improved by using optimized encoding reorderings for rectilinear three-dimensional (3D) multi-shot acquisitions. For example, L. Cordero-Grande, G. Ferrazzi, R. P. A. G. Teixeira, J. O'Muircheartaigh, A. N. Price, and J. V. Hajnal, "*Motion-corrected MRI with DISORDER: Distributed and incoherent sample orders for reconstruction deblurring using encoding*

redundancy," Magn. Reson. Med., vol. 84, pp. 713-726, 2020, propose a jittered checkerboard reordering scheme for 3D acquisitions (referred to herein as "DISORDER" or "checkered"). By uniformly distributing the samples of each shot across k-space, this reordering was shown to have computational advantages, including improved convergence stability and speed. Another possibility is to additionally acquire k-space data that samples the relevant part of k-space for motion estimation.

[0008] Various MRI-compatible external motion measurement systems exist, for example optical or radio-frequency (RF) based methods. Optical methods usually involve one or more cameras, often combined with targets affixed to the subject. The motion of the targets is captured by the camera and thereby, subject motion may be deduced from the optical images. One example of an RF based method is the so-called "Pilot Tone" method. The principle of Pilot Tone is to irradiate the body with an RF signal just outside the receive bandwidth of the MR data being acquired, but within the frequency range of the MR receive system, for example within the oversampling bandwidth which is acquired during every readout. The Pilot Tone signal interacts with the human body and is received via multiple antennas, for example the local RF coil(s). The received multi-channel Pilot Tone signal may be analysed in order to extract motion information. Other RF-based approaches exist, which often require additional hardware on the receive side.

[0009] For the pilot tone and other external motion measurement systems, the received signals (e.g. pixel values from optical cameras, RF signal from pilot tone, etc.) cannot usually be directly used to correct for motion, because they do not record the motion parameters directly, for example as rigid translation and rotation parameters. The measurements must first be calibrated to the actual motion parameters.

[0010] One solution would be to execute a training phase in which MRI and the external motion sensor simultaneously acquire data, while the subject and therefore the anatomy of interest assumes different positions. However, this requires additional scan time. Moreover, one has to ask the subject to assume different positions and therefore, this approach does not necessarily capture the full range of poses observed across the examination, and requires the subject to deliberately move, which may not be appropriate for a clinical scenario. Further, the calibration from the training phase must be assumed to remain valid for the data acquired throughout the remainder of the examination. This assumption might break down when the training phase and acquisition are distant in time.

BRIEF DESCRIPTION AND SUMMARY

[0011] The scope of the embodiments is defined solely by the appended claims and is not affected to any degree by the statements within this summary. The present embodiments may obviate one or more of the drawbacks or limitations in the related art. Independent of the grammatical term usage, individuals with male, female or other gender identities are included within the term.

[0012] Embodiments provide a method for calibrating an external motion signal acquired in parallel to an MRI examination, that is robust and does not require patient cooperation.

[0013] Embodiments provide a method for retrospectively calibrating an external motion signal acquired by an external motion sensor in parallel to a magnetic resonance imaging examination of a subject, wherein the magnetic resonance imaging examination includes several magnetic resonance imaging scans, the method including the steps of: acquiring a plurality of motion calibration k-space data packets using a magnetic resonance imaging protocol in between the magnetic resonance imaging scans; combining the k-space data packets acquired across the magnetic resonance imaging examination and applying an optimization algorithm to the combined k-space data packets in order to estimate motion states of the subject during acquisition of the k-space data packets; estimating a calibration motion model from the motion states and the external motion signals acquired simultaneously with the data packets, wherein the calibration motion model maps the external motion signal to a corresponding motion state.

[0014] The method includes a novel approach to calibration of external motion sensors in magnetic resonance imaging (MRI). A plurality of motion calibration k-space data packets are acquired in-between the diagnostic magnetic resonance scans. These motion calibration k-space data packets are also referred to as “distributed motion calibration” (DMC) data, because they are acquired in a distributed fashion across the entire examination. By “examination” an imaging session is meant, in which a subject—for example a patient—is positioned on a patient bed, such that the anatomy of interest is inside the sensitive volume of a magnetic resonance imaging apparatus, e.g. inside the bore of an MRI main magnet. An MRI examination may include one or more adjustment scans, an overview imaging scan often referred to as scout scan, and one or more (diagnostic) magnetic resonance (MR) scans. About two to ten MR scans are performed, for example to acquire images of the anatomy of interest with different contrasts, and/or before and after the administration of contrast agent. The MR scans, also called diagnostic MR scans, serve to acquire the diagnostic image data that is the purpose of the MR examination. The DMC data is acquired in-between the diagnostic MR scans, for example in dead-times where for example the next MR scan is being planned, or the operator is talking to the patient to ensure his/her continued well-being inside the MRI apparatus. In an example, the DMC data includes fast, motion-sensitized k-space samples that are acquired in a distributed fashion across the entire examination. An external motion signal is acquired at the same time as the DMC data, for example across the entire examination as well. The DMC data is acquired for the sole purpose of estimating motion parameters, the imaging information contained therein is for example not used at all. The motion states estimated from the DMC data may then be used to calibrate the external motion sensor. The distributed nature of the DMC acquisitions ensures that all relevant levels of motion occurring during the examination are captured. The DMC data may either be identical acquisitions each time, or they may vary, such they complement each other when retrospectively combined.

[0015] In order to improve the estimation of the motion states from the DMC data, all DMC acquisitions across the entire MRI examination are combined into a single estimation algorithm. Thereby, data-consistency across all DMC acquisitions is enhanced. This improves the robustness of the estimation process.

[0016] Embodiments use a joint estimation from unintrusively sampled data, for example the plurality of motion calibration k-space data packets, also referred to as DMC data, to obtain accurate and comprehensive motion information across the examination, that may be used for calibration of an external motion sensor acquiring an external motion signal. Embodiment provide the following advantages among others.

[0017] Instruction-free: Since the DMC data is acquired in a distributed way, and hence distant in time, the full range of patient motion is likely to be captured across all acquisitions. This is in contrast with pre-calibrated training steps as described above. The range of motion detected will also naturally match the range to be corrected—this is helpful for an optimized calibration model.

[0018] Efficient: DMC acquisitions may be obtained quickly in dead times within the examination, and thus without time penalty and without changing the main examination: The operator selects whatever MR scans they need for the diagnostic questions and the DMC acquisitions sit in the gaps that exist anyway.

[0019] Robust: Combining all DMC data into a single estimation process (step (b)) will generate robust motion estimation. The use of data interleaved with the full examination means that the calibration is intrinsically valid for the complete data set (no calibration drift). Both of these contrast with prior art approaches.

[0020] Because the DMC data are combined across the MRI examination, the external motion signal is calibrated retrospectively. Therefore, the external motion signal is for example used for retrospective motion correction, for example, using the data-driven retrospective correction techniques using an MR forward model as described above.

[0021] The external motion signal may be acquired by any external motion sensor. For example, the external motion sensors may include optical cameras, nuclear magnetic resonance (NMR) probes, electroencephalography-based markers, infrared-cameras, ultrasound-probes or RF-antennas. Optical cameras and RF-antennas may be used. An optical camera may for example acquire an external motion signal in the form of a video footage of the patient from one or more video cameras mounted inside or at the edge of the sensitive area of the MRI apparatus, for example at the entrance to the bore or inside the bore of a main magnet. The RF-antenna may be a separate antenna from the RF coil used to acquire the MR signals. For example, it is an RF coil used to acquire MR signals. For example, the external motion signal is a pilot tone (PT) signal. For the PT method, an RF signal just outside the bandwidth of the MRI examination, but inside the receive bandwidth of the RF coils, is radiated into the sensitive area of the MR scanner, for example, by an additional RF-antenna. The RF signal interacts with the subject's body and varies therefore with the subject's motion. It is picked up by the MR receiver coil or coils, for example by an array coil having several channels. Because the PT and MR signals are acquired using the same receiver system, without interfering with each other since they occupy different frequency bands, the external motion signals and the MR signals, for example the motion calibration k-space data packets, are automatically synchronized. This, in addition to its quick and easy workflow setup, makes PT a preferred candidate for the external notion signal, although the embodiments are not limited thereto.

[0022] The magnetic resonance scans may be acquired using any known imaging protocol. They may, for example, include two-dimensional (2D) and/or three-dimensional (3D) scans. They may be acquired using any imaging protocol, for example spin-echo based or gradient-echo based imaging protocols. There is no limitation on the type of imaging protocol that may be used for the several magnetic resonance scans acquired during the MRI examination, because these scans are not modified in any way by the method. The method aims at acquiring additional data, namely the motion calibration k-space data packets in-between the MR scans. To this end, it may be possible that the control unit of the MR apparatus (also referred to as MR scanner) issues a trigger signal every time an MR scan is finished. The trigger signal may be used to start the acquisition of the motion calibration k-space data packets. This DMC acquisition may either have a fixed duration, or the acquisition may continue for as long as the next MR scan is not started. In this embodiment, when the operator, e.g. an MR technician, has finished planning the next MR scan and starts the acquisition thereof, the acquisition of the DMC data is automatically interrupted, until the end of the next MR scan. Thereby, k-space data packets for motion calibration may be acquired in-between the several MR scans throughout the MRI examination.

[0023] In a step that is performed at the end of the MRI examination, the DMC data acquired across the MRI examination are combined. An optimization algorithm is applied in order to estimate the motion states of the subject during acquisition of the DMC data. A “motion state” may for example include positional information of the anatomy of interest, e.g. the volume from which the MR scans and the DMC data is acquired. In an embodiment, the motion states are expressed by rigid body motion parameters, for example by three rotational and three translational parameters. However, the embodiments are not limited thereto, and non-rigid motion may also be estimated using the method. Several motion states detected over time are referred to herein as “motion trace”. The motion parameters may be estimated from the DMC data using known methods such as a perturbation model, or a scout-based model. A perturbation-based model is described for example in Thomas Ulrich, Malte Riedel, Klaas P. Pruessmann “Servo navigators: Linear regression and feedback control for rigid-body motion correction”, Magn. Reson. Med., online version first published on 17 Jan. 2024, https://doi.org/10.1002/mrm.29967. In a scout-based method, the k-space data packets are essentially compared against a low-resolution scout reference image, that may be the scout image that is acquired in order to plan the MR scans at the beginning of the MR examination. It may also be an additional scout image acquired at the beginning of the imaging scan. This method is described in D. Polak et al. “Scout accelerated motion estimation and reduction (SAMER)”, Magn. Reson. Med., vol. 87, pp. 163-178, 2022, and that is incorporated

herein by reference.
[0024] Given a total number N of DMC acquisitions, Σ.sub.n=1.sup.NM.sub.nM motion states are available for the calibration step, with M.sub.n the number of motion states within each DMC n. When the external motion signal is received using D channels, a calibration motion model may be estimated in a step that maps from the external motion signal to the motion states of the subject. No restrictions apply to the type of model that may be used. In an embodiment, a linear model is used, that includes a calibration matrix C, that maps between both domains. An example of the underlying mathematics is given herein below.
[0025] According to an embodiment, the calibration motion model is thus a linear model and includes a calibration matrix that maps an external motion signal on a motion state of the subject. This is a useful simplification that makes the estimation step stable and computationally robust.
[0026] Further, according to an embodiment, the external motion signal is a pilot tone signal, for example, a multi-channel pilot tone signal acquired with a magnetic resonance receiver coil array. The PT has the advantage that it requires no or little additional hardware.
[0027] According to an embodiment, the acquisition of the k-space data packets is distributed across a significant portion of the subject's magnetic resonance imaging examination, for example over more than half, for example more than ¾ of the examination.
[0028] The acquisition of the k-space data packets (DMC data) may be distributed across the complete MRI examination. This has the advantage that all kinds of relevant motion of the subject, that may occur throughout the examination, will be captured in the DMC data. It may be achieved by triggering a DMC acquisition after each MR scan, and possibly also after the initial adjustment and/or scout scans.
[0029] According to an embodiment, the k-space data packets are acquired in the dead times between the magnetic resonance imaging scans, and wherein for example the duration of acquisition of each k-space data packet is adapted to the duration of the dead time between the respective magnetic resonance imaging scans. “Dead time” refers to the times that are typically required in an MRI examination in-between the MR scans, for checking the quality of the MR scan that has just been completed, and/or for planning the next MR scan, and/or for injecting contrast agent and/or for communicating with the subjects to ensure his/her well-being. The dead time is time that is usually unused, and is now used to acquire the motion calibration k-space data packets. The length of acquisition of each k-space data packet may vary from acquisition to acquisition, according to the length of the dead time available. In other embodiments, the k-space data packets all have the same, pre-set duration. The duration may for example be between 0.3 and 30 seconds, for example 5-20 seconds.
[0030] According to an embodiment, the method includes a further step of using the calibration motion model and the acquired external motion signal for retrospective motion correction of the data acquired in the magnetic resonance imaging scans. Thereby, the MRI scans may be retrospectively motion corrected. To achieve this, known retrospective data deconstruction methods may be used, for example, techniques using an MR forward model described by L. Cordero-Grande mentioned above. Thus, the method of this embodiment is a method for acquiring motion-corrected magnetic resonance imaging data.
[0031] The motion-corrected MRI data may be obtained by two possible embodiments.
[0032] According to a first embodiment, the method includes a step of obtaining a motion trace of the subject, by applying the calibration motion model to the external motion signal acquired throughout the magnetic resonance imaging examination, and using the motion trace in retrospective motion correction of the data acquired in the magnetic resonance imaging scans.
[0033] Thus, the motion trace of the subject is estimated first, for example by applying the calibration motion model to the external motion signal acquired throughout the MRI examination and for example during the MR scans. This motion trace including motion states during the acquisition of the MR scans, is then used to retrospectively motion correct the data acquired in the

MR scans. This has the advantage that it is easy to apply, however, it assumes that the calibration motion model remains the same throughout the MRI examination. Since this may not always hold true, another embodiment is also provided.
[0034] According to another embodiment, the method includes a further step of reconstructing images from the k-space data acquired in the magnetic resonance imaging scans by minimizing the data consistency error between the k-space data acquired in the magnetic resonance imaging scans and an image reconstruction forward model described by an encoding matrix, wherein the encoding matrix includes motion states of the subject, optionally the sensitivity profiles(S) of a receiver coil array, Fourier encoding (F), and a sampling mask (A), and wherein the motion states in the encoding matrix are obtained by using a motion model applied to the external motion signal, and wherein the calibration motion model is used as an initial estimate for the motion model.
[0035] In this embodiment, both the motion trace and the motion-corrected images are estimated in a single step. The calibration motion model is not even absolutely required, for example, in the event that the MR scans are acquired using a distributed reordering scheme, wherein each shot covers k-space samples in the center of k-space, an initial estimate for the motion model may not be required. Usually, however, the MR scans will use normal, sequential k-space sampling schemes because these yield better results in other respects. In this case, it is advantageous to use the calibration motion model estimated from the motion states extracted from the combined k-space data packets as an initial estimate for the motion model. An example for a mathematical description of the image reconstruction forward model is given herein below. This embodiment has the advantage that the data-consistency across all acquisitions is maximized. Thus, retrospective joint motion and image estimation leverages the data-consistency between DMC data. Therefore, it may take into account such cases where the calibration motion model changes during the MR examination.
[0036] According to an embodiment, the motion calibration k-space data packets are acquired using a low-resolution three-dimensional imaging protocol, and wherein the acquisition of one three-dimensional image is distributed over several data packets, or is completed in one data packet. For example, the 3D imaging protocol may be a gradient echo imaging protocol. Low resolution may mean more than 2×2×2 mm.sup.3 resolution, for example up to 6×6×6 mm.sup.3 resolution. In the example, experiments were performed at 4×4×4 mm.sup.3 resolution. The total acquisition time to acquire a full k-space in this imaging protocol may be between 1.0 and 100 secs, for example between 2.0 and 60 secs, for example between 5 and 40 secs. In the example acquisitions, the sequence parameters were TE/TR=1.93/3.8 ms, flip angle 8°, scan duration 22 s. Such a 3D scan may be acquired as one k-space data packet. This has been done in the example, but it is not necessary. Alternatively, the acquisition of a 3D image may be distributed over several k-space data packets. This gives more flexibility to use even shorter dead times between MR scans. In an embodiment, a single k-space may only be fully sampled by the end of the examination.
[0037] According to an embodiment, each k-space data packet is divided into one or more temporal segments, wherein the calibration motion model includes a motion state for each temporal segment. A temporal segment for example corresponds to a shot, wherein several k-space samples are acquired in each shot. For example, each calibration k-space data packets includes a plurality of shots, wherein several k-space lines are acquired in one shot. An “shot,” also referred to as “echo train,” includes a plurality of magnetic resonance (MR) echoes, e.g. spin echoes and/or gradient echoes. During each echo, a line in k-space is sampled (termed “k-space sample.” In most sequences, a shot includes a preparation pulse, and then all echoes have their own excitation/refocusing pulses. Thus, a shot may mean a series of gradient echoes or spin echoes, each echo corresponding to one line in k-space. There may be 8 to 512 echoes in one shot, wherein the acquisition duration of a shot may be between 0.1 and 4 s, for example between 0.2 and Is. It has been found useful to estimate one motion state per shot, because this results in a time resolution that is useful to capture most patient movements. Each k-space data packet may include for

example between 1 and 30 shots. The duration of each temporal segment is for example between 0.1 sec and 3.0 sec, for example between 0.2 and 1.2 sec, for example between 0.3 and 0.6 sec. Thereby, high temporal resolution motion estimates may be achieved. Further, this embodiment has the advantage that the temporal resolution for the motion states may be determined by the user by determining the length of the temporal segments that are used in the optimization algorithm to represent one motion state.

[0038] According to an embodiment, motion calibration k-space data packets are acquired using a distributed sampling order, in which samples acquired during one temporal segment are distributed across k-space, wherein for example successively acquired k-space samples are not adjacent to each other in k-space. In a 3D-imaging protocol, a thick slab of tissue is excited together. In such 3D-imaging, spatial encoding may be performed using phase-encoding gradients along two spatial dimensions, and frequency encoding along the third spatial dimension, referred to as readout direction. Accordingly, with each MR echo in a shot, a k-space sample oriented along the readout direction is sampled. By modifying the phase-encoding gradient before each readout, it is possible to design different sampling orders (also referred to as “reordering,” “sampling order”, or “reordering scheme”), that may refer to the order in which the k-space samples are acquired. For example, in a linear reordering, the phase-encoding gradient is increased step by step for each k-space sample, resulting in a sampling of k-space line-by-line, from one end of k-space to the other. However, a distributed sampling scheme, for example as disclosed by Cordero-Grande in MRM 2020 (“DISORER”, full reference see above) may be used, because thereby the k-space data packets are effectively motion-sensitized. This is because patient motion is reflected in different areas of k-space to different degrees. A central region of k-space may be sampled in each time segment, so as to best capture patient motion in the DMC data. Therefore, distributed sampling schemes may be used.

[0039] According to an embodiment, 3 to 20, for example 5 to 10 motion calibration k-space data packets are acquired throughout the magnetic resonance imaging examination, and/or wherein each motion calibration k-space data packet is acquired during 1 to 200 sec, for example during 5 to 100 sec, for example 10 to 60 sec. It has been shown that this amount of DMC data is sufficient to achieve a satisfactory calibration of the external motion sensors.

[0040] According to an embodiment, the optimization algorithm used to estimate motion states of the subject from the acquired k-space data packets includes a step of minimizing the data consistency error between the k-space data of the data packets and an image reconstruction forward model described by an encoding matrix, wherein the encoding matrix includes motion states of the subject, for example the sensitivity profiles of a receiver coil array, Fourier encoding and a sampling mask. For example, the PT-aligned SENSE construction model may be used, as described herein below. However, embodiments are not limited thereto, other optimization algorithms may be used. For example, other optimization algorithms could use the “perturbation model” (see above) or methods using the image-equivalent of the acquired k-space samples within a shot and performing image registration. An example of this method is described by Emil Ljungberg et al. in “Motion corrected silent ZTE neuroimaging”, Magn. Reson. Med, Vol. 88, pp. 195-210 (2022)

[0041] In a further aspect, a magnetic resonance imaging apparatus is provided that includes a radio frequency controller configured to drive an RF-coil, for example including a multi-channel coil-array, a gradient controller configured to control gradient coils, and a control unit configured to control the radio frequency controller and the gradient controller to execute the imaging protocol. The MRI-apparatus may be a commercially available MRI-apparatus that has been programmed to perform the method.

[0042] The advantages and features of the method may also apply to the MRI apparatus and vice versa. The MRI apparatus may include a MR scanner. Apart from the external motion sensor, the MRI apparatus does not require additional hardware in order to execute the method.

[0043] According to a further aspect, a computer program is provided that includes program code, that causes a magnetic resonance imaging apparatus-such as the apparatus described herein—to execute the method, for example the method for acquiring an MR image dataset. However, the program code may also encode the described method for generating a motion-corrected magnetic resonance image dataset, and the program code may run on a computer as described herein.

[0044] According to a further aspect, a non-transitory computer-readable medium containing a computer program is provided. The computer-readable medium may be any digital storage medium, such as a hard disc, a cloud, an optical medium such as a CD or DVD, a memory card such as a compact flash, memory stick, a USB-stick, multimedia stick, secure digital memory card (SD) etc.

[0045] The advantages and features given for the MRI apparatus and the method also apply to the computer program, computer program product, digital storage medium and vice versa. The computer program may be executed by any MRI imaging apparatus that may receive the signal of an external motion sensor, for example a pilot tone signal.

[0046] In the following, a mathematical description of an example embodiment of the optimization algorithm and estimation step is given. However, embodiments are not limited to this model.

[0047] Both the Pilot Tone signal and the MRI data are acquired using an array receiver coil having a number of D channels. In this example, it is a head coil, and the anatomy of interest is the head. The motion to be corrected is assumed to be rigid motion. Evidently, similar mathematics may be used to describe other external motion signals.

[0048] To describe the variation of the PT signal with head position, one assumes a linear relationship between the 6 rigid motion parameters (3 rotational and 3 translational parameters) (z.sub.t) and the PT signal at time t (p.sub.t), that has D channels, D being the number of channels of the coil receiver array:

[00001] $z_t = Cp_t$ [1]

[0049] where p.sub.t is a complex vector containing the D-channel PT signal at time t. The PT signal is for example concatenated with a 1 to allow for a motion offset. C is a 6×(D+1) matrix with calibration coefficients for each of the 6 rigid motion parameters.

[0050] Thus, the calibration matrix C is an example of a calibration motion model that maps the external motion signal at time t, p.sub.t, to a corresponding motion state z.sub.t.

[0051] An example using an MR forward model is the alignedSENSE reconstruction problem (J. Cordero-Grande, L., Teixeira, R., Hughes, E., Hutter, J., Price, A., & Hajnal, "*Sensitivity Encoding for Aligned Multishot Magnetic Resonance Reconstruction*," IEEE Trans. Comput. Imaging, vol. 2, no. 3, pp. 266-280, 2016) with rigid motion correction and parallel imaging, that may be formulated as an inverse problem in matrix form:

[00002] $(\hat{x},) = \text{argmin}_{x, z_n}$ .Math.$_n$ .Math. $A_n FST_{z_n} x - y_n$ .Math.$_2^2$ [2]

[0052] Where x is the volumetric image to be reconstructed, S is the sensitivity profile of the D-element coil receiver array and F the discrete Fourier transform. For each temporal segment or shot n, T.sub.z.sub.n is the rigid motion operator with motion parameters z.sub.n, A.sub.n the sampling mask and y.sub.n the acquired k-space data of the imaging scan for all coil elements.

[0053] By inserting equation 1 into equation 2, the aligned SENSE reconstruction problem may be expanded to include the Pilot Tone signal p as an input, and to estimate the calibration matrix C together with the reconstructed image x. p.sub.n as the averaged PT signal at shot n, and inserting equation 1 into equation 2 results in the following inverse problem, referred to as PT-aligned SENSE:

[00003] $(\hat{x}, \hat{C}) = \text{argmin}_{x, C}$ .Math.$_n$ .Math. $A_n FST_{\mathrm{Cp}_n} x - y_n$ .Math.$_2^2$ [3]

[0054] Equation 3 may be solved by iteratively updating x and C, for example using Conjugate Gradient (CG) and Levenberg-Marquardt (LM) algorithms, respectively. Processing of the DMC

acquisitions
[0055] For example, a pre-calibrated C, C.sub.calib, is used to solve equation [3]. C.sub.calib may be estimated, for example from the k-space data packets, also referred to as DMC acquisitions, and a set of motion states of the subject during the acquisition of the k-space data packets. This may be preferred for standard, sequential sampling schemes of the MR scans, because for those standard, sequential sampling schemes, equation [3] would not yield satisfactory results. Rather, robust performance would require the use of distributed sampling schemes (like DISORDER, VD-CASPER, Linear+, etc) in the MR scans, in which each shot collects samples spanning across k-space. That is possible, but required modification of existing MR scan protocols. Embodiments, however, are configured to work with any MR scan protocols.
[0056] Therefore, the embodiments distribute individual motion calibration (MC) k-space data packets acquisitions y.sub.MC throughout the examination. After combining all MC acquisitions into y.sub.DMC, motion parameters z.sub.DCM.sub.m corresponding to each shot y.sub.DCM.sub.m are obtained using the alignedSENSE reconstruction (Equation 2):

[00004] $(,) = \text{argmin}_{x, z_{\text{DCM}_m}}$ .Math.$_m$ .Math. $A_m FST_{Z_{\text{DCM}_m}} x_{\text{DMC}} - y_{\text{DCM}, m}$ .Math.$_2^2$ [4]

[0057] In embodiments, multiple shots m may be contained within a single y.sub.MC. To enable robust motion estimation, a self-navigated (=distributed) reordering scheme is for example used for all motion calibration (MC) k-space data packets. Since the distributed motion calibration k-space data packets acquisitions are only used for motion estimation, acquisitions are low-resolution and the estimated image x.sub.DMC is not used. After the motion parameters z.sub.DCM.sub.m are obtained and the simultaneously acquired PT signals p.sub.DCM.sub.m are extracted from the acquired MR data, custom-character may be estimated using a least-squares fit:

[00005] $() = \text{argmin}_C$ .Math.$_m$ .Math. $Z_{\text{DMC}, m} - Cp_{\text{DMC}, m}$ .Math.$_2^2$ [5]

[0058] This custom-character may be used as an initial estimate in equation 3, in order to iteratively estimate the motion corrected images for the MR scans.
[0059] Alternatively, custom-character as estimated from equation 5 may be taken as the final calibration motion model that is applied to the external motion signal p to obtain a motion trace, that in turn is used for retrospective motion correctio of the MR data acquired in the MR scans.

Description

BRIEF DESCRIPTION OF THE FIGURES
[0060] FIG. **1** depicts a timeline of an embodiment;
[0061] FIG. **2** depicts a flow diagram of an embodiment of the method;
[0062] FIG. **3** depicts an embodiment of an MRI apparatus.
DETAILED DESCRIPTION
[0063] FIG. **1** depicts the timeline of an MRI examination according to an embodiment of the method. The entire examination **2** might take between 15 and 70 minutes, for example between 20 and 50 minutes. It is constituted by the timespan that the subject or patient stays inside the sensitive area or bore of the MRI apparatus. At the beginning, there may be a scout scan **4**, that is a very fast, low-resolution 2D or 3D imaging scan, that is taken to provide the operator with an overview of the anatomy of interest, and an image on which the operator plans the further diagnostic scans **6**. The scout may be followed by a reference scan **5**. However, in between the scout and resonance scan, a DMC acquisition **6** may be placed. As mentioned above, the DMC acquisition **6** may for example be triggered at the end of the scout scan **4** and may be carried up to a maximum pre-determined duration, unless another scan is initiated by the operator during the DMC acquisition in which case it may be interrupted. In another embodiment, the DMC acquisition **6** is a fixed type of acquisition having a fixed length, that cannot be interrupted by further scans. For example, the DMC

acquisition **6** may be a low-resolution 3D imaging scan having a duration of between 15 and 40 seconds and including 20-100 shots. After the reference scan **5**, several diagnostic imaging scans **7***a* and **7***b* are carried out. In between, again DMC acquisition **6** are placed, wherein k-space data packets are acquired in order to estimate motion states of the subject throughout the MRI examination **2**.
[0064] FIG. **2** depicts the processing of the DMC acquisition **6** according to an embodiment. In step **10**, the DMC data packets are combined, for example concatenated, into one data set termed y.sub.DMC, that includes all k-space data acquired during the DMC acquisition **6**. In this embodiment, the external motion signal is a pilot tone signal, that is acquired together with the MR signal. Therefore, the method includes a step **11** of extracting the pilot tone signal p.sub.DMC **12** from the combined DMC data. The further processing is done with the y.sub.DMC data **14**. In the next step **16**, that may for example use an optimisation algorithm to optimise equation 3, the motion parameters z.sub.DMC **18** are estimated from the combined DMC data **14**. A motion corrected image **17** is also the result of this optimisation but is not used in the further processing. The motion trace **18**, that may for example include rigid body motion parameters for each shot of the DMC acquisitions, is used instead in step **20**, in order to find out the calibration motion model **22**. Step **20** may for example be carried out using the mathematical model of equation 5. However, other mathematical descriptions/models are also possible.
[0065] FIG. **3** schematically depicts a magnetic resonance (MR) apparatus **31**. The MR apparatus **31** has an MR data acquisition scanner **32** with a magnet **33** that generates the constant magnetic field, a gradient coil arrangement **35** that generates the gradient fields, one or several radio-frequency (RF) antennas **37** for radiating and receiving RF signals, and a control computer **39** configured to perform the method. The radio-frequency antennas **37** may include a multi-channel coil array including at least two coils, for example the schematically shown coils **37.1** and **37.2**, that may be configured to transmit and/or receive RF signals (MR signals).
[0066] In order to acquire MR data from an examination subject U, for example a patient or a phantom, the subject U is introduced on a bed B into the measurement volume of the scanner **32**. MR data may be acquired using a method according to an embodiment from 3D slab S. The control computer **39** controls the MR apparatus **1**, and the gradient coil arrangement **35** with a gradient controller **35**′ and the RF antenna **37** with a RF transmit/receive controller **37**′. The RF antenna **37** has multiple channels corresponding to the multiple coils **37.1**, **37.2** of the coil arrays, in which signals may be transmitted or received. The control computer **39** also has an imaging protocol processor **44** that determines the imaging protocol, including the sampling order and the acquisition of the k-space data packets. A control unit **43** of the control computer **39** is configured to execute all the controls and computation operations required for acquisitions. Intermediate results and final results required for this purpose or determined in the process may be stored in a memory **41** of the control computer **39**. A user may enter control commands and/or view displayed results, for example image data, an input/output interface E/A. A non-transitory data storage medium **36** may be loaded into the control computer **39**, and may be encoded with programming instructions (program code) that cause the control computer **39**, and the various functional units thereof described above, to implement any or all embodiments of the method.
[0067] A method according to an embodiment was implemented on a **7**T Siemens Terra system, using a ITX coil (NOVA medical) using a 32-element adult head coil array. MRI examinations were conducted on twelve healthy volunteers, wherein the MRI scans were for example MPRAGE acquisition, some with a DISORDER sampling (Acquisition time per shot=0.76 sec), some using a standard linear sampling scheme. The k-space data packets included six individual fully sampled DMC acquisitions placed throughout the examination. Each DMC acquisition was a 3D acquisition using am RF+gradient-spoiled gradient echo sequence having a 3×3×3 mm.sup.3 resolution, FOV=240×212×240 mm.sup.3, TE/TR=1,93/3.8 ms, flip angle 8°, scan duration 22 s. After each MRI examination, motion parameters were estimated using equation 4 and subsequently used to

construct C.sub.calib in equation 5. C.sub.calib was validated using the DISORDER MPRAGE acquisition. The latter, being a self-navigated sequence, may be considered to achieve ground through motion parameters after motion correction. The external motion signal was the pilot tone signal. Motion parameters are predicted using the PT signals extracted from the DISORDER MPRAGE. The duration of a shot in the example was 0.33 sec, achieving high-temporal resolution motion estimates. Using such setup, it was shown to produce effective calibration of motion parameters to the externally acquired motion signal. The calibration motion model achieved successful motion correction in standard MPRAGE acquisitions in volunteers that were not instructed to move during the calibration scans.

[0068] The embodiments use data acquired in unused time throughout the examination and samples the range of motions the subject actually does. This means there is no time penalty and the calibration is based on motions that are likely to match those that disrupted the data to be corrected. Also, the calibration model is intrinsically valid for the duration of the examination. Since there is no change in the main examination, the results obtained are the standard results (uncorrected) or better results if the calibration process and motion corrected reconstruction is effective—this gives a non-inferiority guarantee.

[0069] It is to be understood that the elements and features recited in the appended claims may be combined in different ways to produce new claims that likewise fall within the scope of the present embodiments. Thus, whereas the dependent claims appended below depend from only a single independent or dependent claim, it is to be understood that these dependent claims may, alternatively, be made to depend in the alternative from any preceding or following claim, whether independent or dependent, and that such new combinations are to be understood as forming a part of the present specification.

[0070] While the present embodiments have been described above by reference to various embodiments, it may be understood that many changes and modifications may be made to the described embodiments. It is therefore intended that the foregoing description be regarded as illustrative rather than limiting, and that it be understood that all equivalents and/or combinations of embodiments are intended to be included in this description.

Claims

1. A method for retrospectively calibrating an external motion signal in parallel to a magnetic resonance imaging examination of a subject, wherein the magnetic resonance imaging examination comprises a plurality of magnetic resonance imaging scans, the method comprising: acquiring a plurality of motion calibration k-space data packets using a magnetic resonance imaging protocol in between the plurality of magnetic resonance imaging scans; combining the plurality of motion calibration k-space data packets acquired across the magnetic resonance imaging examination and applying an optimization algorithm to the combined motion calibration k-space data packets to estimate motion states of the subject during acquisition of the plurality of motion calibration k-space data packets; and estimating a calibration motion model from the motion states and ab external motion signal acquired simultaneously with the plurality of motion calibration k-space data packets, wherein the calibration motion model maps the external motion signal to a corresponding motion state.

2. The method of claim 1, wherein the acquisition of the plurality of motion calibration k-space data packets is distributed across a portion that is over more than half of the subject's magnetic resonance imaging examination.

3. The method of claim 2, wherein the portion is more than ¾ of the examination.

4. The method of claim 1, wherein the plurality of motion calibration k-space data packets are acquired in dead times between the magnetic resonance imaging scans, and wherein a duration of acquisition of each motion calibration k-space data packet is configured to a duration of a dead

time between the respective magnetic resonance imaging scans.
5. The method of claim 1, further comprising: using the calibration motion model and the acquired external motion signal for retrospective motion correction of the data acquired in the magnetic resonance imaging scans.
6. The method of claim 1, further comprising: obtaining a motion trace of the subject, by applying the calibration motion model to the external motion signal acquired throughout the magnetic resonance imaging examination; and using the motion trace in retrospective motion correction of the data acquired in the magnetic resonance imaging scans.
7. The method of claim 1, further comprising: reconstructing images from k-space data acquired in the magnetic resonance imaging scans by minimizing a data consistency error between the k-space data acquired in the magnetic resonance imaging scans and an image reconstruction forward model described by an encoding matrix, wherein the encoding matrix includes motion states of the subject, and wherein the motion states in the encoding matrix are obtained by using a motion model applied to the external motion signal, and wherein the calibration motion model is used as an initial estimate for the motion model.
8. The method of claim 7, wherein the encoding matrix further includes sensitivity profiles of a receiver coil array, Fourier encoding, and a sampling mask.
9. The method of claim 1, wherein the external motion signal is a pilot tone signal acquired with a magnetic resonance receiver coil array.
10. The method of claim 9, wherein the pilot tone signal is a multi-channel pilot tone signal.
11. The method of claim 1, wherein the plurality of motion calibration k-space data packets are acquired using a low-resolution three-dimensional imaging protocol, and wherein the acquisition of one three-dimensional image is distributed over several data packets.
12. The method of claim 1, wherein each motion calibration k-space data packet is divided into one or more temporal segments, wherein the calibration motion model comprises a motion state for each temporal segment, and wherein a temporal segment corresponds to a shot, wherein several k-space samples are acquired in each shot.
13. The method of claim 1, wherein the plurality of motion calibration k-space data packets are acquired using a distributed sampling order, in which samples acquired during one temporal segment are distributed across k-space, wherein successively acquired k-space samples are not adjacent to each other in k-space.
14. The method claim 1, wherein 5 to 10 motion calibration k-space data packets are acquired throughout the magnetic resonance imaging examination, and/or wherein each motion calibration k-space data packet is acquired during 10 to 60 sec.
15. The method of claim 1, wherein the optimization algorithm used to estimate motion states of the subject from the acquired plurality of motion calibration k-space data packets includes a step of minimizing a data consistency error between the k-space data of the data packets and an image reconstruction forward model described by an encoding matrix, wherein the encoding matrix includes motion states of the subject.
16. The method of claim 1, wherein the calibration motion model is a linear model and comprises a calibration matrix that maps an external motion signal on a motion state of the subject.
17. A magnetic resonance imaging apparatus comprising: a radio frequency controller configured to drive an RF-coil comprising a multi-channel coil array; a gradient controller configured to control gradient coils; and a control unit configured to control the radio frequency controller and the gradient controller to: acquire a plurality of motion calibration k-space data packets using a magnetic resonance imaging protocol in between a plurality of magnetic resonance imaging scans; combine the plurality of motion calibration k-space data packets acquired across the magnetic resonance imaging examination and applying an optimization algorithm to the combined motion calibration k-space data packets to estimate motion states of a subject during acquisition of the plurality of motion calibration k-space data packets; and estimate a calibration motion model from

the motion states and ab external motion signal acquired simultaneously with the plurality of motion calibration k-space data packets, wherein the calibration motion model maps the external motion signal to a corresponding motion state.

18. A non-transitory computer implemented storage medium, including machine-readable instructions stored therein for retrospectively calibrating an external motion signal in parallel to a magnetic resonance imaging examination of a subject, wherein the magnetic resonance imaging examination comprises a plurality of magnetic resonance imaging scans, the instructions when executed by at least one processor, cause the processor to: acquire a plurality of motion calibration k-space data packets using a magnetic resonance imaging protocol in between the plurality of magnetic resonance imaging scans; combine the plurality of motion calibration k-space data packets acquired across the magnetic resonance imaging examination and applying an optimization algorithm to the combined motion calibration k-space data packets to estimate motion states of the subject during acquisition of the plurality of motion calibration k-space data packets; and estimate a calibration motion model from the motion states and ab external motion signal acquired simultaneously with the plurality of motion calibration k-space data packets, wherein the calibration motion model maps the external motion signal to a corresponding motion state.