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RESPIRATORY-STATE RESOLVED MAGNETIC RESONANCE IMAGING

Abstract

Disclosed herein is a medical system (**100, 400**) comprising: a magnetic resonance imaging system (**102**) configured for providing a respiratory signal. The respiratory signal is descriptive of a respiratory position as well as of inhalation and exhalation of the subject. The execution of machine executable instructions (**140**) causes the computational system to repeatedly: perform (**200**) the individual acquisition of k-space data using the magnetic resonance imaging system; receive (**202**) the respiratory signal; bin (**204**) the individually acquired k-space data into one of a predetermined number of k-space bins (**148**) using the respiratory signal and perform outlier rejection. Execution of the machine executable instructions further causes the computational system to reconstruct (**208**) a magnetic resonance image for each of the predetermined number of k-space bins to provide a respiratory-state resolved magnetic resonance image (**150**).

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Background/Summary

FIELD OF THE INVENTION

[0001] The invention relates to magnetic resonance imaging, in particular to respiratory-state magnetic resonance imaging.

BACKGROUND OF THE INVENTION

[0002] A large static magnetic field is used by Magnetic Resonance Imaging (MRI) scanners to align the nuclear spins of atoms as part of the procedure for producing images within the body of a patient. This large static magnetic field is referred to as the B0 field.

[0003] During an MRI scan, Radio Frequency (RF) pulses generated by one or more transmitter coils cause a called B1 field. Additionally applied gradient fields and the B1 field cause perturbations to the effective local magnetic field. RF signals are then emitted by the nuclear spins and detected by one or more receiver coils. These RF signals are recorded as k-space data and are used to reconstruct the MR images, typically using a Fourier or other sparse transform. By repeatedly acquiring the k-space data respiratory-state resolved magnetic resonance images may be acquired. If the k-space data is acquired for a three-dimensional or multi-slice two-dimensional space, then the respiratory-state resolved magnetic resonance images are typically referred to as 4D or four-dimensional magnetic resonance images.

[0004] United States patent application publication US 2020/0150206 A1 discloses a method of MR imaging of an object. MR imaging uses the stack-of-stars acquisition scheme with an enhanced control of the contrast of the reconstructed MR image. The method of the invention comprises the steps of: a) generating MR signals by subjecting the object to a number of shots of a multi-echo imaging sequence comprising RF pulses and switched magnetic field gradients, wherein a train of echo signals is generated by each shot; b) acquiring the echo signals according to a stack-of-stars (i.e. a hybrid radial 3D acquisition scheme wherein radial sampling is performed in each slice plane and phase encoding is performed along the slice encoding direction) or stack-of-spirals scheme, wherein the echo signals are acquired as radial or spiral k-space profiles arranged at different positions along a slice direction in k-space, wherein echo signals from different k-space slices are acquired in each shot of the imaging sequence and wherein the echo signals are acquired from each k-space slice with different relaxation time weightings; and c) reconstructing at least one MR image of a desired contrast from the acquired echo signals using a k-space weighted image contrast (KWIC) filter. Moreover, the invention relates to a MR device and to a computer program for a MR device.

[0005] The publication Grimm R ET AL, “Self-gating Reconstructions of Motion and Perfusion for Free-breathing T1-weighted DCE-MRI of the Thorax Using 3D Stack-of stars GRE Imaging”, 20 Apr. 2012, describes a retrospective self-gating technique that can be employed to extract information from a single continuous free-breathing scan acquired with a stack-of-stars 3D VIBE sequence. According to the publication, this technique can be used to compute different sliding-window reconstructions that show a complete ‘virtual’ respiratory cycle with high spatial resolution, or, alternatively, a time series of the contrast-enhancement at a specified level of inspiration and with high temporal resolution.

[0006] The publication ROBERT GRIMM ET AL: “Self-gated MRI motion modeling for respiratory motion compensation in integrated PET/MRI”, MEDICAL IMAGE ANALYSIS, DOI: 10.1016/j.media.2014.08.003, describes how MRI self-gating is applied to perform respiratory gating of the MRI data and simultaneously acquired PET raw data. After gated PET reconstruction, the MRI motion model is used to fuse the individual gates into a single, motion-compensated volume with high signal-to-noise ratio (SNR).

[0007] The United States patent application publication US 2016/0324500 A1 describes utilizing a continuous spoiled gradient echo sequence with 3D radial trajectory and 1D self-gating for respiratory motion detection. In certain embodiments, data acquired are retrospectively sorted into different respiratory phases based on their temporal locations within a respiratory cycle, and each phase is reconstructed via a self-calibrating CG-SENSE program.

[0008] WIPO patent application publication WO 2020/214725 A1 describes a method for proton resonance frequency shift (PRF) and T1-based temperature mapping using a magnetic resonance imaging (MRI) system includes acquiring, using the MRI system, a set of magnetic resonance (MR) data from a region of interest of a subject by performing a variable-flip-angle multi-echo gradient-echo 3D stack-of-radial pulse sequence. The pulse sequence is configured to acquire radial k-space data in a plurality of segments, each segment acquired with each of a plurality of flip angles.

[0009] The publication Stemkens Bjorn ET AL: “Optimizing 4-Dimensional Magnetic Resonance Imaging Data Sampling for Respiratory Motion Analysis of Pancreatic Tumors”, INTERNATIONAL JOURNAL OF RADIATION: ONCOLOGY BIOLOGY PHYSICS., DOI: 10.1016/j.ijrobp.2014.10.050, describes a study aimed to determine the optimum sampling strategy for retrospective reconstruction of 4-dimensional (4D) MR data for nonrigid motion characterization of tumor and organs at risk for radiation therapy purposes. 2 surrogate signals (external respiratory bellows and internal MRI navigators) and 2 MR sampling strategies (Cartesian and radial) are compared in terms of image quality and robustness.

SUMMARY OF THE INVENTION

[0010] The invention provides for a medical system, a computer program product, and a method in the independent claims. Embodiments are given in the dependent claims.

[0011] Embodiments may provide for an improved means of making respiratory state resolved magnetic resonance images by binning not only for the respiratory position but also using the inhalation or exhalation state of the subject to assign bins. The motion of tumor in a subject's thoracic, lung, abdomen (liver, pancreas and kidney) or heart region may have a different position depending whether the subject is inhaling or exhaling. This improved binning method may enable the reconstruction of improved respiratory-state resolved magnetic resonance images.

[0012] A respiratory-state resolved magnetic resonance image may, for example, be useful for radiotherapy planning. Respiration-induced motion of the abdomen and thorax can hinder the accurate determination of treatment margins for target tumors, as may be useful for radiotherapy planning. Techniques using breath holds and abdominal compression can have consequences for patient comfort and treatment plan reproducibility. To overcome these challenges 4D MRI has been introduced that captures organ or tumor motion in the abdomen and thorax under free-breathing with automatic respiratory state sorting in bins using external or intrinsic breathing signal during the entire acquisition time. Target region, organs at risk may be better targeted or avoided based on breathing states.

[0013] As used herein, a respiratory-state resolved magnetic resonance image encompasses a cyclical time-resolved magnetic resonance image. In other words, a respiratory-state resolved magnetic resonance image is a time series of magnetic resonance images that track an entire respiratory cycle of a subject such that the image is resolved for a temporal respiratory cycle and is not resolved for the position of the subject. A respiratory-state resolved magnetic resonance image may therefore captures hysteresis is the motion of a subject during a respiratory cycle.

[0014] In one aspect the invention provides for a medical system that comprises a magnetic resonance imaging system that is configured for acquiring k-space data for a field of view of a subject. The magnetic resonance imaging system is configured for providing a respiratory signal. The respiratory signal is descriptive of a respiratory position of the subject. The respiratory signal is further descriptive of inhalation and exhalation of the subject. In other words, the respiratory signal not only details the position of the subject but whether the subject is in the process of inhaling or exhaling. Having a respiratory signal that provides this information may be beneficial because the position of the organs may be slightly different when the subject is inhaling or exhaling for a particular respiratory position.

[0015] Respiratory-state binning using the inhalation or exhalation state can be done by sorting on the amplitude of the respiratory signal with the so-called amplitude binning method or the respiratory phase aligning end-expiration or inspiration with the so-called phase binning method.

[0016] The medical system further comprises a memory that stores machine-executable instructions and pulse sequence commands. The pulse sequence commands are configured to control the magnetic resonance imaging system to perform the acquisition of the k-space data as multiple acquisitions of k-space data according to a multi-dimensional k-space sampling pattern. The pulse sequence commands are further configured such that the multi-dimensional k-space sampling pattern is varied between each individual k-space data acquisition of the multiple acquisitions of the k-space data. So in other words, the multi-dimensional k-space sampling pattern is changed each time an individual k-space data acquisition is made. Typically, this may be done by rotating the multi-dimensional k-space sampling pattern. A common way of doing this is rotating a particular k-space sampling pattern by the so-called golden angle. This may enable the free acquisition of k-space data which can then be later binned. Because of the rotation or change in the multi-dimensional k-space sampling pattern it is very unlikely that prior acquisitions will overlap each other exactly. This enables the buildup of k-space data in various bins.

[0017] The medical system further comprises a computational system. The computational system may be configured for controlling the magnetic resonance imaging system. Execution of the machine-executable instructions causes the computational system to repeatedly perform the individual acquisition of k-space data by controlling the magnetic resonance imaging system with the pulse sequence commands. Execution of the machine-executable instructions further causes the computational system to repeatedly receive the respiratory signal during the individual acquisition of the k-space data. For example, the individual acquisition of k-space data may be stamped or labeled with a particular respiratory signal including both the respiratory position as well as if the subject is in the process of inhaling or exhaling. Execution of the machine-executable instructions further causes the computational system to repeatedly bin the individually acquired k-space data into one of the predetermined number of k-space bins using the respiratory signal and inhalation or exhalation of the subject.

[0018] Execution of the machine-executable instructions further causes the computational system to reconstruct a magnetic resonance image for each of the k-space bins to provide a temporally respiratory-state resolved magnetic resonance image of the field of view. This embodiment may be for example beneficial because the inhalation and exhalation of the subject represents a hysteresis movement of the subject. Binning the k-space data according to just respiratory position may result in a lower quality, blurred magnetic resonance image. The improved respiratory-state resolved magnetic resonance image may be useful for providing sharper magnetic resonance images distinguishing tumors and organs at risk over the whole breathing cycle for radiotherapy planning and treatment.

[0019] The respiratory signal may be descriptive of the inhalation and exhalation of a subject in a variety of ways. For example, a derivative of the respiratory signal may be used to indicate the inhalation and exhalation. In other cases, the velocity, which is essentially equivalent to the derivative of the respiratory signal, may also be used. In addition, detecting the respiratory signal in feet head and anterior posterior direction (right left motion typically is negligible) can determine inhalation and exhalation hysteresis effects more quantitatively providing a more precise estimate of the breathing hysteresis effects and outliers, including motion vector fields.

[0020] Execution of the machine-executable instructions further causes the computational system to repeatedly bin the individually acquired k-space data into a respiratory position histogram. The predetermined number of k-space bins is resolved in terms of position of the subject as well as inhalation and exhalation of the subject. The respiratory position histogram is resolved for the position of the subject and does not differentiate in terms of inhalation and exhalation of the subject. Execution of the machine-executable instructions further causes the computational system to identify respiratory outliers using the respiratory position histogram. The respiratory-state resolved magnetic resonance image is corrected for the respiratory outliers. Respiratory outlier may arise from sudden changes in breathing like sighing, deep in- and expiration, coughing. This correction of the respiratory-state resolved magnetic resonance image may be done in several different ways. In one way, the respiratory outliers are removed from the predetermined number of k-space bins. In this case, they do not contribute to the reconstruction of the respiratory-state resolved magnetic resonance image at all. In other cases, the respiratory-state resolved magnetic resonance image may be reconstructed and the various k-space samples may be given different weighting factors. One way of minimizing the effect of the respiratory outliers would be to give a low or lower weighting value to those particular samples in the predetermined number of k-space bins. In either case, the effect is to improve the quality of the respiratory-state resolved magnetic resonance image.

[0021] In another embodiment the multi-dimensional k-space sampling pattern is configured for oversampling a central k-space region. This may be particularly beneficial because this oversampling of the central k-space region may be used in several different ways. In one example, this oversampling of the central k-space region may be useful in correcting for motion of the subject. For example, samples that have higher levels of motion can have their central k-space region given a lower weighting factor or even removed. The k-space data outside of the central k-space region may then be used for reconstructing images. In another example, this oversampling may be used for performing a self-navigation or navigation.

[0022] In another embodiment the multi-dimensional k-space sampling pattern is a variable density stack of stars sampling pattern.

[0023] In another embodiment the multi-dimensional k-space sampling pattern is a variable density spiral sampling pattern.

[0024] In another embodiment the multi-dimensional k-space sampling pattern is a (spiral) Cartesian sampling pattern.

[0025] In another embodiment the multi-dimensional k-space sampling pattern is a variable density sampling pattern.

[0026] In another embodiment the multi-dimensional k-space sampling pattern is a two-dimensional variable density sampling pattern.

[0027] In another embodiment the multi-dimensional k-space sampling pattern is a two-dimensional propeller sampling pattern. A multi-slice two-dimensional propeller sampling with for example a highly desired T2 contrast has an intrinsic high oversampling of the central k-space. Using the respiratory information, the oversampled central k-space can be filtered out using KWIC filtering extracting 4D respiratory-state resolved T2 images within the same multi-slice two-dimensional propeller overview scan.

[0028] In another embodiment the multi-dimensional k-space sampling pattern is a Koosh ball sampling pattern.

[0029] In another embodiment the multi-dimensional k-space sampling pattern is a floret sampling pattern.

[0030] In another embodiment the multi-dimensional k-space sampling pattern is a spiral sampling pattern.
[0031] In another embodiment, execution of the machine executable instructions is configured to cause prospective adaptation of the sampling patterns to get a uniform sampling over the respiratory states using for example the golden angle regime.
[0032] In another embodiment the medical instrument is configured to provide breathing guidance for distribution over respiratory states. The breathing guidance would guide the patient to breath consistently covering all respiratory states in a uniform, equally distributed, sinusoidal way reducing drifts and outliers.
[0033] In another embodiment execution of the machine executable instructions further causes the computational system to perform real-time reconstruction of the individual acquisitions of k-space data to visualize the breathing motion in real-time next to the respiratory-state resolved magnetic resonance image. By real-time the visualization of the breathing motion is appears to be synchronized with respiratory motion of the subject being image. The delay in real-time may for example be on the order of ½ second or the time to make an acquisition of the individually acquired k-space data.
[0034] In another embodiment execution of the machine-executable instructions further causes the computational system to apply a k-space weighting filter to the individual acquisitions of k-space data in the predetermined number of k-space bins before reconstructing the magnetic resonance image for each of the k-space bins. The k-space filter is configured to apply a higher weighting value to the central k-space region than outside the central k-space region.
[0035] This embodiment may be beneficial because the k-space was sampled at a higher rate in the central region. For this region the samples in the central region may be minimized. This may for example be beneficial in reducing the effects of motion within a bin sharpening and defining the breathing state.
[0036] In another embodiment execution of the machine-executable instructions further causes the computational system to adjust the boundaries of the predetermined number of k-space bins. The binning of the individually acquired k-space data could be such that each of the predetermined number of k-space bins has, within a predetermined difference, the same number of individually acquired k-space data. This embodiment may be beneficial because bins may have more k-space than others, so this may for example result in particular bins having a lower signal-to-noise or more artifacts due to undersampling. Equally sized bins may help improve the overall quality of the respiratory-state resolved magnetic resonance image. Another example could be that neighboring bins overlap and share profiles.
[0037] In another embodiment the individual acquisitions of k-space data are assigned a weighting by the k-space weighting filter according to a location determined by the respiratory signal. For example, the center of the bin may be given a particular coordinate according to the respiratory signal. The individually acquired k-space data may vary according to their position within the bin according to this coordinate. K-space samples that are closer to the center of the bin or to any other chosen location of the bin may be given a higher weighting factor. This for example may be useful in reducing the effects of motion within a bin reducing blurring. It however also allows to define the encoded breathing state. End expiration and inspiration encoding states could be defined at the outermost breathing states opposed to the center of a bin.
[0038] In case of overlapping bins, profiles could be shared with the k-space filter applied using the shared profiles only for higher k-space.
[0039] In another embodiment the k-space weighting filter is a k-space weighting image contrast filter. A k-space weighting image contrast filter is also known as a KWIC filter in much of the literature. The use of a k-space weighting image contrast filter may be useful in that it minimizes the central region of radial k-space opposed to the peripheral region. This for example may be useful in constructing magnetic resonance images with reduced motion artifacts or blurring.

[0040] In another embodiment the k-space weighting filter is configured for performing a phase correction to correct for motion and/or increased image sharpness according to a gradient entropy measure. This may be beneficial because it may provide for an improved quality of the respiratory-state resolved magnetic resonance image.

[0041] The image data reconstructed from the k-space data in the predetermined number of bins can be post processed by different techniques for example providing an average (MIP), a mid breathing position or a vector field representation.

[0042] In another embodiment, execution of the machine executable instructions further causes the computational system to calculate extreme respiratory-state resolved image data by calculating a modulus averaging or a complex averaging of extreme inspiration and expiration respiratory states in the respiratory-state resolved magnetic resonance image. The extreme inspiration and expiration respiratory states can be end inspiration, expiration states, but can be also an automated selection of extreme states by gradient entropy comparison and/or selection of pre-selected gating window settings. This may be beneficial because it may provide a model of the end respiratory states of a subject which can be used for radiotherapy planning. This may be useful in constructing radiotherapy control commands which are less likely to cause the irradiation of vital organs of the subject. One could construct the radiotherapy control commands using the respiratory state-resolved segmentation and then check if the extreme inspiration state and/or the extreme expiration state results in unwanted irradiation of vital organs or regions of the subject.

[0043] An average of extreme expiration and inspiration positions are suggested. Tumor and organs of risk movement during breathing is represented in a simple but efficient way showing the clinical information but also the motion margin from breathing for radiation therapy planning (quick ITV). One example of an average of extreme expiration and inspiration positions could be an average of end expiration and end inspiration respiratory-states. Another example is selection of extreme states by a gradient entropy measure and an average of this extreme states. Another example is to take pre-selected gating window settings in inspiration/expiration states into account and provide an average of extreme breathing-states within the selected gating window settings. Vice versa a proposed gating setting could be derived from analysis of these extreme breathing-states optimizing radiation therapy. MIPs, surface rendering and other 3D representation of this average data set can be provided for a simple, intuitive representation. Averaging preferably would be done using modulus averaging, however also complex averaging is possible.

[0044] In another embodiment the memory further stores a segmentation algorithm configured for outputting a respiratory-state resolved segmentation in response to receiving the respiratory-state resolved magnetic resonance image. For example, a segmentation algorithm may be applied to each of the individual images which make up the respiratory-state resolved magnetic resonance image. Assembling this collection of segmentations may then result in the respiratory-state resolved segmentation. Execution of the machine-executable instructions further causes the computational system to provide the respiratory-state resolved segmentation of the respiratory-state resolved magnetic resonance image by inputting the respiratory-state resolved magnetic resonance image into the segmentation algorithm. This embodiment may be beneficial because the segmentation may be useful for applications such as radiotherapy planning when a subject is breathing.

[0045] In another embodiment the memory further stores a radiation therapy system control module configured for outputting control commands for a radiotherapy system in response to receiving the respiratory-state resolved segmentation and a radiotherapy plan as input. Execution of the machine-executable instructions further causes the computational system to provide the radiotherapy control commands in response to inputting the respiratory-state resolved segmentation and the radiotherapy plan into the radiotherapy system control module.

[0046] In another embodiment the medical system further comprises the radiotherapy system. Execution of the machine-executable instructions further causes the computational system to control the radiotherapy system to irradiate the subject using the radiotherapy control commands.

The irradiation of the subject is at least partially controlled or gated using the respiratory signal.
[0047] The radiotherapy system may be implemented in a variety of ways. In some instances, the radiotherapy system is integrated with the magnetic resonance imaging system and the system is capable of performing magnetic resonance imaging before, during and after the radiotherapy. For example, it may be a magnetic resonance image guided LINAC. In other examples, the magnetic resonance imaging system and the radiation therapy system may be separate. For example, the magnetic resonance imaging may be performed at one location and then the subject may be transported to another location and the respiratory signal may be measured on the radiation therapy system also. The multi-dimensional segmentation may still be useful at the second location where only the radiation therapy system is present. In the case where there are two separate locations between the magnetic resonance imaging system and the radiation therapy system restraints and/or vacuum mattress and/or corset may be used to hold the subject in a particular place.
[0048] In another embodiment the magnetic resonance image for each of the k-space bins is reconstructed using compressed sensing. This may be particularly beneficial because if there are fewer k-space samples in some bins it may enable a high quality respiratory-state resolved magnetic resonance image to be constructed nonetheless.
[0049] In another embodiment the magnetic resonance image for each of the predetermined number of k-space bins is reconstructed using an artificial intelligence-based reconstruction. Likewise, with this embodiment, if there is undersampling of the k-space the use of an artificial intelligence-based reconstruction may be useful for improving the image quality.
[0050] In another embodiment the motion signal is a respiratory belt signal.
[0051] In another embodiment the motion signal is an intrinsic k-space navigator. An internal source using a startup cycle can be used to extract quantitative motion information allowing for an accurate motion estimate without the need for a respiratory belt placement. Hereby before each shot, a startup echo of the central k space profile allows extracting quantitative motion information from the projection data (in AP, RL and SI as illustrated below) using a band pass filtered center of mass calculation.
[0052] In another embodiment the motion signal is a respiratory tube signal. For example, the subject may be breathing through a tube or may be provided with a means of assisting respiration. The respiratory tube signal may then be a measure of the breathing assistance and/or the actual respiration measured from the subject.
[0053] In another embodiment the motion signal is a k-space navigator.
[0054] In another embodiment the motion signal is an image navigator. For example, individual acquisitions of the k-space data may be reconstructed and this image, although it may not be of sufficient quality for clinical use, may nonetheless identify anatomical locations such that it can provide navigation.
[0055] In another embodiment the motion signal is a noise navigator.
[0056] In another embodiment the motion signal is a camera-based motion signal. For example, there may be a camera mounted to observe the subject during the acquisition of the k-space data and observation of the motion can be used to provide a navigator signal.
[0057] In another embodiment the respiratory-state resolved magnetic resonance image is corrected for the respiratory outliers by deleting outliers from the k-space bins or by giving respiratory outliers a predetermined weighting value during reconstruction of the magnetic resonance image for each of the predetermined number of k-space bins.
[0058] In another aspect the invention provides for a computer program product that comprises machine-executable instructions for execution by a computational system controlling a medical system. In some examples the computer program product may also comprise the pulse sequence commands. The medical system comprises a magnetic resonance imaging system configured for acquiring k-space data for a field of view of the subject. The magnetic resonance imaging system is configured for providing a respiratory signal. The respiratory signal is descriptive of a respiratory

position of the subject. The respiratory signal is further descriptive of inhalation and exhalation of the subject.
[0059] Execution of the machine-executable instructions causes the computational system to repeatedly perform the individual acquisition of k-space data by controlling the magnetic resonance imaging system with the pulse sequence commands. The pulse sequence commands are configured to perform the acquisition of the individual acquisitions of k-space data according to a multi-dimensional k-space sampling pattern. The pulse sequence commands are configured such that the multi-dimensional k-space sampling pattern is varied between each individual k-space data acquisition of the multiple acquisitions of k-space data. Execution of the machine-executable instructions further causes the computational system to repeatedly receive the respiratory signal during the acquisition of the individual acquisitions of k-space data.
[0060] Execution of the machine-executable instructions further causes the computational system to repeatedly bin the individually acquired k-space data into one of the predetermined number of k-space bins using the respiratory signal and inhalation or exhalation of the subject. Execution of the machine-executable instructions further causes the computational system to reconstruct a magnetic resonance image for each of the k-space bins to provide a respiratory-state resolved magnetic resonance image of the field of view.
[0061] Execution of the machine executable instructions causes the computational system to repeatedly bin the individually acquired k-space data into a respiratory position histogram, wherein the machine executable instructions causes the computational system to identify respiratory outliers using the respiratory position histogram, and wherein the respiratory-state resolved magnetic resonance image is corrected for the respiratory outliers.
[0062] In another aspect the invention provides for a method of operating a medical system. The medical system comprises a magnetic resonance imaging system configured for acquiring k-space data for a field of view of the subject. The magnetic resonance imaging system is configured for providing a respiratory signal. The respiratory signal is descriptive of a respiratory position of the subject. The respiratory signal is further descriptive of inhalation and exhalation of the subject. The method comprises repeatedly performing the individual acquisition of k-space data by controlling the magnetic resonance imaging system with the pulse sequence commands. The pulse sequence commands are configured to perform the acquiring of the k-space data as multiple acquisitions of k-space data according to a multi-dimensional k-space sampling pattern. The pulse sequence commands are configured such that the multi-dimensional k-space sampling pattern is varied between each individual k-space data acquisition of the multiple acquisitions of k-space data.
[0063] The method comprises repeatedly receiving the respiratory signal during acquisition of the individual acquisitions of the k-space data. The method further comprises repeatedly binning the individually acquired k-space data into one of a predetermined number of k-space bins using the respiratory signal and inhalation or exhalation of the subject. The method further comprises reconstructing a magnetic resonance image for each of the k-space bins to provide a respiratory-state resolved magnetic resonance image of the field of view.
[0064] The method comprises repeatedly binning the individually acquired k-space data into a respiratory position histogram, identifying respiratory outliers using the respiratory position histogram, and correcting the respiratory-state resolved magnetic resonance image for the respiratory outliers.
[0065] It is understood that one or more of the aforementioned embodiments of the invention may be combined as long as the combined embodiments are not mutually exclusive.
[0066] As will be appreciated by one skilled in the art, aspects of the present invention may be embodied as an apparatus, method or computer program product. Accordingly, aspects of the present invention may take the form of an entirely hardware embodiment, an entirely software embodiment (including firmware, resident software, micro-code, etc.) or an embodiment combining software and hardware aspects that may all generally be referred to herein as a “circuit,”

"module" or "system." Furthermore, aspects of the present invention may take the form of a computer program product embodied in one or more computer readable medium(s) having computer executable code embodied thereon.

[0067] Any combination of one or more computer readable medium(s) may be utilized. The computer readable medium may be a computer readable signal medium or a computer readable storage medium. A 'computer-readable storage medium' as used herein encompasses any tangible storage medium which may store instructions which are executable by a processor or computational system of a computing device. The computer-readable storage medium may be referred to as a computer-readable non-transitory storage medium. The computer-readable storage medium may also be referred to as a tangible computer readable medium. In some embodiments, a computer-readable storage medium may also be able to store data which is able to be accessed by the computational system of the computing device. Examples of computer-readable storage media include, but are not limited to: a floppy disk, a magnetic hard disk drive, a solid-state hard disk, flash memory, a USB thumb drive, Random Access Memory (RAM), Read Only Memory (ROM), an optical disk, a magneto-optical disk, and the register file of the computational system. Examples of optical disks include Compact Disks (CD) and Digital Versatile Disks (DVD), for example CD-ROM, CD-RW, CD-R, DVD-ROM, DVD-RW, or DVD-R disks. The term computer readable-storage medium also refers to various types of recording media capable of being accessed by the computer device via a network or communication link. For example, data may be retrieved over a modem, over the internet, or over a local area network. Computer executable code embodied on a computer readable medium may be transmitted using any appropriate medium, including but not limited to wireless, wire line, optical fiber cable, RF, etc., or any suitable combination of the foregoing.

[0068] A computer readable signal medium may include a propagated data signal with computer executable code embodied therein, for example, in baseband or as part of a carrier wave. Such a propagated signal may take any of a variety of forms, including, but not limited to, electro-magnetic, optical, or any suitable combination thereof. A computer readable signal medium may be any computer readable medium that is not a computer readable storage medium and that can communicate, propagate, or transport a program for use by or in connection with an instruction execution system, apparatus, or device.

[0069] 'Computer memory' or 'memory' is an example of a computer-readable storage medium. Computer memory is any memory which is directly accessible to a computational system. 'Computer storage' or 'storage' is a further example of a computer-readable storage medium. Computer storage is any non-volatile computer-readable storage medium. In some embodiments computer storage may also be computer memory or vice versa.

[0070] A 'computational system' as used herein encompasses an electronic component which is able to execute a program or machine executable instruction or computer executable code. References to the computational system comprising the example of "a computational system" should be interpreted as possibly containing more than one computational system or processing core. The computational system may for instance be a multi-core processor. A computational system may also refer to a collection of computational systems within a single computer system or distributed amongst multiple computer systems. The term computational system should also be interpreted to possibly refer to a collection or network of computing devices each comprising a processor or computational systems. The machine executable code or instructions may be executed by multiple computational systems or processors that may be within the same computing device or which may even be distributed across multiple computing devices.

[0071] Machine executable instructions or computer executable code may comprise instructions or a program which causes a processor or other computational system to perform an aspect of the present invention. Computer executable code for carrying out operations for aspects of the present invention may be written in any combination of one or more programming languages, including an object-oriented programming language such as Java, Smalltalk, C++ or the like and conventional procedural programming languages, such as the "C" programming language or similar programming languages and compiled into machine executable instructions. In some instances, the computer executable code may be in the form of a high-level language or in a pre-compiled form and be used in conjunction with an interpreter which generates the machine executable instructions on the fly. In other instances, the machine executable instructions or computer executable code may be in the form of programming for programmable logic gate arrays.

[0072] The computer executable code may execute entirely on the user's computer, partly on the user's computer, as a stand-alone software package, partly on the user's computer and partly on a remote computer or entirely on the remote computer or server. In the latter scenario, the remote computer may be connected to the user's computer through any type of network, including a local area network (LAN) or a wide area network (WAN), or the connection may be made to an external computer (for example, through the Internet using an Internet Service Provider).

[0073] Aspects of the present invention are described with reference to flowchart illustrations and/or block diagrams of methods, apparatus (systems) and computer program products according to embodiments of the invention. It is understood that each block or a portion of the blocks of the flowchart, illustrations, and/or block diagrams, can be implemented by computer program instructions in form of computer executable code when applicable. It is further under stood that, when not mutually exclusive, combinations of blocks in different flowcharts, illustrations, and/or block diagrams may be combined. These computer program instructions may be provided to a computational system of a general-purpose computer, special purpose computer, or other programmable data processing apparatus to produce a machine, such that the instructions, which execute via the computational system of the computer or other programmable data processing apparatus, create means for implementing the functions/acts specified in the flowchart and/or block diagram block or blocks.

[0074] These machine executable instructions or computer program instructions may also be stored in a computer readable medium that can direct a computer, other programmable data processing apparatus, or other devices to function in a particular manner, such that the instructions stored in the computer readable medium produce an article of manufacture including instructions which implement the function/act specified in the flowchart and/or block diagram block or blocks.

[0075] The machine executable instructions or computer program instructions may also be loaded onto a computer, other programmable data processing apparatus, or other devices to cause a series of operational steps to be performed on the computer, other programmable apparatus or other devices to produce a computer implemented process such that the instructions which execute on the computer or other programmable apparatus provide processes for implementing the functions/acts specified in the flowchart and/or block diagram block or blocks.

[0076] A 'user interface' as used herein is an interface which allows a user or operator to interact with a computer or computer system. A 'user interface' may also be referred to as a 'human interface device.' A user interface may provide information or data to the operator and/or receive information or data from the operator. A user interface may enable input from an operator to be received by the computer and may provide output to the user from the computer. In other words, the user interface may allow an operator to control or manipulate a computer and the interface may allow the computer to indicate the effects of the operator's control or manipulation. The display of data or information on a display or a graphical user interface is an example of providing information to an operator. The receiving of data through a keyboard, mouse, trackball, touchpad, pointing stick, graphics tablet, joystick, gamepad, webcam, headset, pedals, wired glove, remote control, and accelerometer are all examples of user interface components which enable the receiving of information or data from an operator.

[0077] A 'hardware interface' as used herein encompasses an interface which enables the computational system of a computer system to interact with and/or control an external computing device and/or apparatus. A hardware interface may allow a computational system to send control signals or instructions to an external computing device and/or apparatus. A hardware interface may also enable a computational system to exchange data with an external computing device and/or apparatus. Examples of a hardware interface include, but are not limited to: a universal serial bus, IEEE 1394 port, parallel port, IEEE 1284 port, serial port, RS-232 port, IEEE-488 port, Bluetooth connection, Wireless local area network connection, TCP/IP connection, Ethernet connection, control voltage interface, MIDI interface, analog input interface, and digital input interface.

[0078] A ‘display’ or ‘display device’ as used herein encompasses an output device or a user interface adapted for displaying images or data. A display may output visual, audio, and or tactile data. Examples of a display include, but are not limited to: a computer monitor, a television screen, a touch screen, tactile electronic display, Braille screen,

[0079] Cathode ray tube (CRT), Storage tube, Bi-stable display, Electronic paper, Vector display, Flat panel display, Vacuum fluorescent display (VF), Light-emitting diode (LED) displays, Electroluminescent display (ELD), Plasma display panels (PDP), Liquid crystal display (LCD), Organic light-emitting diode displays (OLED), a projector, and Head-mounted display.

[0080] Medical imaging data is defined herein as being recorded measurements made by a tomographic medical imaging system descriptive of a subject. The medical imaging data may be reconstructed into a medical image. A medical image is defined herein as being the reconstructed two- or three-dimensional visualization of anatomic data contained within the medical imaging data. This visualization can be performed using a computer.

[0081] K-space data is defined herein as being the recorded measurements of radio frequency signals emitted by atomic spins using the antenna of a Magnetic resonance apparatus during a magnetic resonance imaging scan. Magnetic resonance data is an example of tomographic medical image data.

[0082] A Magnetic Resonance Imaging (MRI) image or MR image is defined herein as being the reconstructed two- or three-dimensional visualization of anatomic data contained within the magnetic resonance imaging data. This visualization can be performed using a computer.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0083] In the following preferred embodiments of the invention will be described, by way of example only, and with reference to the drawings in which:

[0084] FIG. **1** illustrates an example of a medical system;

[0085] FIG. **2** shows a flow chart which illustrates a method of using the medical system of FIG. **1**;

[0086] FIG. **3** shows a flow chart which illustrates a further method of using the medical system of FIG. **1**;

[0087] FIG. **4** illustrates a further example of a medical system;

[0088] FIG. **5** shows a flow chart which illustrates a method of using the medical system of FIG. **4**;

[0089] FIG. **6** illustrates a motion hysteresis effect caused by respiration;

[0090] FIG. **7** shows a plot of a k-space intrinsic navigator;

[0091] FIG. **8** illustrates a group of predetermined number of k-space bins **148** and a respiratory position histogram **152**;

[0092] FIG. **9** illustrates a single KWIC filter for weighting k-space data based on position within or relative to a k-space bin;

[0093] FIG. **10** illustrates a group of KWIC filters for multiple k-space bins;

[0094] FIG. **11** illustrates an example of a three-dimensional golden angle stack of stars k-space sampling pattern and a three-dimensional variable density radial stack of stars k-space sampling pattern;

[0095] FIG. **12** shows a multi-slice Propeller k-space sampling pattern **1202**;
[0096] FIG. **13** shows two possible bins and at different respiratory states with the color code illustrating KWIC filter strengths; profiles within the blue margin is weighted strong whereas green and red are weighted much lower; and
[0097] FIG. **14** illustrates contrast weighting of blades with respect to the respective respiratory states in FIG. **13** for k-space and blade composition for a standard propeller k-space sampling pattern. Standard Propeller with no contrast weighting is shown in **1400** and **1402** for k-space and blade composition.

DESCRIPTION OF EMBODIMENTS

[0098] Like numbered elements in these figures are either equivalent elements or perform the same function. Elements which have been discussed previously will not necessarily be discussed in later figures if the function is equivalent.
[0099] FIG. **1** illustrates an example of a medical system **100** that comprises a magnetic resonance imaging system **102** and a computer **130**. The magnetic resonance imaging system **102** comprises a magnet **104**. The magnet **104** is a superconducting cylindrical type magnet with a bore **106** through it. The use of different types of magnets is also possible; for instance it is also possible to use both a split cylindrical magnet and a so called open magnet. A split cylindrical magnet is similar to a standard cylindrical magnet, except that the cryostat has been split into two sections to allow access to the iso-plane of the magnet, such magnets may for instance be used in conjunction with charged particle beam therapy. An open magnet has two magnet sections, one above the other with a space in-between that is large enough to receive a subject: the arrangement of the two sections area similar to that of a Helmholtz coil. Open magnets are popular, because the subject is less confined. Inside the cryostat of the cylindrical magnet there is a collection of superconducting coils.
[0100] Within the bore **106** of the cylindrical magnet **104** there is an imaging zone **108** where the magnetic field is strong and uniform enough to perform magnetic resonance imaging. A field of view **109** is shown within the imaging zone **108**. The magnetic resonance data that is acquired typically acquired for the field of view **109**. A subject **118** is shown as being supported by a subject support **120** such that at least a portion of the subject **118** is within the imaging zone **108** and the field of view **109**.
[0101] Within the bore **106** of the magnet there is also a set of magnetic field gradient coils **110** which is used for acquisition of preliminary magnetic resonance data to spatially encode magnetic spins within the imaging zone **108** of the magnet **104**. The magnetic field gradient coils **110** connected to a magnetic field gradient coil power supply **112**. The magnetic field gradient coils **110** are intended to be representative. Typically magnetic field gradient coils **110** contain three separate sets of coils for spatially encoding in three orthogonal spatial directions. A magnetic field gradient power supply supplies current to the magnetic field gradient coils. The current supplied to the magnetic field gradient coils **110** is controlled as a function of time and may be ramped or pulsed.
[0102] Adjacent to the imaging zone **108** is a radio-frequency coil **114** for manipulating the orientations of magnetic spins within the imaging zone **108** and for receiving radio transmissions from spins also within the imaging zone **108**. The radio frequency antenna may contain multiple coil elements. The radio frequency antenna may also be referred to as a channel or antenna. The radio-frequency coil **114** is connected to a radio frequency transceiver **116**. The radio-frequency coil **114** and radio frequency transceiver **116** may be replaced by separate transmit and receive coils and a separate transmitter and receiver. It is understood that the radio-frequency coil **114** and the radio frequency transceiver **116** are representative. The radio-frequency coil **114** is intended to also represent a dedicated transmit antenna and a dedicated receive antenna. Likewise the transceiver **116** may also represent a separate transmitter and receivers. The radio-frequency coil **114** may also have multiple receive/transmit elements and the radio frequency transceiver **116** may have multiple receive/transmit channels. For example if a parallel imaging technique such as SENSE is performed, the radio-frequency could **114** will have multiple coil elements.

[0103] The transceiver **116** and the gradient controller **112** are shown as being connected to the hardware interface **106** of the computer system **102**. In this example, a respiratory belt **122** is seen as being connected to the thorax of the subject **118**. The respiratory belt **122** provides the respiratory signal **146**. The respiratory signal **146** provides not only the position of the subject's **118** thorax but by looking at the trend or the velocity the inhalation or exhalation of the subject **118** may also be determined.
[0104] The medical system **100** is further shown as comprising a computer **130**. The computer **130** is intended to represent one or more computing or computational devices located at one or more locations. The computer **130** is shown as containing a computational system **132**. The computational system **132** is intended to represent one or more computational systems that could for example be one or more processing cores located at one or more locations. Various combinations of computational systems **132** and/or computers **130** could be connected and work together cooperatively using a network. The computational system **132** is shown as being in communication with a hardware interface **134**, a user interface **136**, and a memory **138**. The hardware interface **134** is an interface which enables the computational system **132** to communicate with and/or control other components of the medical system **100** such as the magnetic resonance imaging system **102**. The user interface **136** is a user interface that enables an operator of the medical system **100** to control and operate the medical system **100**. The memory **138** is intended to represent various types of memory which may be in communication with the computational system **132**.
[0105] The memory **138** is shown as containing machine-executable instructions **140**. The machine-executable instructions contain instructions which enable the computational system **132** to control the magnetic resonance imaging system **102** as well as perform various data and image processing tasks. The memory **138** is further shown as containing pulse sequence commands **142**. The pulse sequence commands **142** are commands or data which may be converted into commands which enable the computational system **132** to control the operation of the magnetic resonance imaging system **102**. Often times the pulse sequence commands **142** are in the form of a timing diagram or timing commands which contain information which commands are used to control the magnetic resonance imaging system **102** at a particular time. The memory **138** is further shown as containing individual acquisitions of k-space data **144** that have been acquired from the magnetic resonance imaging system **102** using the pulse sequence commands **142**. The memory **138** is further shown as containing the respiratory signal **146** that has been measured using the respiratory belt **122**. Although a respiratory belt **122** is shown, various other techniques such as using camera images of the subject **118** or using various k-space navigation techniques may also be used.
[0106] As the individual acquisitions of k-space data **144** are acquired, they may be assigned a particular respiratory signal **146**. The respiratory signal **146** is then used to bin the individual acquisitions of k-space data **144** into a group of a predetermined number of k-space bins **148**. This predetermined number of k-space bins **148** is resolved both in terms of position and the respiratory state of the subject **118**. Therefore, it records the inhalation and exhalation as separate bins although the position may be the same. The memory **138** is further shown as containing a respiratory-state resolved magnetic resonance image **150** that has been reconstructed by making an image for each one of the predetermined number of k-space bins **148**. This may then be assembled into a respiratory-state resolved magnetic resonance image **150**.
[0107] The memory is further shown as containing a respiratory position histogram **152**. The respiratory position histogram **152** is used to bin the individual acquisitions of k-space data **144** except in this case the respiratory state is ignored and is based purely on the position of the subject **118**. The respiratory position histogram **152** is used to identify respiratory outliers or basically when the subject was in an extreme position as measured by the respiratory signal **146**. The respiratory outliers **154** may be removed from the group of predetermined number of k-space bins **148** before the respiratory-state resolved magnetic resonance image **150** is reconstructed.

Alternatively, weighting factors may be used to reduce the influence of the respiratory outliers **154** on the respiratory state resolved magnetic resonance image **150**.

[0108] FIG. **2** shows a flowchart which illustrates a method of operating the medical system **100** of FIG. **1**. First, in step **200**, the individual acquisitions of k-space data **144** are acquired by controlling the magnetic resonance imaging system **102** with the pulse sequence commands **142**. At the same time the respiratory signal **146** is received. The particular individual acquisition of k-space data is then paired with the respiratory signal at that time of acquisition **146**. Next, in step **204**, the individually acquired k-space data **144** is then binned into one of a predetermined number of k-space bins **148** using the respiratory signal **146**. This respiratory signal indicates the position of the subject **118** who is breathing as well as the inhalation or exhalation state. The method then proceeds to step **206**. Step **206** is a decision box, which is ‘is the acquisition finished?’ This may for example be for a predetermined number of acquisitions or it may be such that each of the bins has a minimum number of acquisitions. If the answer is no then the method repeats back to step **200** and another individual acquisition of k-space data is acquired and binned. If the answer is yes, the method proceeds to step **208**. In step **208** the computational system reconstructs a magnetic resonance image for each of the k-space bins **148** to provide a respiratory-state resolved magnetic resonance image **150**.

[0109] FIG. **3** illustrates a further method of operating the medical system of FIG. **1**. The method illustrated in FIG. **3** is similar to the method illustrated in FIG. **2**. In FIG. **3** the method starts with steps **200**, **202**, and **204** as was illustrated in FIG. **2**. Next, in step **300**, the individually acquired k-space data **144** is additionally binned into the respiratory position histogram **152**. The method then proceeds to step **206** as was illustrated in FIG. **2**. When all of the acquisitions are finished the method proceeds to step **302**. In step **302**, the respiratory outliers **154** are identified in the respiratory position histogram **152**. After the respiratory outliers **154** are identified, the method proceeds to step **208**, where again the magnetic resonance image for each of the k-space bins is reconstructed. However, this time the respiratory-state resolved magnetic resonance image **150** is corrected for the respiratory outliers **154**. This could for example involve removing respiratory outliers **154** from the group of predetermined number of k-space bins **148** or assigning the respiratory outliers **154** a reduced weighting so that they affect the respiratory-state resolved magnetic resonance image **150** less.

[0110] FIG. **4** illustrates a further example of a medical system **400**. The medical system **400** depicted in FIG. **4** is similar to that in FIG. **1** except that it additionally comprises a radiation therapy system **402**. The radiation therapy system **402** comprises a gantry **404** and a radiotherapy source **406**. The gantry **404** is for rotating the radiotherapy source **406** about an axis of gantry rotation or rotational axis **414**. Adjacent to the radiotherapy source **406** is a collimator **408**.

[0111] The magnet **104** shown in this embodiment is a standard cylindrical superconducting magnet. The magnet **104** has a cryostat **410** with superconducting coils **412** within it. A split magnet may also be used instead.

[0112] Within the subject **118** there is a target zone **418**. The axis of gantry rotation **414** is coaxial in this particular embodiment with the cylindrical axis of the magnet **104**. The radiation source **406** is aimed at the axis of rotation **414** such that the radiation source has a target volume about the axis of the rotation **140**.

[0113] The subject support **120** has been positioned such that the target zone **418** lies on the axis **414** of gantry rotation. The radiation source **406** is shown as generating a radiation beam **416** which passes through the collimator **408** and through the target zone **418**. As the radiation source **406** is rotated about the axis **414** the target zone **418** will always be targeted by the radiation beam **416**. The radiation beam **416** passes through the cryostat **410** of the magnet **104**. The magnetic field gradient coil may have a gap which separate the magnetic field gradient coil into two sections. If present, this gap reduces attenuation of the radiation beam **416** by the magnetic field gradient coil **110**. In some embodiments the radio frequency coil **114** may also have gaps or be separated to reduce attenuation of the radiation beam **416**.

[0114] The memory **138** is further shown as containing a segmentation algorithm **420**. The segmentation algorithm **420** may be used to segment the individual images that make up the respiratory-state resolved magnetic resonance image **150** and be used to generate a respiratory-state resolved segmentation **422**. The respiratory-state resolved segmentation **422** could for example identify the target location within the subject **118** as well as critical organs which should not be irradiated. Having these in a respiratory-state resolved fashion may be useful in that it may provide for less damage to the subject **118** during irradiation. The memory **138** is shown as containing the respiratory-state segmentation **422** after segmenting the respiratory-state resolved magnetic resonance image **150** with the segmentation algorithm **420**. The memory **138** is further shown as containing a radiation therapy system control module **424**. The radiation therapy system control module **424** is configured for outputting radiotherapy control commands **428** in response to receiving a radiation therapy plan **426** and the respiratory-state resolved segmentation **422**. The radiation therapy plan **426** and the radiotherapy control commands **428** are shown as being stored in the memory **138**.

[0115] In this example, a respiratory belt is not shown. However, the respiratory signal **146** may for example be derived from the individual acquisitions of k-space data **144**, for example, using a self-navigation technique.

[0116] FIG. **5** shows a flowchart which illustrates a method of operating the medical system **400** of FIG. **4**. The method in FIG. **5** is similar to that as illustrated in FIG. **3**; in fact the method proceeds in performing the steps of FIG. **3**. When the method in FIG. **3** ends in step **208** additional steps are performed. After step **208** is performed, in step **500** the respiratory-state resolved segmentation **422** is provided by inputting the respiratory-state resolved magnetic resonance image **150** into the segmentation algorithm **420**. Next, in step **502**, the radiotherapy control commands **428** are generated by inputting the radiation therapy plan **426** and the respiratory-state resolved segmentation **422** into the radiation therapy system control module **424**. Finally, in step **504**, the radiation therapy system **402** is controlled to irradiate the subject **118** by controlling it with the radiotherapy control commands **428**. It should be noted that in some examples the respiratory signal **146** is acquired during execution of the radiotherapy control commands **428** and the respiratory signal **146** may be used, for example, to gate or adjust the radiotherapy control commands, possibly in real time. Motion robustness may likely be improved by respiratory soft gating.

[0117] One type of multi-dimensional k-space acquisition may be performed using 4D radial stack of stars. 4D radial stack of stars based on respiratory binning offers several promising advantages for radiation therapy planning and motion management like significantly higher robustness to motion, benign aliasing artifacts and retrospective respiratory binning possibilities.

[0118] Despite the benefits, current technology still does not provide the temporal and spatial fidelity required for 4D motion management, showing in not distinguishing breathing hysteresis effects showing in streaking and signal fluctuations. Distinguishing respiratory hysteresis effects are important for MR Radiotherapy since the treated area may move differently between inspiration to expiration or expiration to inspiration respiratory states.

[0119] Some examples may provide for an improve multi-dimensional or 4D binning scheme.

[0120] Examples may comprise one or more of the following features: [0121] Acquiring 3D k-space with a temporally interleaved oversampling of the central k-space preferably with a 3D variable density radial stack of stars sampling [0122] Detecting and classifying respiratory states distinguishing inspiration to expiration and expiration to inspiration respiratory states and breathing hysteresis effects [0123] Providing a respiratory histogram separating inspiration to expiration and expiration to inspiration respiratory states [0124] Removing respiratory outliers or weighting them with a low weight [0125] Sorting and binning the acquired data with respect to the detected and classified respiratory states [0126] Applying a k-space weighted filter in the respiratory state domain, weighting the oversampled central k-space stronger at equidistant respiratory states

[0127] The invention proposal suggests an optimal binning scheme as illustrated in FIGS. **4** to **6**.

[0128] FIG. **6** is used to illustrate a hysteresis effect for tumor motion when a subject breathes. There is a magnetic resonance image **600** shown. Within the image **600** is a segmentation **602** of a tumor. In this particular example, the position of the tumor **602** was noted for ten different locations along the phase trajectory of the subject's breathing. The plot **604** locates the centroid of the tumor **602** in the TM plane as a function of respiratory states. It can be seen that the tumor trajectory has a hysteresis effect and has a different location for inhalation and exhalation.

[0129] In FIGS. **7** and **8**, the respiratory data is divided into eight different respiratory states. FIG. **7** shows a plot of a k-space intrinsic navigator **700**. An expanded view of the k-space intrinsic navigator for the box **710** is shown below. The k-space intrinsic navigator **700** is shown as a function of time **712** and navigator value **714**. The navigator is divided into eight portions or bins: **701** represents respiratory state or bin 1, **702** represents respiratory state or bin 2, **703** represents respiratory state or bin 3 and **704** represents respiratory state or bin 4. Bins **701**, **702**, **703**, and **704** represent the inhalation of the subject. Respiratory state or bin **705** represents respiratory state or bin 5, **706** represents respiratory state or bin 6, **707** represents respiratory state or bin 7 and **708** represents respiratory state or bin 8. Bins **705**, **706**, **707**, and **708** represent the exhalation of the subject.

[0130] FIG. **8** illustrates a group of predetermined number of k-space bins **148** and a respiratory position histogram **152** that were sorted using the navigator as illustrated in FIG. **7**. The predetermined number of k-space bins **148** can be shown as containing k-space data for each of the eight respiratory states or bins **701-708**. Additionally, there are some respiratory outliers **154** which are not used to reconstruct the respiratory-state resolved magnetic resonance image **150**. To reconstruct the respiratory-state resolved magnetic resonance image **150** an image for each of the bins **701-708** is reconstructed.

[0131] The respiratory position histogram **152** sorts the k-space data according to its position and does not differentiate for the respiratory state, in which case states **701** and **708** are grouped together, states **702** and **707** are grouped together, states **703** and **706** are grouped together, and finally states **704** and **705** are grouped together. In other words, the respiratory position histogram **152**, the k-space intrinsic navigator **700** is binned based on only the value of the navigator, inhalation and exhalation states are binned together This enables easy identification of the respiratory outliers **154**.

[0132] 3D k-space is acquired with a temporally interleaved oversampling of the central k-space. A 3D golden angle variable density radial stack of stars sampling may, in some examples, be used since it guarantees a good k-space sampling distribution, motion robustness with a higher k-space density at central kz-space providing a more efficient scanning and optimized filtering capability. The acquisition can be combined with an irregular sampling pattern optimized for compressed sensing and AI.

[0133] Respiratory states may be detected either from intrinsic k-space or externally from a camera —are classified with respect to the inspiration to expiration and expiration to inspiration respiratory state based on history accounting for respiratory hysteresis effects.

[0134] The acquired 3D k-space data is then sorted and binned with respect to the detected and classified respiratory states separating inspiration to expiration and expiration to inspiration respiratory states using a respiratory histogram (respiratory position histogram **152**).

[0135] Respiratory outliers **154** are removed based on the histogram **152**. Starting from the first and last bins, respectively, the bin is rejected if it is under a certain threshold. The threshold is a defined a factor (e.g., 0.1) times the height of the highest bin. The rejection of the outer bins is continued as long as the first bin over the threshold is encountered.

[0136] FIG. **9** illustrates a KWIC filter **900** for a single k-space bin. This provides a weighting factor **904** as a function of the position in the bin **902**. In this case it would be likely the navigator position. This weighting factor has a maximum located within a bin. The value of the KWIC filter may decrease rapidly to reduce the effect of outliers or samples outside of the particular bin.

[0137] FIG. **10** illustrates a collection of KWIC filters **900** that are applied to a histogram **1002** of k-space samples located in bins which are a function of navigator phase **902**. In this example the KWIC filters **900** are used to define the boundaries and interaction of various bins. The k-space filter (KWIC) is applied to the acquired 3D k-space data for different respiratory bins. Vertical bars represent the center k-space **1000** that is weighted stronger at equidistant respiratory states.

[0138] Then a k-space weighted filter (KWIC) in the respiratory state domain is applied. Hereby the oversampled central k-space is weighted stronger at equidistant respiratory states than more distant k-space profiles. For illustration purposes the filtering is illustrated in FIG. **4** not accounting for the respiratory hysteresis effect. In the ideal those effects are accounted for by filtering the oversampled central k-space only with the correctly classified respiratory state.

[0139] FIG. **11** illustrates several k-space sampling patterns. Sampling pattern **1100** is a standard three-dimensional golden angle stack of stars k-space sampling pattern. Sampling pattern **1102** is for a three-dimensional variable density radial stack of stars k-space sampling pattern. The lines **1104** marked in the three-dimensional variable density radial stack of stars k-space sampling pattern **1104** indicate how the different layers of the sampling pattern **1102** can be reduced in sampling by linear or quadratic radial densities for example. Outside of the regions marked **1104**, the sampling pattern **1102** can be made sparser. Both sampling patterns **1100** and **1102** are examples of multi-dimensional k-space sampling patterns.

[0140] A very simplistic representation of the KWIC filter is shown with the peripheral k-space **1106** and **1108** shared over adjacent overlapping bins, while the central k-space part **1110** filters out respiratory-state distant profiles.

[0141] Regular undersampling, compressed sensing (CS) and artificial intelligence (AI) can be used to reconstruct respiratory state images distinguishing respiratory hysteresis effects. Next to spatial CS, a respiratory-state resolved CS reconstruction could be applied using a temporal total variation constraint. AI could be integrated in the (non-cartesian) CS reconstruction for improving de-noising and undersampling artifacts, but also for sharpening and providing super resolution images from the different respiratory states.

[0142] FIGS. **12**, **13**, and **14** are used to illustrate the approach tuned to multi slice Propeller imaging. FIG. **12** shows a multi slice Propeller k-space sampling **1202**. A multi slice two-dimensional propeller sampling with for example a desired T2 contrast has an intrinsic high oversampling of the central k-space. Using the respiratory information, the oversampled central k-space can be filtered out using KWIC filtering extracting 4D respiratory-state resolved T2 images within the same multi slice two-dimensional propeller overview scan.

[0143] FIG. **13** shows two possible bins **1300** and **1302** at different respiratory states with differing KWIC filter strengths. Each bin **1300** and **1302** each has 3 boxes: an inner box **1304**, a middle box **1306**, and an outer box **1308** which indicate the weighting of the KWIC filter. In both of these, provides the inner box **1304** is weighted the most and the outer box **1308** is weighted the least. As one moves further away from the inner region indicted by the inner box **1304** the weighting of the KWIC filter is reduced.

[0144] FIG. **14** illustrates contrast weighting of blades with respect to the respective respiratory states in FIG. **13** for k-space **1404** and blade composition **1406** for a standard propeller k-space sampling pattern. Standard Propeller with no contrast weighting is shown in **1400** and **1402** for k-space and blade composition. Propeller reconstruction can be combined with joint blade reconstruction and compressed sensing applying k-space weighting.

[0145] While the invention has been illustrated and described in detail in the drawings and foregoing description, such illustration and description are to be considered illustrative or exemplary and not restrictive; the invention is not limited to the disclosed embodiments.

[0146] Other variations to the disclosed embodiments can be understood and effected by those skilled in the art in practicing the claimed invention, from a study of the drawings, the disclosure, and the appended claims. In the claims, the word “comprising” does not exclude other elements or steps, and the indefinite article “a” or “an” does not exclude a plurality. A single processor or other unit may fulfill the functions of several items recited in the claims. The mere fact that certain measures are recited in mutually different dependent claims does not indicate that a combination of these measured cannot be used to advantage. A computer program may be stored/distributed on a suitable medium, such as an optical storage medium or a solid-state medium supplied together with or as part of other hardware, but may also be distributed in other forms, such as via the Internet or other wired or wireless telecommunication systems. Any reference signs in the claims should not be construed as limiting the scope. In the claims, the word “respiratory-state resolved” can be interchanged by “breathing resolved”, “time resolved”, “temporally resolved”.

REFERENCE SIGNS LIST

[0147] **100** medical system [0148] **102** magnetic resonance imaging system [0149] **104** magnet [0150] **106** bore of magnet [0151] **108** imaging zone [0152] **109** field of view [0153] **110** magnetic field gradient coils [0154] **112** magnetic field gradient coil power supply [0155] **114** radio-frequency coil [0156] **116** transceiver [0157] **118** subject [0158] **120** subject support [0159] **122** respiratory belt [0160] **130** computer [0161] **132** computational system [0162] **134** hardware interface [0163] **136** user interface [0164] **138** memory [0165] **140** machine executable instructions [0166] **142** pulse sequence commands [0167] **144** individual acquisitions of k-space data [0168] **146** respiratory signal [0169] **148** group of a predetermined number of k-space bins [0170] **150** respiratory-state resolved magnetic resonance image [0171] **152** respiratory position histogram [0172] **154** respiratory outliers [0173] **200** perform the individual acquisition of k-space data by controlling the magnetic resonance imaging system with the pulse sequence commands [0174] **202** receive the respiratory signal when the individual acquisition of k-space data is acquired by the magnetic resonance imaging system [0175] **204** bin the individually acquired k-space data into one of a predetermined number of k-space bins using the respiratory signal and inhalation or exhalation of the subject [0176] **206** acquisition finished? [0177] **208** reconstruct a magnetic resonance image for each of the predetermined number of k-space bins to provide a respiratory-state resolved magnetic resonance image of the field of view [0178] **300** repeatedly bin the individually acquired k-space data into a respiratory position histogram [0179] **302** identify respiratory outliers using the respiratory position histogram, wherein the respiratory-state resolved magnetic resonance image is corrected for the respiratory outliers [0180] **400** medical system [0181] **402** radiation therapy system [0182] **404** gantry [0183] **406** radiotherapy source [0184] **408** collimator [0185] **410** cryostat [0186] **412** superconducting coil [0187] **414** rotational axis [0188] **416** radiation beam [0189] **418** target zone [0190] **420** segmentation algorithm [0191] **422** respiratory-state resolved segmentation [0192] **424** radiation therapy system control module [0193] **426** radiation therapy plan [0194] **428** radiotherapy control commands [0195] **500** provide the respiratory-state resolved segmentation of the respiratory-state resolved magnetic resonance image by inputting the respiratory-state resolved magnetic resonance image into the segmentation algorithm [0196] **502** provide the radiotherapy control commands in response to inputting the respiratory-state resolved segmentation and the radiotherapy plan into the radiation therapy system control module [0197] **504** control the radiation therapy system to irradiate the subject using the radiotherapy control commands [0198] **600** magnetic resonance image [0199] **602** tumor segmentation [0200] **604** motion of centroid in TM plane [0201] **700** k-space intrinsic navigator [0202] **701** respiratory state or bin 1 [0203] **702** respiratory state or bin 2 [0204] **703** respiratory state or bin 3 [0205] **704** respiratory state or bin 4 [0206] **705** respiratory state or bin 5 [0207] **706** respiratory state or bin 6 [0208] **707** respiratory state or bin 7 [0209] **710** box [0210] **712** time [0211] **714** navigator value [0212] **900** KWIC filtersingle bin [0213] **902** position in bin (navigator position) [0214] **904** weighting factor [0215] **1000** center of bin [0216] **1100** three-dimensional golden angle stack of stars k-space sampling pattern [0217] **1102** three-dimensional variable density radial stack of stars k-space sampling pattern [0218] **1104** region [0219] **1106** radial k-space sampling pattern [0220] **1108** radial k-space sampling pattern [0221] **1110** central region of k-space [0222] **1200** multi-dimensional k-space sampling pattern [0223] **1202** individual propeller sampling patterns [0224] **1300** continuous sampling of central k-space [0225] **1302** samples performed where the central k-space is partially filtered using a KWIC filter [0226] **1304** inner box [0227] **1306** middle box [0228] **1308** outer box

Claims

1. A medical system comprising: a magnetic resonance imaging system configured to acquire k-space data for a field of view of a subject, wherein the magnetic resonance imaging system is configured to provide a respiratory signal, wherein the respiratory signal is descriptive of a respiratory position of the subject, wherein the respiratory signal is further descriptive of inhalation and exhalation of the subject; a memory configured to store machine executable instruction and pulse sequence commands, wherein the pulse sequence commands are configured to control the magnetic resonance imaging system to acquire the k-space data as multiple acquisitions of individually acquired k-space data according to a multi-dimensional k-space sampling pattern, wherein the pulse sequence commands are configured such that the multi-dimensional k-space sampling pattern is varied between each individual k-space data acquisition of the multiple acquisitions of k-space data; a computational system, wherein execution of the machine executable instructions causes the computational system to repeatedly: perform the individual acquisition of k-space data by controlling the magnetic resonance imaging system with the pulse sequence commands; receive the respiratory signal when the individual acquisition of k-space data is acquired by the magnetic resonance imaging system; bin the individually acquired k-space data into one of a predetermined number of k-space bins using the respiratory signal and inhalation or exhalation of the subject; wherein execution of the machine executable instructions further causes the computational system to reconstruct a magnetic resonance image for each of the predetermined number of k-space bins to provide a respiratory-state resolved magnetic resonance image of the field of view; and wherein execution of the machine executable instructions causes the computational system to repeatedly bin the individually acquired k-space data into a respiratory position histogram, wherein execution of the machine executable instructions further causes the computational system to identify respiratory outliers using the respiratory position histogram, and wherein the respiratory-state resolved magnetic resonance image is corrected for the respiratory outliers.
2. The medical system of claim 1, wherein execution of the machine executable instructions further causes the computational system to calculate extreme respiratory-state resolved image data by calculating a modulus averaging or a complex averaging of extreme inspiration and expiration respiratory states in the respiratory-state resolved magnetic resonance image, wherein the extreme inspiration and expiration respiratory states can be end inspiration or end expiration states, but can be also an automated selection of extreme states by gradient entropy comparison and/or selection of pre-selected gating window settings.
3. The medical system of claim 1, wherein the multi-dimensional k-space sampling pattern is configured to oversample a central k-space region.
4. The medical system of claim 1, wherein the multi-dimensional k-space sampling pattern is any one of the following: a 3D stack of stars sampling pattern, a 3D variable density stack of stars sampling pattern, a 3D variable density spiral cartesian sampling pattern, cartesian sampling pattern, variable density sampling pattern, 2D variable density cartesian sampling pattern, 2D propeller sampling pattern, KOOSH ball sampling pattern, a Floret sampling pattern, or a spiral sampling pattern including golden angle sampling strategies.
5. The medical system of claim 1, wherein execution of the machine executable instructions causes

the computational system to applying a k-space weighting filter to each of the individual acquisitions of k-space data in the predetermined number of k-space bins before reconstructing the magnetic resonance image for each of the k-space bins, wherein the k-space filter is configured to apply a higher weighting to the central k-space region than outside the central k-space region.

6. The medical system of claim 5, wherein the individual acquisitions of k-space data are assigned a weighting by the k-space weighting filter according to location within or adjacent k-space bins determined by the respiratory signal.

7. The medical system of claim 5, wherein the k-space weighting filter is a k-space weighting image contrast filter and/or wherein the k-space weighting filter is configured to perform a phase correction to correct for motion and/or increase image sharpness according to a gradient entropy measure.

8. The medical system of claim 1, wherein the memory further stores a segmentation algorithm configured to output a respiratory-state resolved segmentation in response to receiving the respiratory-state resolved magnetic resonance image, wherein execution of the machine executable instructions further causes the computational system to provide the respiratory-state resolved segmentation of the respiratory-state resolved magnetic resonance image by inputting the respiratory-state resolved magnetic resonance image into the segmentation algorithm.

9. The medical system of claim 8, wherein the memory further stores a radiation therapy system control module configured to output control commands for a radiotherapy system in response to receiving the respiratory-state resolved segmentation and a radiotherapy plan as input, wherein execution of the machine executable instructions further causes the computational system to provide the radiotherapy control commands in response to inputting the respiratory-state resolved segmentation and the radiotherapy plan into the radiation therapy system control module.

10. The medical system of claim 9, wherein the medical system further comprises the radiation therapy system, wherein execution of the machine executable instructions further causes the computational system to control the radiation therapy system to irradiate the subject using the radiotherapy control commands, wherein the irradiation of the subject is at least partially controlled, gated, tracked, and/or followed using the respiratory signal.

11. The medical system of claim 1, wherein the magnetic resonance image for each of the predetermined number of k-space bins is reconstructed using compressed sensing or an artificial intelligence based reconstruction.

12. The medical system of claim 1, wherein the respiratory-state resolved magnetic resonance image is corrected for the respiratory outliers by deleting outliers from the k-space bins or by giving respiratory outliers a predetermined weighting value during reconstruction of the magnetic resonance image for each of the predetermined number of k-space bins.

13. A computer program product comprising machine executable instructions, stored on a non-transitory computer readable medium, for execution by a computational system controlling a medical system, wherein the medical system comprises a magnetic resonance imaging system configured to acquire k-space data for a field of view of a subject, wherein the magnetic resonance imaging system is configured to provide a respiratory signal, wherein the respiratory signal is descriptive of a respiratory position of the subject, wherein the respiratory signal is further descriptive of inhalation and exhalation of the subject, wherein execution of the machine executable instructions causes the computational system to repeatedly: perform the individual acquisition of k-space data by controlling the magnetic resonance imaging system with pulse sequence commands, wherein the pulse sequence commands are configured to perform the acquiring of the k-space data as multiple acquisitions of individually acquired k-space data according to a multi-dimensional k-space sampling pattern, wherein the pulse sequence commands are configured such that the multi-dimensional k-space sampling pattern is varied between each individual k-space data acquisition of the multiple acquisitions of k-space data; receive the respiratory signal during acquisition of the individual acquired k-space data; and bin the individually acquired k-space data into one of a predetermined number of k-space bins using the respiratory signal and inhalation or exhalation of the subject; wherein execution of the machine executable instructions further causes the computational system to reconstruct a magnetic resonance image for each of the k-space bins to provide a respiratory-state resolved magnetic resonance image of the field of view; and wherein execution of the machine executable instructions causes the computational system to repeatedly bin the individually acquired k-space data into a respiratory position histogram, wherein execution of the machine executable instructions causes the computational system to identify respiratory outliers using the respiratory position histogram, and wherein the respiratory-state resolved magnetic resonance image is corrected for the respiratory outliers.

14. A method of operating a medical system wherein the medical system comprises a magnetic resonance imaging system configured to acquire k-space data for a field of view of a subject, wherein the magnetic resonance imaging system is configured to provide a respiratory signal, wherein the respiratory signal is descriptive of a respiratory position of the subject, wherein the respiratory signal is further descriptive of inhalation and exhalation of the subject; wherein the method comprises repeatedly: performing the individual acquisition of k-space data by controlling the magnetic resonance imaging system with pulse sequence commands, wherein the pulse sequence commands are configured to perform the acquiring of the k-space data as multiple acquisitions of individually acquired k-space data according to a multi-dimensional k-space sampling pattern, wherein the pulse sequence commands are configured such that the multi-dimensional k-space sampling pattern is varied between each individual k-space data acquisition of the multiple acquisitions of k-space data; receiving the respiratory signal during acquisition of the individual acquired k-space data; and binning the individually acquired k-space data into one of a predetermined number of k-space bins using the respiratory signal and inhalation or exhalation of the subject; wherein the method further comprises reconstructing a magnetic resonance image for each of the k-space bins to provide a respiratory-state resolved magnetic resonance image of the field of view, and wherein the method comprises repeatedly binning the individually acquired k-space data into a respiratory position histogram, identifying respiratory outliers using the respiratory position histogram, and correcting the respiratory-state resolved magnetic resonance image for the respiratory outliers.