1210 and Compressed Sensing (CS) as referenced in *Lustig M et al; Sparse MRI: The application of compressed sensing for Rapid MR Imaging; Magn Reson Med 2007; 58:1182-1195* have also been employed to increase spatial and/or temporal resolution of a dynamic MRI scan. While PMRI methods rely on spatial encoding provided by multiple RF coils to complement the MRI gradient encoding process, CS methods are applicable when certain conditions related to the sparsity of the MRI image or its representation in a transform domain are fulfilled. These techniques can be employed either independently or in tandem with any of the methods previously mentioned to accelerate a dynamic MRI scan. Despite the advances, applications such as interventional imaging, contrast enhanced MR Angiography, evaluation of cardiac function and abdominal imaging can always benefit from larger acceleration factors. The fundamental limitation in these and other dynamic imaging applications continues to be the trade-off between spatial and temporal resolution.

Objects of the Invention:

It is an object of the invention to provide an apparatus and a method for MRI that enables a vast reduction in the duration of dynamic MRI scans while ensuring better quality of reconstructed images.

According to one aspect of the invention, there is provided a method for rapid acquisition of MRI data at multiple points in time in an MRI scan, said method comprising the steps of: (a) repeatedly applying an RF excitation module consisting of an RF excitation pulse, a slice-selective magnetic field gradient pulse and a gradient blip in a primary phase encoding direction, whereby the same slice is excited by each RF excitation pulse; (b) acquiring an aliased k-space dataset at a point in time, whereby distinct k-space points are tagged an overlapped by application of said RF excitation modules by varying the amplitude and phase of the RF excitation pulses in time to obtain a k-t dataset; (c) undoing k-space aliasing in the acquired k-space datasets by Fourier transforming them along the time axis to separate the overlapped k-space points, the step of undoing k-space aliasing including a filtering process to separate the k-space points to produce an un-aliased k-t space dataset; and (d) performing a Fourier transformation along one or more axes of the un-aliased k-space datasets to generate image frames for the different time points at which data was acquired.

Summary of the invention:

~~According to this invention, t~~There is also provided a method for rapid acquisition of MRI data at multiple points in time in an MRI scan using tailored signal excitation modules, said method comprises the steps of:

(a) Obtaining tailored signal excitation modules by using RF excitation pulses in combination with one or more magnetic field gradients;

(b) acquiring an aliased k-space dataset at a point in time using a pulse sequence that employs said obtained tailored signal excitation modules, which tag and overlap distinct k-space points;

Typically, the step (a) includes the step of obtaining tailored signal excitation modules designed for effecting 2D or 3D k-space aliasing.

Alternatively, the step (a) includes the step of obtaining tailored signal excitation modules designed for overlapping a plurality of k-space points spaced apart on a Cartesian k-space sampling trajectory.

Alternatively, the step (a) includes the step of obtaining tailored signal excitation modules designed for overlapping a plurality of k-space points spaced apart on a Non-Cartesian k-space sampling trajectory.

Typically, the step (c) includes the step of reconstructing a series of image frames from the k-t dataset produced.

In one embodiment, the step (a) includes the step of obtaining tailored signal excitation modules using a plurality of receiver coils to produce a corresponding plurality of accelerated k-space datasets and in which step (c) includes the step of processing a plurality of image frames and/or k-space datasets using a PMRI method for accelerating the MRI scan.

In another embodiment, the step (a) includes the step of obtaining tailored signal excitation modules to produce a corresponding plurality of k-space datasets and in which step (c) includes the step of processing a plurality of image frames and/or k-space datasets using a CS method for accelerating the MRI scan.

Alternatively, a corresponding plurality of k-space datasets and the plurality of image frames and/or k-space datasets are processed using image and/or k-space information acquired from a prior reference MRI scan.

~~According to this invention, t~~There is also provided a system for rapid acquisition of MRI data at multiple points in time in an MRI scan using tailored signal excitation modules, said system comprises:

AMENDED CLAIMS
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I claim

1. A method for rapid acquisition of MRI data at multiple points in time in an MRI scan using tailored signal excitation modules, said method comprising the steps of:
   (a) obtaining tailored signal excitation modules by using RF excitation pulses, in combination with one or more magnetic field gradients;
   (b) acquiring an aliased k-space dataset at a point in time using a pulse sequence that employs said obtained tailored signal excitation modules, which tag and overlap distinct k-space points;
   (c) repeating steps (a) and (b) for acquiring aliased k-space datasets at multiple time points in a scan while tagging the overlapped k-space points as a function of time to obtain an accelerated k-t dataset, said step (c) further comprising a step of varying the amplitude and phase of tagging coefficients to enable separation of overlapped k-space points to produce the full un-aliased k-t space dataset, said step (c) still further comprising a step of acceleration along a selected k-space axis, said axis of acceleration being a phase encoding axis;
   (d) undoing k-space aliasing in the acquired k-space datasets by Fourier transforming them along the time axis followed by a filtering process to separate the overlapped points; and
   (e) performing a Fourier transformation along one or more axes of the un-aliased k-space datasets to generate image frames for the different time points at which data was acquired.

2. The method as recited in claim 1 in which step (a) of obtaining tailored signal excitation modules includes the step of sampling an object directly in at least one spatial dimension.

3. The method as recited in claim 1 in which step (a) of obtaining tailored signal excitation modules includes the step of obtaining RF excitation pulses given by the following equation:

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$$P_{rf}(t) = \sum_{n=1}^{N} a_n P_n (t - n\Delta t)$$

4. The method as recited in claim 1 in which step (c) of obtaining an accelerated k-t dataset includes the step of obtaining a signal at the overlapped k-space point given by the following equation:

$$k(t)_{alias} = \sum_{n=1}^{N} A_n k_n(t) e^{j\Phi(n,t)}$$

5. The method as recited in claim 1 in which step (d) includes the step of filtering the temporal frequency spectrum of said accelerated k-t dataset to separate the overlapped k-space points and produce the full un-aliased k-t space dataset.

6. The method as recited in claim 1 in which step (a) includes the step of obtaining tailored signal excitation modules that cause overlap of k-space points that lie on a plurality of lines in k-space spaced apart along a k-space axis.

7. The method as recited in claim 1 in which step (a) includes the step of obtaining tailored signal excitation modules designed for effecting 2D or 3D k-space aliasing.

8. The method as recited in claim 1 in which step (a) includes the step of obtaining tailored signal excitation modules designed for overlapping a plurality of k-space points spaced apart on a Cartesian k-space sampling trajectory.

9. The method as recited in claim 1 in which step (a) includes the step of obtaining tailored signal excitation modules designed for overlapping a plurality of k-space points spaced apart on a Non-Cartesian k-space sampling trajectory.

10. The method as recited in claim 1 in which step (c) includes the step of reconstructing a series of image frames from the k-t dataset produced.

11. The method as recited in claim 1 in which step (a) includes the step of obtaining tailored signal excitation modules using a plurality of receiver coils to produce a corresponding plurality of accelerated k-space datasets and in which step (c) includes the step of processing a plurality of image frames and/or k-space datasets using a PMRI method for accelerating the MRI scan.

12. The method as recited in claim 1 in which step (a) includes the step of obtaining tailored signal excitation modules to produce a corresponding plurality of k-space datasets and in which step (c) includes the step of processing a plurality of image frames and/or k-space datasets using a CS method for accelerating the MRI scan.

13. The method as recited in claim 1 in which a corresponding plurality of k-space datasets and the plurality of image frames and/or k-space datasets are processed using image and/or k-space information acquired from a prior reference MRI scan.

14. A system for rapid acquisition of MRI data at multiple points in time in an MRI scan using tailored signal excitation modules, said system comprising:

(a) MRI signal excitation means adapted to obtain tailored signal excitation modules by using RF excitation pulses along with one or more magnetic field gradients;

(b) aliasing means adapted to acquire aliased k-space datasets at a time point using a pulse sequence that employs said obtained tailored signal excitation modules, which tag and overlap distinct k-space points and further adapted to repeat the step of acquiring aliased k-space datasets at multiple time points in the scan while tagging the overlapped k-space points as a function of time to obtain an accelerated k-t dataset;

(c) first Fourier Transformation means adapted to undo k-space aliasing in the acquired k-space datasets by Fourier transforming the acquired k-space datasets along the time axis followed by a filtering process to separate the overlapped k-space points;

(d) amplitude varying means and phase varying means adapted to vary the amplitude and phase, respectively, of tagging coefficients to enable separation of overlapped k-space points to produce the full un-aliased k-t space dataset;

(e) acceleration means for obtaining an accelerated k-t space dataset along a selected k-space axis, said axis of acceleration being a phase encoding axis; and

(f) second Fourier Transformation means adapted to generate image frames, from the un-aliased k-space datasets, for the multiple time points at which data was acquired.

15. The system as recited in claim 14 in which said excitation means includes sampling means adapted to sample an object directly in at least one spatial dimension.

16. The system as recited in claim 14 in which said excitation means includes RF excitation pulse obtaining means adapted to obtain RF excitation pulses given by the following equation:

$$P_{rf}(t) = \sum_{n=1}^{N} a_n P_n(t - n\Delta t)$$

17. The system as recited in claim 14 in which said aliasing means includes signal obtaining means adapted to obtain a signal at the overlapped k-space point given by the following equation:

$$k(t)_{alias} = \sum_{n=1}^{N} A_n k_n(t) e^{j\Phi(n,t)}$$

18. The system as recited in claim ~~16~~ 14 in which said system includes filtering means for filtering the temporal frequency spectrum of said accelerated k-t dataset to separate the overlapped k-space points and produce the full un-aliased k-t space dataset.

19. The system as recited in claim 14 in which said system includes MRI signal excitation means adapted to obtain tailored signal excitation modules that cause overlap of k-space points that lie on a plurality of lines in k-space spaced apart along a k-space axis.

20. The system as recited in claim 14 in which said MRI signal excitation means includes 2D MRI signal excitation means or 3D MRI signal excitation means adapted to obtain tailored signal excitation modules designed for effecting 2D or 3D k-space aliasing, respectively.

21. The system as recited in claim 14 in which said MRI signal excitation means includes Cartesian MRI signal excitation means adapted to obtain tailored signal excitation modules designed for overlapping a plurality of k-space points spaced apart on a Cartesian k-space sampling trajectory.

22. The system as recited in claim 14 in which said MRI signal excitation means includes Non-Cartesian MRI signal excitation means adapted to obtain tailored signal excitation modules designed for overlapping a plurality of k-space points spaced apart on a Non-Cartesian k-space sampling trajectory.

23. The system as recited in claim 14 in which said system includes image frame reconstruction means adapted to reconstruct a series of image frames from the k-t dataset produced.

24. The system as recited in claim 14 in which said system includes a plurality of receiver coils for obtaining tailored signal excitation modules in order to produce a corresponding plurality of k-space datasets and further includes PMRI means adapted to process a plurality of image frames and/or k-space datasets using a PMRI method for accelerating the MRI scan.

25. The system as recited in claim 14 in which said system includes a plurality of receiver coils for obtaining tailored signal excitation modules in order to produce a corresponding plurality of k-space datasets and further includes CS means adapted to process a plurality of image frames and/or k-space datasets using a CS method for accelerating the MRI scan.

26. The system as recited in claim 14 in which said system includes processing means wherein a corresponding plurality of k-space datasets and the plurality of image frame datasets are processed using image and/or k-space information acquired from a prior reference MRI scan.

Statement under Article 19(1)

We refer to PCT/ISA/220 in respect of PCT/IN2012/000127 and our subsequent comments are as follows:

As per the ISR, the claims of PCT/IN2012/000127 are novel, inventive and have industrial applicability.

With reference to objections of Serial No. 3.1.2, 3.1.6, and 3.1.4, earlier claims 6 and 7 have been incorporated in claim 1 in order to secure essential features in Claim 1.

With reference to objections of Serial No. 3.1.2, it is to be noted that the design of the module is a function of multiple imaging parameters, such as the pulse sequence that is employed, and the anatomy that is to be imaged. Several factors, in turn, further dictate these differences and therefore cannot be stated concretely as they all depend on the scan imaging parameters. Therefore, the Applicant does not wish to limit the scope of claim 1 by incorporating the defined mathematical formula of claim 3 into claim 1.

With reference to objections of Serial No. 3.1.3, attention is drawn towards references of prior art where there is a priori information available for a variety of clinical imaging applications on the energy distribution proposition of k-space. The k-space data is obtained by performing Fourier Transform on a 2D / 3D image. The Fourier Transform inherently concentrates energy in lower spatial frequencies. Hence, the system and method has sufficient knowledge a priori about how to tag coefficients. Furthermore, for any new clinical application, one can always be obtain all relevant information for determining the tagging coefficients by running a calibration scan run prior to the accelerated scan. Thus, under all possible imaging conditions, sufficient a priori knowledge will always be available to the system and method for appropriately defining the tagging coefficients.

With reference to objections of Serial No. 3.1.4, it is to be noted that data in accelerated dataset refers to k-space data collected in time. In the art, this is known as k-t dataset. 'Accelerated

dataset' is obtained by repeating the steps of 'a' and 'b' of claim 1. Earlier claim 7 (now incorporated in claim 1) refers to the direction in which aliasing occurs.

With reference to objections of Serial No. 3.1.7, it is to be noted that the term, 'unaliasing', refers to 'undoing k-space aliasing'. Hence, previous claim 5 (currently amended claim 4) is dependent on claim 1(d).

With reference to objections of Serial No. 3.2, claim 2 has been retained for explicitly stating a 'direction' related limitation.

With reference to objections of Serial No. 3.3, formula in claim 4 has been separately claimed in order to not limit the scope of claim 1 by means of a defined mathematical formula.

With reference to objections of Serial No. 3.4, Applicant does not wish to identify the filtering process as a limitation in claim 1.

With reference to objections of Serial No. 3.6, corresponding changes have been made in the system claims, too.

Claims

1. A method for rapid acquisition of MRI data at multiple points in time in an MRI scan, said method comprising the steps of:

(a) repeatedly applying an RF excitation module consisting of an RF excitation pulse, a slice-selective magnetic field gradient pulse and a gradient blip in a primary phase encoding direction, whereby the same slice is excited by each RF excitation pulse;

(b) acquiring an aliased k-space dataset at a point in time, whereby distinct k-space points are tagged an overlapped by application of said RF excitation modules by varying the amplitude and phase of the RF excitation pulses in time to obtain a k-t dataset;

(c) undoing k-space aliasing in the acquired k-space datasets by Fourier transforming them along the time axis to separate the overlapped k-space points, the step of undoing k-space aliasing including a filtering process to separate the k-space points to produce an un-aliased k-t space dataset; and

(d) performing a Fourier transformation along one or more axes of the un-aliased k-space datasets to generate image frames for the different time points at which data was acquired.

2. The method as recited in claim 1 in which the step of applying RF excitation pulses during the application of the slice selective magnetic field gradient pulses cause an overlap of k-space points that lie on a plurality of lines in k-space spaced apart along a k-space axis, or cause an overlap of a plurality of k-space points spaced apart on a Cartesian k-space sampling trajectory, or cause an overlap of a plurality of k-space points spaced apart on a Non-Cartesian k-space sampling trajectory.

3. The method as recited in claim 1 in which step (b) includes the step of reconstructing a series of image frames from the k-t dataset produced.

4. The method as recited in claim 1 in which a plurality of receiver coils is used to produce the k-space datasets and in which step (b) includes the step of processing a plurality of image frames and/or k-space datasets using a PMRI method or a CS method for accelerating the MRI scan.

5. A system for rapid acquisition of MRI data at multiple points in time in an MRI scan, said system comprising:

(a) MRI signal excitation means adapted to repeatedly apply an RF excitation module consisting of an RF excitation pulse, a slice-selective magnetic field gradient pulse and a gradient blip in a primary phase encoding direction, whereby the same slice is excited by each RF excitation pulse;

(b) aliasing means adapted to acquire an aliased k-space dataset at a point in time, whereby said MRI signal excitation means is adapted to tag and overlap distinct k-space points by application of said RF excitation modules by varying the amplitude and phase of the RF excitation pulses in time to obtain a k-t dataset;

(c) first Fourier Transformation means adapted to undo k-space aliasing in the acquired k-space datasets by Fourier transforming the acquired k-space datasets along the time axis to separate the overlapped k-space points, the step of undoing k-space aliasing including a filtering process to separate the k-space points to produce an un-aliased k-t space dataset; and

(d) second Fourier Transformation means adapted to generate image frames, from the un-aliased k-space datasets, for the different time points at which data was acquired.

6. The system as recited in claim 6 in which said MRI signal excitation means is adapted to apply said RF excitation modules such as to cause overlap of k-space points that lie on a plurality of lines in k-space spaced apart along a k-space axis, or to cause overlap of a plurality of k-space points spaced apart on a Cartesian k-space sampling trajectory, or to cause overlap of a plurality of k-space points spaced apart on a Non-Cartesian k-space sampling trajectory.

7. The system as recited in claim 6 including image frame reconstruction means adapted to reconstruct a series of image frames from the k-t dataset produced, or including a plurality of receiver coils to produce the k-t datasets and further including PMRI means adapted to process a plurality of image frames and/or k-space datasets using a PMRI method for accelerating the MRI scan.