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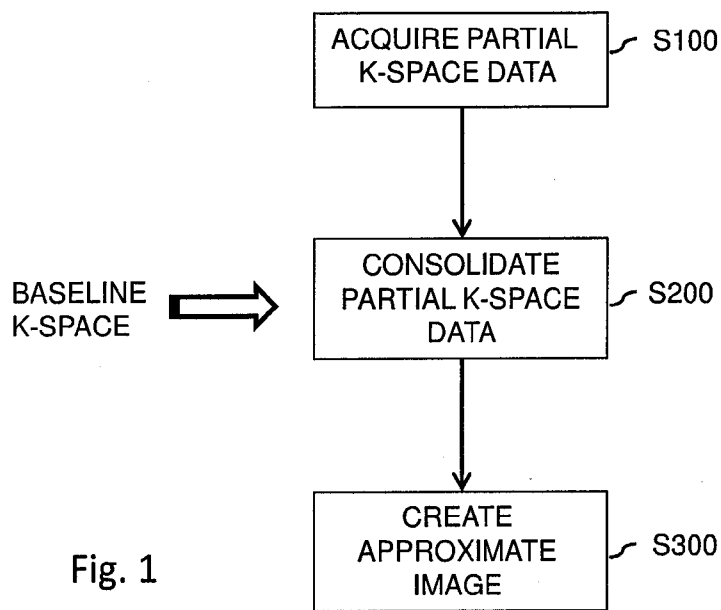


Fig. 1

(57) Abstract: The present disclosure provides a method of magnetic resonance imaging based on a prior magnetic resonance baseline image of an object, the method comprising: partially sampling a magnetic resonance signal originating from said object so as to collect partial k-space data; consolidating the partial k-space data using the k-space data of the baseline image to obtain consolidated k-space data; and creating an approximate image of the object using the consolidated k-space data. The method includes a unique hardware, real time control module within the MR system.

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## METHOD OF AND SYSTEM FOR ACCELERATING REPEATED MAGNETIC RESONANCE IMAGING

### TECHNOLOGICAL FIELD

The present disclosure relates generally to a method of and a system for Magnetic Resonance (MR) imaging. More particularly, the present disclosure relates to a method of and a system for accelerating MR imaging using a preliminarily acquired  
5 MR baseline image.

### BACKGROUND ART

References considered to be relevant as background to the presently disclosed subject matter are listed below:

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Acknowledgement of the above references herein is not to be inferred as meaning that these are in any way relevant to the patentability of the presently disclosed subject matter.

## BACKGROUND

The present invention relates generally to medical imaging, and more particularly to acquisition and reconstruction of MR images.

Magnetic Resonance Imaging (MRI) has become a well-established medical diagnostic tool for imaging structures within the body of a patient. Image quality may be characterized by a host of parameters, including resolution, signal to noise, field of view, contrast, edge definition, and artifacts (for example, ghosts and streaks). Under a broad range of conditions, image quality improves with increasing data acquisition time. If the data acquisition time is increased, however, the patient is subjected to a longer scan time, which increases patient discomfort. In some instances, long scan times may actually degrade image quality because of movement of the region of interest during the scan. Short scan times are also necessary for near-real-time measurements, such as used in functional MRI. There is, thus, a fundamental trade-off between image quality and scan time.

Images are displayed on physical media; for example, emulsions on film or pixels on a monitor. The normal physical world may be referred to as real space. In one method for producing high-quality images, MR signals are captured in k-space. In some fields of study, k-space is also referred to as spatial-frequency domain. In general terms, data values in real space are then generated by taking the inverse Fourier transform of

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data values in k-space. In general, MR signals are not measured as a continuous function of position in k-space. They are sampled at discrete k-values. Subject to specific constraints and boundary conditions, image quality generally improves as the density and range of discrete k-space sampling points are increased. Recording a large  
5 number of samples, however, has disadvantages. One is the extended scan time discussed above. The other is low temporal resolution.

Current approaches for MRI acquisition speed up include hardware improvements, data acquisition and sophisticated reconstruction techniques. Hardware improvements are based on enhancing various scanner elements to speed up the  
10 scanning procedure such as the use of faster gradient hardware in conjunction with shorter data acquisition periods and parallel imaging. However, technological and physiological limitations with hardware improvements are quickly reached. Enhanced reconstruction techniques are mostly based on under-sampled MRI data. These methods often lead to reduced signal-to-noise ratio (SNR) and to image degradation, and they  
15 require extended computational time and high memory usage.

Today, many repeatable MR images are acquired to track a patient's disease progression and to evaluate his/her treatment efficacy. What is needed is a method which utilizes the patient's earlier scan in order to reduce the time needed for the repeated MRI scanning.

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## GENERAL DESCRIPTION

From the forgoing it is readily appreciated that there is a need for an improved and fast repeated MR imaging method that takes advantage of an existing MR scan acquired at a previous time. Further, from the foregoing it is readily appreciated that  
25 there is a need for an improved MR imaging system and an improved computer program product adapted to carry out the method according to the invention.

In the present disclosure, the acquisition of a magnetic resonance imaging of an object may involve existing data of the same object acquired at an earlier time point.

In the present disclosure, the following terms and their derivatives may be  
30 understood in light of the below explanations:

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### **K-space**

The terms k-space or k-space data refer to data collected from the magnetic resonance signals acquired by a MRI system. As is known in the art of MRI, when  
5 acquiring an image of a sliced object, spatial encoding may be performed by a phase encoding and frequency encoding which enable to identify a site of origin of an MRI signal collected. The k-space may have two axes with the horizontal axis ( $K_x$ ) representing the frequency information and the vertical axis ( $K_y$ ) representing the phase information and as such, the k-space maps the collected signal. The k-space may be  
10 represented as a graphic matrix of digitized MR data which represents the MR image before Fourier transformation is performed. An MR image may be created from the k-space data by application of a two-dimensional Fourier transformation. **Figs. 7A-7B** provide an illustration of a MR image of an orange slice and corresponding k-space data collected. It is noted that 3D MRI as obtained through parallel imaging techniques may  
15 also be encompassed by the present disclosure.

### **K-space full/partial sampling**

Collecting the MR signal may comprise scanning the object while acquiring local values of the MR. The collecting of the MR signal may therefore correspond to a sampling of the k-space according to a sampling pattern. The sampling pattern may be  
20 defined by a trajectory type and a trajectory density. It is noted that a sampling point density defining how the sampling points are acquired along the sampling trajectories for each trajectory may be constant for a given MRI scan. The trajectory type may define a shape of the sampling trajectories, for example, the shape of the trajectories may be selected from any of: a row, a column, a spiral, a radial line, blades, etc. The  
25 trajectory density may define how the sampling trajectories are distributed over the object. The sampling trajectories may be lines or curves along which the scanning is performed. .

Therefore, sampling of the k-space may be performed with different methods. For example, as illustrated in **Figs.6A-6C**, sampling of the k-space may be performed  
30 with a linear trajectory type i.e. by scanning along linear trajectories (scanning lines). A trajectory density of the scanning lines may vary within the scanned field of view. A

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density of the scanning lines may vary from one sampling to the other. For example, the scan illustrated on **Fig. 6A** may have a lower density of scanning trajectories than the scans illustrated on **Figs. 6B-6C**. As illustrated on **Fig. 6D**, the k-space may also be scanned (sampled) along spiral trajectories or along radial trajectories as illustrated on  
5 **Figs. 6E-6F**.

In the present disclosure, it is assumed that a prior MR baseline image (also referred to as existing data acquired at an earlier time point) may result from a k-space sampling including a higher amount of sampling points than further partial k-space data. In particular, the prior baseline k-space and the later partial k-space may result from  
10 sampling patterns having an identical or different trajectory type and/or different trajectory density and/or sampling point density. In general, the prior baseline k-space sampling pattern and the later partial k-space sampling pattern may be of different trajectory types. In other words, the prior baseline k-space sampling pattern and the later partial k-space sampling pattern may be independent.

15 In particular, the prior MR baseline image may result from a full sampling of the k-space also referred to as "full k-space". The term "full k-space" or full sampling of the k-space, may refer to a sampling which satisfies a Nyquist criterion. A partial k-space sampling may refer to a sampling with less sampling points than a full k-space sampling. In other words, the partial k-space may be a partial scanning of the object for  
20 example obtained by incompletely scanning the sampling trajectories of the baseline sampling pattern. For example, if the baseline k-space is scanned along rows, a partial sampling may constitute selecting certain rows of the entire k-space. In general, however, the prior baseline sampling pattern and the later partial sampling pattern may have different trajectory types.

25 The present disclosure provides a method of magnetic resonance imaging based on a prior magnetic resonance baseline image of an object. The method comprises: partially sampling a magnetic resonance signal originating from said object so as to collect partial k-space data; consolidating the partial k-space data with the k-space data of the baseline image to obtain consolidated k-space data; and creating an approximate  
30 image of the object using the consolidated k-space data.

In some embodiments, partially sampling the magnetic resonance signal comprises acquiring an initial partial k-space and automatically refining the initial

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partial k-space by adding additional sampling points so as to obtain a refined partial k-space.

In some embodiments, the method further comprises automatically refining the refined partial k-space by adding additional sampling points to the refined partial k-space.

In some embodiments, automatically refining the initial partial k-space or the refined partial k-space is performed based on detecting changes of the object.

In some embodiments, detecting changes of the object comprises detecting k-space discrepancies between the k-space data of the baseline image and the initial partial k-space or the refined partial k-space.

In some embodiments, adding sampling points to the initial partial k-space or to the refined partial k-space comprises adding sampling points in the vicinity of the detected k-space discrepancies.

In some embodiments, detecting changes of the object comprises detecting image discrepancies between an intermediate image derived from the initial partial k-space or from the refined partial k-space and the baseline image.

In some embodiments, the method further comprises registering the intermediate image and the baseline image.

In some embodiments, adding additional sampling points to the partial k-space or to the refined partial k-space comprises adding additional sampling points so as to image a vicinity of said detected image discrepancies.

In some embodiments, insignificant k-space discrepancies or insignificant image discrepancies are discarded.

In some embodiments, automatically refining the refined partial k-space is performed iteratively as long as additional sampling points cause changes of the object to be detected.

In some embodiments, automatically refining the refined partial k-space is iterated until the refined partial k-space reaches a predetermined amount of sampling points.

In some embodiments, automatically improving the initial partial k-space or the refined partial k-space comprises updating k-space sampling trajectories.

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In some embodiments, consolidating the partial k-space data with the k-space data of the baseline image comprises fully completing the partial k-space data with the k-space data of the baseline image.

In some embodiments, the k-space data of the baseline image is a full k-space  
5 sampled to satisfy the Nyquist criterion.

In some embodiments, creating the approximate image is based on compressed sensing.

In some embodiments, the compressed sensing reconstruction is based on sparsity in the difference between the partial k-space data and the baseline k-space data.

10 The present disclosure further provides a method of resonance magnetic scanning of a three dimensional object based on a prior magnetic resonance baseline scan comprising a set of baseline slice images preliminarily acquired at different depths of the three dimensional object, the method comprising: defining a subset of depths  
15 approximate slice images for said subset of depths according to the method of magnetic resonance imaging as previously described.

The present disclosure further provides an image reconstruction module for a magnetic resonance imaging system, the image reconstruction module being configured for cooperating with the magnetic resonance system so as to perform the method  
20 according to any of the preceding claims.

The present disclosure further provides a magnetic resonance imaging system adapted to perform the method according to any of the preceding claims.

The present disclosure further provides an image reconstruction module for a magnetic resonance imaging system, the image reconstruction module being configured  
25 for cooperating with a magnetic resonance imaging system and comprising: a data acquisition server configured to obtain a prior magnetic resonance baseline image of an object and partial k-space data from partially sampling a magnetic resonance signal originating from said object; and a data processing server configured to consolidate the partial k-space data with the k-space data of the baseline image to obtain consolidated  
30 k-space data; and creating an approximate image of the object using the consolidated k-space data.

In some embodiments, partially sampling the magnetic resonance signal comprises acquiring an initial partial k-space and the data acquisition server is further

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configured to enable the magnetic resonance system to perform automatically refining the initial partial k-space by adding additional sampling points so as to obtain a refined partial k-space.

In some embodiments, the data processing server is configured to detect changes  
5 of the object and the data acquisition server is configured to automatically refine the initial partial k-space based on the detected changes.

The present disclosure further provides a magnetic resonance imaging system comprising the image reconstruction module as previously described.

The present disclosure further provides a computer program product  
10 implemented on a non-transitory computer usable medium having computer readable program code embodied therein to cause the computer to perform a method of magnetic resonance imaging based on a prior magnetic resonance baseline image of an object, the method comprising: obtaining partial k-space data from partially sampling a magnetic resonance signal originating from said object; consolidating the partial k-space data  
15 with the k-space data of the baseline image to obtain consolidated k-space data; and creating an approximate image of the object using the consolidated k-space data.

In some embodiments, the method may comprise acquiring magnetic resonance datasets in the k-space, where the data sampling in the k-space domain is controlled during acquisition, based on comparison with the existing MRI of the object, in real-  
20 time mode.

In accordance with another aspect of the present disclosure a method is provided for generating a reconstructed image of an object from image data obtained with an MRI system, comprising a processor receiving the image data obtained with the medical imaging system by k-space sampling in trajectories computed in real-time, the processor  
25 compares the partially acquired image to an earlier time-point image of the same object and decides upon the optimal sampling of the k-space. As a result, an MR image of the object is obtained with sub-sampled k-space data (thus reducing the time required for acquisition), based on the previous time-point MR image of the object.

In addition, the datasets acquired in full k-space (baseline k-spaces) and the data  
30 acquired with any under-sampling technique (partial k-spaces), may not represent the same physical contrast of the object (i.e. may relate to different MR sequences for

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example the T1 weighted sequence or the T2 weighted sequence). Thus, the combination (consolidated k-space) may be provided with a different image contrast,

Embodiments of the present disclosure have the advantage that the quality of MR data is improved allowing for higher spatial resolution while keeping the data acquisition time and data processing time low. This permits an improved diagnostic quality of, for example, tumor detection.

Consequently, the present disclosure can for example be used to facilitate accelerated and high quality brain cancer diagnosis and grading.

In accordance with an embodiment of the present disclosure, the datasets are acquired in k-space, where an undersampling technique is designed in real time based on the comparison between the image being acquired and the early time-point image. This permits reduced scanning time, but still guarantees high image quality.

In accordance with a further embodiment, an object's regions of interest (ROIs) are detected in real-time scanning and only these regions are scanned, where regions outside the ROIs are taken from the early time-point existing scan of the object.

In accordance with a further embodiment of the present disclosure, sub-sampled data is reconstructed with compressed sensing, under the assumption of sparsity in the image domain, in the difference between the current object being scanned and the same object scanned at an earlier time point (temporal sparsity).

In accordance with a further embodiment of the present disclosure, additional sparsifying transforms, such as Wavelet or Discrete Cosine Transform (DCT) are used in conjunction with the temporal sparsifying transform during the reconstruction.

In another aspect, the present disclosure relates to a computer program product comprising computer executable instructions to perform any of the method steps described above.

In another aspect, the present disclosure relates to a magnetic resonance imaging apparatus for performing fast magnetic resonance imaging of an object, where an additional scan of the object from an earlier time point serves as an input. The apparatus comprises a magnetic resonance imaging scanner for acquiring magnetic resonance image data, a controller adapted for controlling a scanner operation of acquiring magnetic resonance datasets in the k-space domain, wherein the controller is further

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adapted to perform the dataset acquisition employing undersampling, a control system adapted for applying trajectory changes in the k-space domain in real-time and a data reconstruction system which is further adapted to support the integration of existing prior information about the object being scanned from its previous scan.

5 Additional features and advantages of the invention will be apparent from the detailed description which follows, taken in conjunction with the accompanying drawings, which together illustrate, by way of example, features of the invention.

### **BRIEF DESCRIPTION OF THE DRAWINGS**

10 In order to better understand the subject matter that is disclosed herein and to exemplify how it may be carried out in practice, embodiments will now be described, by way of non-limiting example only, with reference to the accompanying drawings, in which:

**Fig. 1** is a flowchart illustrating schematically steps of a method of magnetic resonance imaging according to embodiments of the present disclosure.

**Fig. 2** is a flow chart illustrating schematically steps of automatically improving the partial sampling according to embodiments of the present disclosure.

**Fig. 3** is a flowchart illustrating steps of an exemplary image reconstruction method utilizing an existing prior scan of the object according to embodiments of the present disclosure.

**Figs. 4A-4B** are pictorial representations of an exemplary MRI of subject, acquired respectively at an early time point and after two months.

**Fig. 5** is a block diagram of an exemplary magnetic resonance imaging ("MRI") system that employs some embodiments of the present invention.

25 **Figs. 6A-6F**, already described, illustrate different k-space sampling patterns according to embodiments of the present disclosure.

**Figs. 7A-7B** illustrate respectively a resonance magnetic image of an object and corresponding collected k-space data.

**Figs. 8A-8C** represent respectively a partial k-space, an intermediate image derived from said partial k-space and an differential image representing image discrepancies between the intermediate image and a baseline image in an example of the present disclosure.

## DETAILED DESCRIPTION OF EMBODIMENTS

Described herein are some examples of systems and methods useful for accelerating resonance magnetic imaging of an object, wherein a prior resonance magnetic baseline image of the object is available.

5 In the following detailed description, numerous specific details are set forth in order to provide a thorough understanding of the subject matter. However, it will be understood by those skilled in the art that some examples of the subject matter may be practiced without these specific details. In other instances, well-known methods, procedures and components have not been described in detail so as not to obscure the  
10 description.

As used herein, the phrase "for example," "such as", "for instance" and variants thereof describe non-limiting examples of the subject matter.

Reference in the specification to "one example", "some examples", "another example", "other examples", "one instance", "some instances", "another instance", "other  
15 instances", "one case", "some cases", "another case", "other cases" or variants thereof means that a particular described feature, structure or characteristic is included in at least one example of the subject matter, but the appearance of the same term does not necessarily refer to the same example.

It should be appreciated that certain features, structures and/or characteristics  
20 disclosed herein, which are, for clarity, described in the context of separate examples, may also be provided in combination in a single example. Conversely, various features, structures and/or characteristics disclosed herein, which are, for brevity, described in the context of a single example, may also be provided separately or in any suitable sub-combination.

25 Unless specifically stated otherwise, as apparent from the following discussions, it is appreciated that throughout the specification discussions utilizing terms such as "generating", "determining", "providing", "receiving", "using", "transmitting", "performing", "analyzing", " " or the like, may refer to the action(s) and/or process(es) of any combination of software, hardware and/or firmware. For example, these terms may  
30 refer in some cases to the action(s) and/or process(es) of a programmable machine, that manipulates and/or transforms data represented as physical, such as electronic quantities, within the programmable machine's registers and/or memories into other data similarly represented as physical quantities within the programmable machine's

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memories, registers and/or other such information storage, transmission and/or display element(s).

It is further noted that in the present disclosure, the term "prior RM baseline image" may refer to an RM image of the same object acquired at an earlier time point.

5 The object may be a human or animal body portion. The earlier baseline image and later image of the object may be such that significant medical changes may have occurred in the object i.e. a time difference between the acquisition of the baseline image and the further image may be in the scale of one or more days.

Furthermore, it is noted that in the present disclosure the term object may refer  
10 to a sliced object or to a three-dimensional object. It is further noted that the present disclosure may be similarly applied to parallel acquisition (3D MRI) of a plurality of k-spaces corresponding to a plurality of slices of the object.

A system and method for fast MRI acquisition and reconstruction is provided. In this regard, raw k-space data may be partially acquired, thus reducing the time required  
15 for acquisition. The remainder of missing k-space data may be filled in by utilizing existing MRI data of the same object from a previous scan, and the image may be reconstructed. The acquisition process may be monitored and updated in real-time. The monitoring and updating may be so as to acquire only necessary data required for repeated image reconstruction when the prior image is available.

20 **Fig. 1** illustrates generally a method of magnetic resonance imaging using a prior magnetic resonance baseline image of an object according to embodiments of the present disclosure. In a step **S100**, sampling partially a MR signal originating from the object, so as to collect partial k-space data, may be performed. The object may be a sliced object or a given slice of a three dimensional object. The partial sampling may be  
25 performed for example using a MRI system, for example as described in **Fig. 5**. The implementation of the method may be controlled by an image reconstruction module implemented on a data acquisition server and a data processing server of the MRI system. In particular, the partial sampling step may be commanded by the data acquisition server of the MRI system. As explained above, the baseline image may be  
30 associated with k-space data including a higher amount of sampling points than the partial k-space acquired in **S100**. In particular, the baseline k-space data may be a full k-space satisfying a Nyquist criterion. The baseline k-space data may be acquired according to a baseline sampling pattern. The partial k-space data may be acquired with

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a similar sampling pattern including fewer sampling points. In a step **S200**, the partial k-space collected in step **S100** may be consolidated using the k-space data of the baseline image to obtain a consolidated k-space data. Consolidating the partial k-space data may comprise completing missing k-space data of the partial k-space data using the baseline  
5 k-space data. The consolidating of the partial k-space may be performed for example using the data processing server. The partial k-space data may be partially or fully completed using the baseline k-space data. In other words, missing sampling values of the acquired partial k-space may be filled by preliminarily acquired baseline k-space data. In a step **S300**, an approximate image may be created using the consolidated k-  
10 space data. The approximate image may be obtained by Fourier transformation of the consolidated k-space data. The creation of the approximate image may be performed for example using the data processing server of the MRI system as illustrated on **Fig. 5**.

**Fig. 2** illustrates optional additional steps of automatically improving the partial sampling by selectively adding sampling points to the partial sampling acquired in step  
15 **S100**. These optional additional steps may be performed using the image reconstruction module implemented on the data processing server and the data acquisition server of the MRI system as illustrated on **Fig. 5**. These optional steps may also be performed using a dedicated module implemented on a dedicated hardware. The image reconstruction module may be configured to cooperate with the MRI system so as to be capable of  
20 commanding the data processing server and the data acquisition server of the MRI system to perform an initial partial sampling step and/or a further refining of the initial partial sampling. Following step **S101** in which an initial partial sampling is acquired, in a step **S110**, changes of the object may be detected. In a first variant, changes of the object may be detected in the k-space, for example by comparing the acquired values of  
25 the initial partial k-space with the baseline k-space to detected discrepancies between the collected partial k-space and the baseline k-space. The detected k-space discrepancies may provide k-space positions for which the initial partial k-space differs from the baseline k-space. In a second variant, changes may be detected in the image space. For example, change detection in the image space may comprise: creating an  
30 intermediate image from the initial partial k-space and detecting discrepancies between the intermediate image and the baseline image, for example by comparing pixel intensities of the intermediate image with corresponding pixel intensities in the baseline image. The detected image discrepancies may provide pixel positions for which the

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intermediate image differs from the baseline image. **Fig. 8A** illustrates a partial k-space acquired by a vertical scanning of central rows and **Fig. 8B** illustrates an intermediate image obtained by a Fourier transformation of the partial k-space of **Fig. 8A**. **Fig. 8C** illustrates detected image discrepancies between the intermediate image of **Fig. 8B** and  
5 a baseline image of the same object (not shown). In a step **S120** (optional), insignificant k-space discrepancies (in the first variant) or insignificant image discrepancies (in the second variant) may be discarded. In some embodiments, certain discrepancies may be discarded as related to a movement of the object. In some embodiments, discrepancies may be discarded based on a threshold defining a minimal extension either in the k-  
10 space or in the image space. In a step **S130**, additional sampling points may be added to the initial partial k-space so as to obtain a refined partial k-space. The additional sampling points may be acquired according to the sampling pattern used for acquiring the initial partial k-space data in step **S100**. The additional sampling points may be acquired according to additional trajectories determined based on the detected  
15 discrepancies. In other words, the additional sampling points may be acquired by sampling additional trajectories, wherein the additional trajectories follow the trajectory type of the partial sampling pattern. The additional sampling trajectories may be selected so as to acquire specific sampling points based on the detected discrepancies. For example, the additional sampling points can be acquired in a spiral pattern whose  
20 origin is the center of the k-space, by alternating horizontal lines across the k-space, or on the bottom half of the k-space. It is noted that the additional trajectories are determined in real-time i.e. during the scanning (imaging) of the object.

In the first variant, the additional sampling points may be acquired in the vicinity of the k-space discrepancies. For example, the additional trajectories may be  
25 selected so as to acquire additional sampling points in the vicinity of the k-space discrepancies. In the second variant, the additional sampling points may be acquired so as to image a vicinity of the detected image discrepancies. For example, the additional trajectories may be selected so as to acquire additional sampling points imaging the vicinity of the detected image discrepancies. These additional sampling points may be  
30 determined by inverse Fourier transformation of the detected image discrepancies. In the first variant, the vicinity of the k-space discrepancies may be defined as a predetermined radius in the k-space, for example said radius may be of about 5 to 10 per mm. In the second variant, the vicinity of the image discrepancies may be defined as a

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predetermined radius in the image space, for example said radius may be of about 1 to 3 pixels. In some embodiments, the automatic improving (refining) of the partial sampling may be iterative. The automatic improving of the partial sampling may be performed for example until changes are not detected or until a certain amount of sampling points  
5 have been acquired.

Referring to FIG. 3, a flow diagram representing a technique for acquisition and reconstruction of an MR image according to an embodiment of the invention is shown. The technique begins at block **100**, where partial image data may be acquired. Since in modern MRI the image is sampled in the k-space domain, the partial data is actually  
10 undersampled k-space data. On account of the well-known characteristics of the k-space, a full scale image can be reconstructed from only a few samples of the k-space, as shown in block **102**. This would probably be a low-resolution image due to the partial data in the k-space domain. Then, an image quality check may be performed in block **104**. If the image quality is dissatisfactory, the existing prior scan of the object is  
15 used to identify the location of the next set of the samples in the k-space, as follows. First, the image produced in block **102** may be spatially registered with the existing prior image at block **106**. In brain MRI, rigid registration techniques may be sufficient for this purpose, while in body MRI non-rigid registration techniques may be used. Then, the registered, low-quality current image may be compared to the prior image of  
20 the object at block **108**. This comparison may result in a priority map of regions to be scanned, where regions with high differences in comparison with the prior image may be given high priority. This priority map can be generated in the image domain, in the k-space domain, or in any other domain (e.g. wavelet domain). Based on this priority map, the k-space sampling trajectories may be updated at block **110**, such that the next  
25 set of k-space samples are acquired to reduce the difference in prioritized regions. This process may be repeated and additional k-space samples may be acquired until satisfactory results are obtained at block **104**. Finally, the image may be stored in block **112**.

The method of image acquisition and reconstruction in **Fig. 3** may have many  
30 advantages over previous work in the field. One major advantage may be the update of the k-space trajectories during real time acquisition. In state-of-the-art MRI, k-space sampling trajectories may be a-priori defined, and the scanner may be somewhat “blind”

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to the object currently being scanned. In the proposed technique, however, the k-space trajectories may be continuously updated during scanning, to acquire only necessary data for optimal results. Indeed, in order to follow up on tumor development, it is generally only necessary to image areas which show changes, while major portions of the body part imaged remain in fact unchanged. In other words, in many clinical applications, such as monitoring disease progression and evaluation of treatment efficacy, the most important information is the difference between the repeated scan and the prior (baseline) scan, rather than the repeated scan as a standalone scan. This difference is what the acquisition and reconstruction techniques of the present disclosure cover.

Referring to **Figs. 4A-4B**, two MR images of the same brain slice of a patient, acquired with a two month gap, are presented. These images illustrate the similarity between recurrent images of the same patient. It can be seen that despite very small differences between the later image (**FIG 4B**) and the earlier one (**FIG 4A**), the two images are very similar. This similarity allows the high quality reconstruction of the later image from partial acquisition of its k-space, and constitutes the basic premise of the technique presented in the present disclosure.

As discussed above, the method of image reconstruction illustrated in **Figs. 1-3** can be implemented with an exemplary magnetic resonance imaging ("MRI") system configured to implement this image reconstruction method. Such a system is illustrated in **Fig. 5**, to which reference is now made. The MRI system **300** may include a Workstation **302** having a display **304** and a keyboard **306**. The Workstation **302** may include a processor **308**, such as a commercially available programmable machine running a commercially available operating system. The Workstation **302** may provide the operator interface that enables scan prescriptions to be entered into the MRI system **300**. The Workstation **302** may be coupled to four servers: a pulse sequence server **310**; a data acquisition server **312**; a data processing server **314**, and a data store server **316**. The method of magnetic resonance imaging based on a prior magnetic resonance baseline image may be performed by an image reconstruction module **315** implemented on the data acquisition server **312** and on the data processing server **314** of the MRI system. The image reconstruction module **315** may be configured to implement the method of magnetic resonance imaging based on a prior magnetic resonance baseline

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image as previously described. In particular, the data processing server **314** may be configured to perform the consolidating step (b), the creating step (c) as well as the processing steps related to the refining of the initial partial sampling. The data acquisition server **312** may be configured to command the MRI system to perform the steps related to the scanning of the object. The workstation **302** and each server **310**, **312**, **314** and **316** may be connected to communicate with each other.

The pulse sequence server **310** may be configured to function in response to instructions downloaded from the workstation **302** to operate a gradient system **318** and a radiofrequency (“RF”) system **320**. Gradient waveforms necessary to perform the prescribed scan may be produced and applied to the gradient system **318**, which excites gradient coils in an assembly **322** to produce the magnetic field gradients  $G_x$ ,  $G_y$ , and  $G_z$  used for position encoding MR signals. The gradient coil assembly **322** may form part of a magnet assembly **324** that includes a polarizing magnet **326** and a whole-body RF coil **328**.

RF excitation waveforms may be applied to the RF coil **328**, or a separate local coil (not shown in **Fig. 5**), by the RF system **320** to perform the prescribed magnetic resonance pulse sequence. Responsive MR signals detected by the RF coil **328**, or a separate local coil (not shown in **Fig. 5**), may be received by the RF system **320**, amplified, demodulated, filtered, and digitized under the direction of commands produced by the pulse sequence server **310**. The RF system **320** may include an RF transmitter configured for producing a wide variety of RF pulses used in MR pulse sequences. The RF transmitter may be configured for being responsive to the scan prescription and direction from the pulse sequence server **310** to produce RF pulses of the desired frequency, phase, and pulse amplitude waveform. The generated RF pulses may be applied to the whole body RF coil **328** or to one or more local coils or coil arrays (not shown in **FIG. 3**).

The pulse sequence server **310** may also be optionally configured to receive patient data from a physiological acquisition controller **330**. The controller **330** may be configured to receive signals from a number of different sensors connected to the patient, such as electro cardiograph (“ECG”) signals from electrodes, or respiratory signals from bellows or another respiratory monitoring device. Such signals may typically be used by the pulse sequence server **310** to synchronize, or “gate,” the

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performance of the scan with the subject's heart beat or respiration. The pulse sequence server **310** may also be configured to connect to a scan room interface circuit **332**. The scan room interface circuit **332** may be configured to receive signals from various sensors associated with the condition of the patient and the magnet system. It is also  
5 through the scan room interface circuit **332** that a patient positioning system **334** may be configured to receive commands to move the patient to desired positions during the scan.

The digitized MR signal samples produced by the RF system **320** may be received by the data acquisition server **312**. The data acquisition server **312** may be  
10 configured to operate in response to instructions downloaded from the workstation **302** to receive the real-time MR data and provide buffer storage, such that no data is lost by data overrun. In some scans, the data acquisition server **312** may transfer the acquired MR data to the data processor server **314**. In scans that require information derived from acquired MR data to control the further performance of the scan, the data acquisition  
15 server **312** may be programmed to produce such information and convey it to the pulse sequence server **310**. For example, during pre-scans, MR data may be acquired and used to calibrate the pulse sequence performed by the pulse sequence server **310**.

Also, navigator signals may be acquired during a scan and used to adjust the operating parameters of the RF system **320** or the gradient system **318**, or to control the  
20 view order in which k-space is sampled. The data acquisition server **312** may also be employed to process MR signals used to detect the arrival of a contrast agent in a magnetic resonance angiography ("MRA") scan. In all these examples, the data acquisition server **312** acquires MR data and processes it in real time to produce information that is used to control the scan.

25 The data processing server **314** may be configured to receive MR data from the data acquisition server **312** and processes it in accordance with instructions downloaded from the workstation **302**. Such processing may include, for example: Fourier transformation of raw k-space MR data to produce two or three-dimensional images; the application of filters to a reconstructed image; the performance of a back projection  
30 image reconstruction of acquired MR data; the generation of functional MR images; and the calculation of motion or flow images. Images reconstructed by the data processing server **314** may be conveyed back to the workstation **302** where they may be stored.

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Real-time images may be stored in a data base memory cache (not shown in Fig. 5), from which they may be transferred to the operator display 312 or to a display 336 that is located near the magnet assembly 324 for use by attending physicians. Batch mode images or selected real time images may be stored in a host database on disc storage  
5 338. When such images have been reconstructed and transferred to storage, the data processing server 314 may notify the data store server 316 on the Workstation 302. The Workstation 302 may be used by an operator to archive the images, produce films, or send the images via a network to other facilities.

It is to be understood that the above-referenced arrangements are only  
10 illustrative of the application for the principles of the present invention. Numerous modifications and alternative arrangements can be devised without departing from the spirit and scope of the present invention. In particular, the present invention encompasses parallel magnetic resonance imaging methods (3D MRI) enabling to acquire a plurality of k-spaces corresponding to a plurality of slices of the object. While  
15 the present invention has been shown in the drawings and fully described above with particularity and detail in connection with what is presently deemed to be the most practical and preferred embodiment(s) of the invention, it will be apparent to those of ordinary skill in the art that numerous modifications can be made without departing from the principles and concepts of the invention as set forth herein.

**CLAIMS:**

1. A method of magnetic resonance imaging based on a prior magnetic resonance baseline image of an object, the method comprising:
  - (a) partially sampling a magnetic resonance signal originating from said object  
5 so as to collect partial k-space data;
  - (b) consolidating the partial k-space data with the k-space data of the baseline image to obtain consolidated k-space data; and
  - (c) creating an approximate image of the object using the consolidated k-space data.  
10
2. The method according to claim 1, wherein partially sampling the magnetic resonance signal comprises acquiring an initial partial k-space and automatically refining the initial partial k-space by adding additional sampling points so as to obtain a refined partial k-space.  
15
3. The method according to claim 2, further comprising automatically refining the refined partial k-space by adding additional sampling points to the refined partial k-space.  
20
4. The method according to any of claims 2 or 3, wherein automatically refining the initial partial k-space or the refined partial k-space is performed based on detecting changes of the object.  
25
5. The method according to claim 4, wherein detecting changes of the object comprises detecting k-space discrepancies between the k-space data of the baseline image and the initial partial k-space or the refined partial k-space..  
30
6. The method according to claim 5, wherein adding sampling points to the initial partial k-space or to the refined partial k-space comprises adding sampling points in the vicinity of the detected k-space discrepancies.

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7. The method according to claim 4, wherein detecting changes of the object comprises detecting image discrepancies between an intermediate image derived from the initial partial k-space or from to the refined partial k-space and the baseline image.
- 5 8. The method according to claim 7, further comprising registering the intermediate image and the baseline image.
9. The method according to any of claims 7 to 8, wherein adding additional sampling points to the partial k-space or to the refined partial k-space comprises adding  
10 additional sampling points so as to image a vicinity of said detected image discrepancies.
10. The method according to claim 5 or claim 7, wherein insignificant k-space discrepancies or insignificant image discrepancies are discarded.
- 15 11. The method according to any of claims 3 to 10, wherein automatically refining the refined partial k-space is performed iteratively as long as additional sampling points cause changes of the object to be detected.
- 20 12. The method according to any of claims 3 to 11, wherein automatically refining the refined partial k-space is iterated until the refined partial k-space reaches a predetermined amount of sampling points.
13. The method according to any of claims 2 to 12, wherein automatically  
25 improving the initial partial k-space or the refined partial k-space comprises updating k-space sampling trajectories.
14. The method according to any of the preceding claims, wherein consolidating the partial k-space data with the k-space data of the baseline image comprises fully  
30 completing the partial k-space data with the k-space data of the baseline image.
15. The method according to any of the preceding claims, wherein the k-space data of the baseline image is a full k-space sampled to satisfy the Nyquist criterion.

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16. The method according to any of the preceding claims, wherein creating the approximate image is based on compressed sensing.
- 5 17. The method according to claim 16, wherein the compressed sensing reconstruction is based on sparsity in the difference between the partial k-space data and the baseline k-space data.
18. A method of resonance magnetic scanning of a three dimensional object based  
10 on a prior magnetic resonance baseline scan comprising a set of baseline slice images preliminarily acquired at different depths of the three dimensional object, the method comprising:
- defining a subset of depths belonging to a volume of lesser interest of the three dimensional object;
  - 15 - creating approximate slice images for said subset of depths according to the method of magnetic resonance imaging of any of the preceding claims.
19. An image reconstruction module for a magnetic resonance imaging system, the image reconstruction module being configured for cooperating with the magnetic  
20 resonance system so as to perform the method according to any of the preceding claims.
20. A magnetic resonance imaging system adapted to perform the method according to any of the preceding claims.
- 25 21. An image reconstruction module for a magnetic resonance imaging system, the image reconstruction module being configured for cooperating with a magnetic resonance imaging system and comprising:
- a data acquisition server configured to obtain a prior magnetic resonance baseline image of an object and partial k-space data from partially sampling  
30 a magnetic resonance signal originating from said object; and
  - a data processing server configured to consolidate the partial k-space data with the k-space data of the baseline image to obtain consolidated k-space

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data; and creating an approximate image of the object using the consolidated k-space data.

22. The image reconstruction module according to claim 21, wherein partially  
5 sampling the magnetic resonance signal comprises acquiring an initial partial k-space and the data acquisition server is further configured to enable the magnetic resonance system to perform automatically refining the initial partial k-space by adding additional sampling points so as to obtain a refined partial k-space.

10 23. The image reconstruction module according to claim 22, wherein the data processing server is configured to detect changes of the object and the data acquisition server is configured to automatically refine the initial partial k-space based on the detected changes.

15 24. A magnetic resonance imaging system comprising the image reconstruction module according to any of claims 21-23.

25 25. A computer program product implemented on a non-transitory computer usable medium having computer readable program code embodied therein to cause the computer to perform a method of magnetic resonance imaging based on a prior magnetic resonance baseline image of an object, the method comprising:

- (a) obtaining partial k-space data from partially sampling a magnetic resonance signal originating from said object;
- (b) consolidating the partial k-space data with the k-space data of the baseline image to obtain consolidated k-space data; and
- (c) creating an approximate image of the object using the consolidated k-space data.

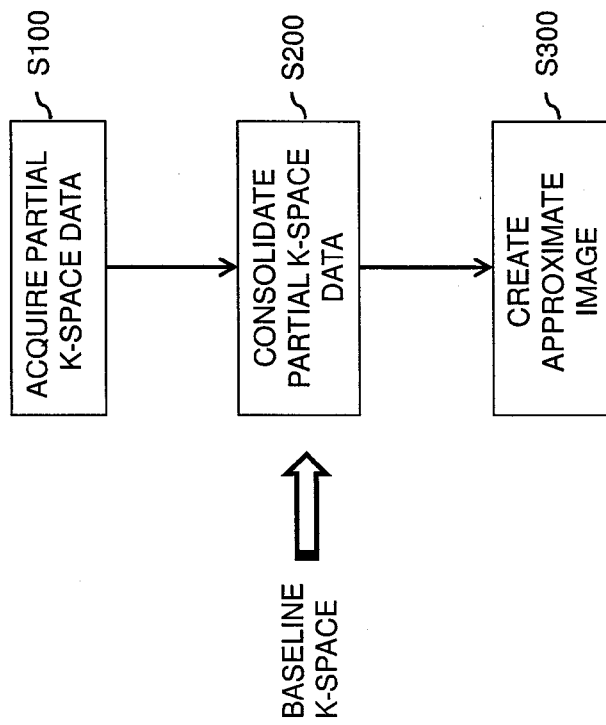


Fig. 1

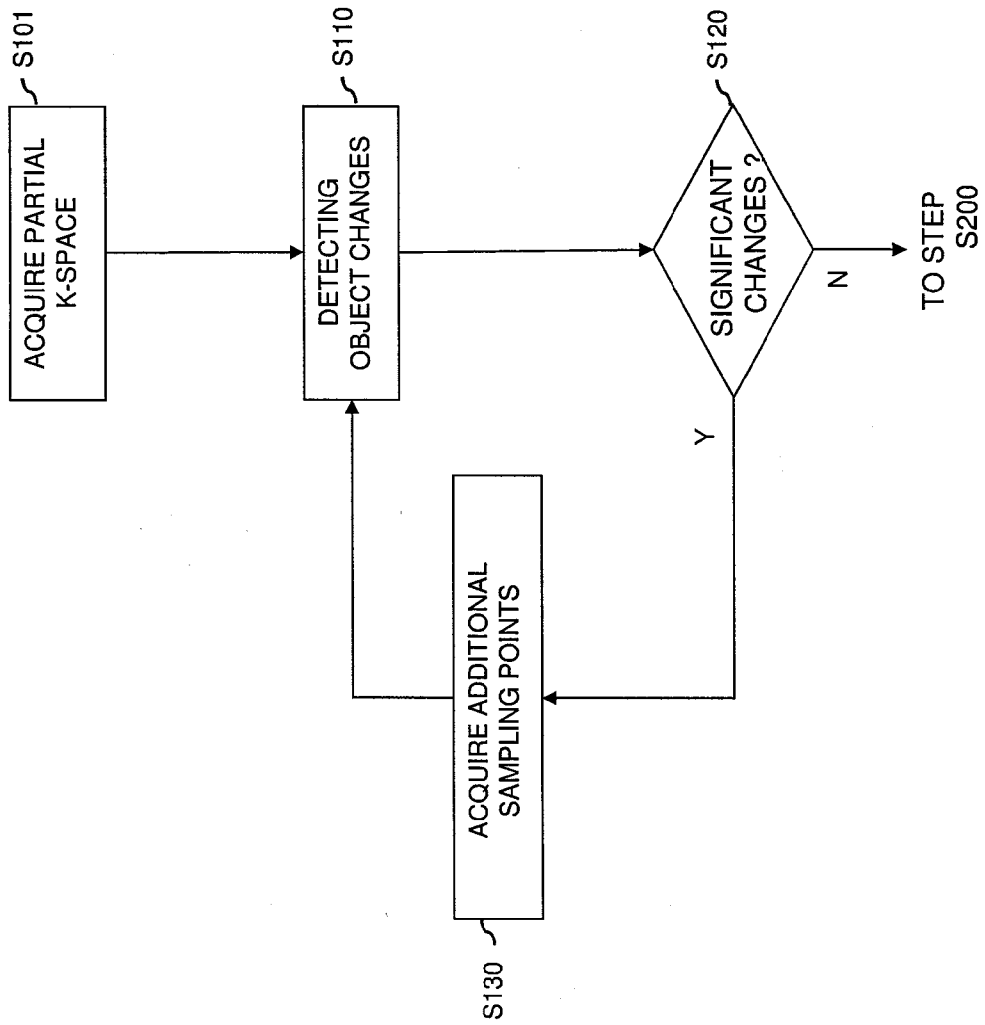


Fig. 2

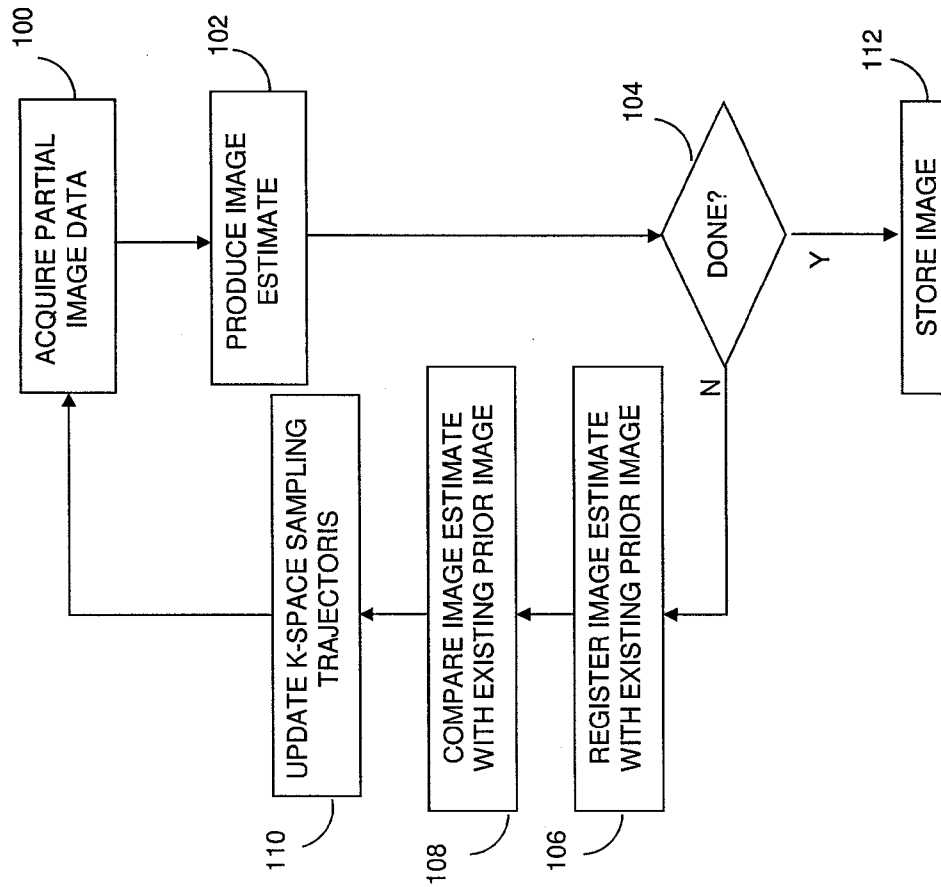


Fig. 3

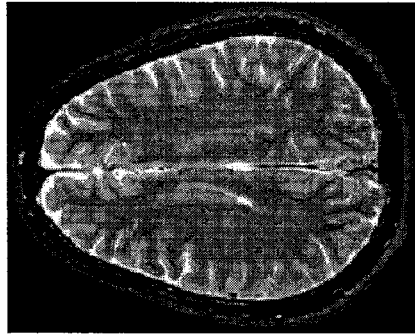


Fig. 4B

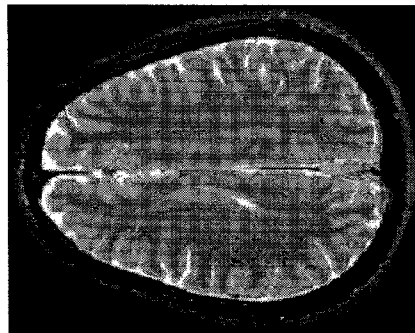


Fig. 4A

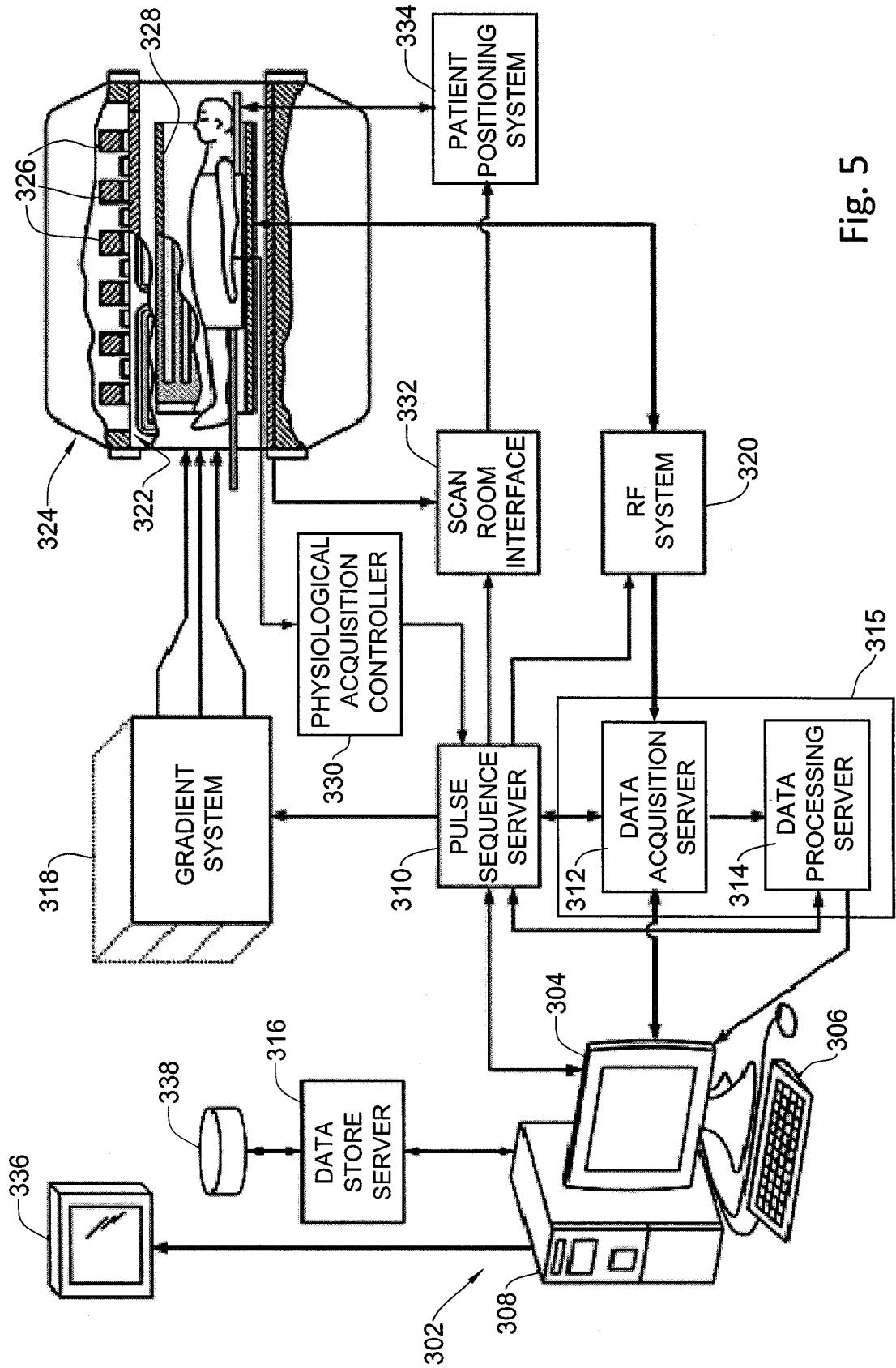


Fig. 5

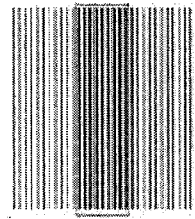


Fig. 6C

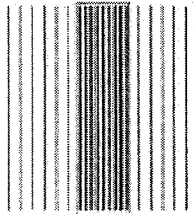


Fig. 6B

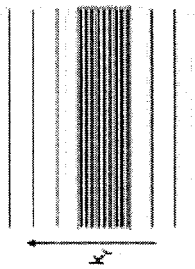


Fig. 6A

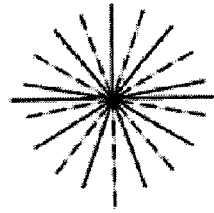


Fig. 6F

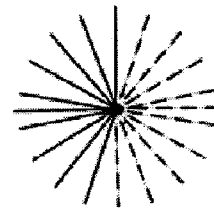


Fig. 6E

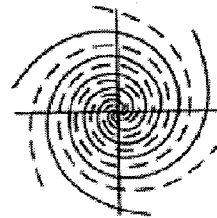


Fig. 6D

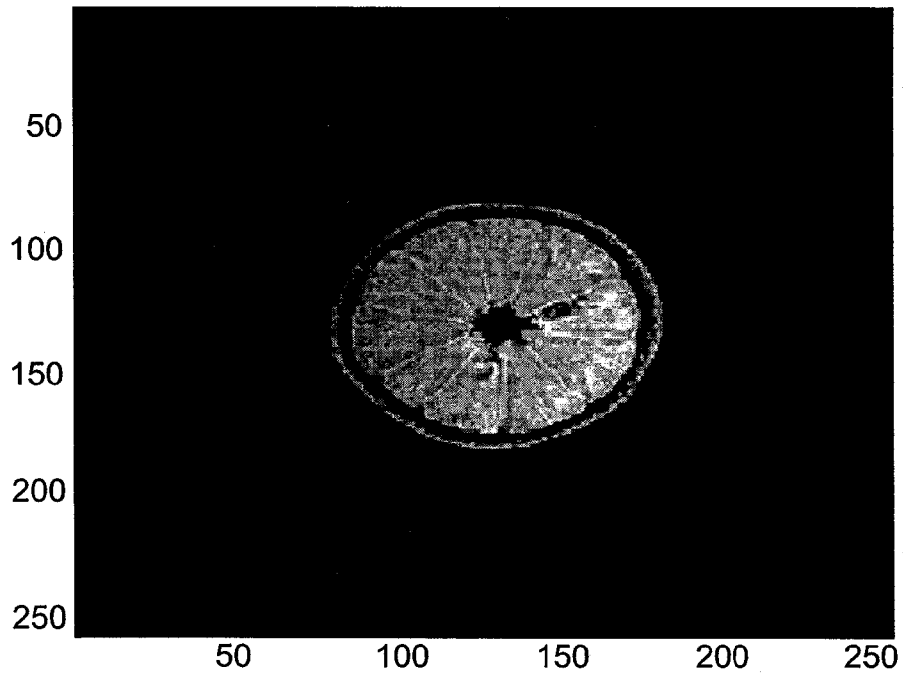


Fig. 7A

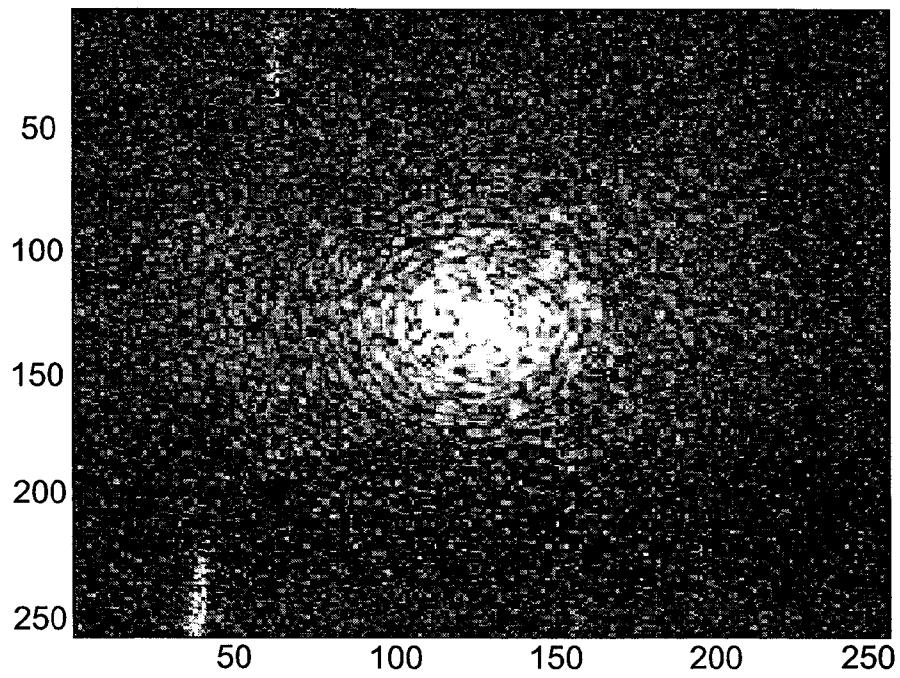


Fig. 7B

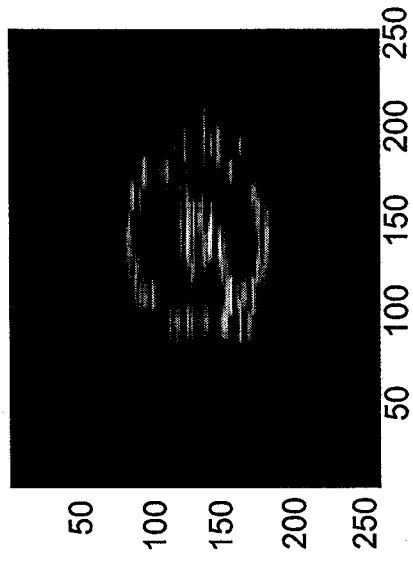


Fig. 8A

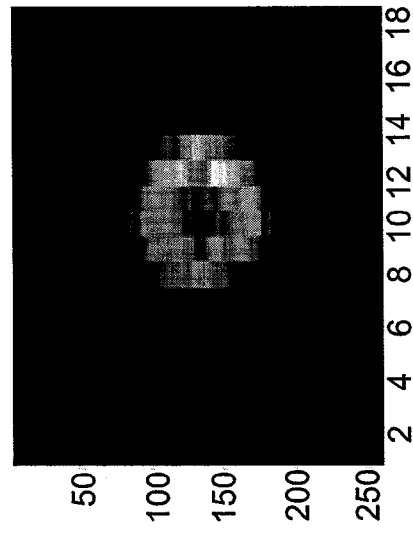


Fig. 8B

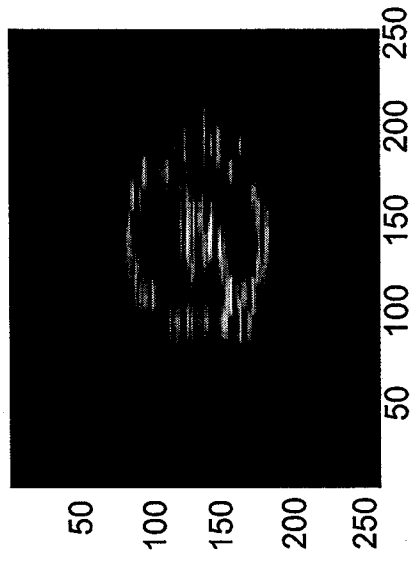


Fig. 8C

**INTERNATIONAL SEARCH REPORT**

International application No  
PCT/IL2015/050071

**A. CLASSIFICATION OF SUBJECT MATTER**  
INV. G01R33/561  
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**  
Minimum documentation searched (classification system followed by classification symbols)  
G01R

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)  
EPO-Internal

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	OESTERLE C ET AL: "IMPROVEMENT OF SPATIAL RESOLUTION OF KEYHOLE EFFECT IMAGES", MAGNETIC RESONANCE IN MEDICINE, JOHN WILEY & SONS, INC, US, vol. 39, no. 2, 1 February 1998 (1998-02-01), pages 244-250, XP000826286, ISSN: 0740-3194 the whole document	1-12,14, 15,18-25
X	YUE CAO ET AL: "Feature-recognizing MRI", MAGNETIC RESONANCE IN MEDICINE, vol. 30, no. 3, 1 September 1993 (1993-09-01), pages 305-317, XP055047564, ISSN: 0740-3194, DOI: 10.1002/mrm.1910300306 the whole document	1-12,14, 15,18-25

Further documents are listed in the continuation of Box C.

See patent family annex.

\* Special categories of cited documents :

- "A" document defining the general state of the art which is not considered to be of particular relevance
- "E" earlier application or patent but published on or after the international filing date
- "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- "O" document referring to an oral disclosure, use, exhibition or other means
- "P" document published prior to the international filing date but later than the priority date claimed

- "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
- "&" document member of the same patent family

Date of the actual completion of the international search  12 March 2015	Date of mailing of the international search report  20/03/2015
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Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer  Lersch, Wilhelm
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## INTERNATIONAL SEARCH REPORT

International application No  
PCT/IL2015/050071

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	<p>WO 99/14616 A1 (ELSCINT LTD [IL]; HARVEY PAUL [IL]) 25 March 1999 (1999-03-25)</p> <p>page 6, line 29 - page 9, line 32 page 14, line 4 - page 15, line 27 page 18, line 26 - page 18, line 31 figure 2</p> <p style="text-align: center;">-----</p>	1-5,7,8, 10-15, 18-25
X	<p>A A SAMSONOV ET AL: "Accelerated Serial MR Imaging in Multiple Sclerosis Using Baseline Scan Information", PROC.INTL.SOC.MAG.RESON.MED., 1 May 2010 (2010-05-01), page 4876, XP055175861, the whole document</p> <p style="text-align: center;">-----</p>	1,14-21, 24,25
X,P	<p>Lior Weizman ET AL: "Compressed sensing for longitudinal MRI: An adaptive-weighted approach",</p> <p>10 July 2014 (2014-07-10), XP055175863, Retrieved from the Internet: URL:<a href="http://arxiv.org/abs/1407.2602">http://arxiv.org/abs/1407.2602</a> [retrieved on 2015-03-12] see chapters 1,2,4 and 5</p> <p style="text-align: center;">-----</p>	1-4,7,8, 11,15, 16,19-25
X,P	<p>LIOR WEIZMAN ET AL: "Fast MRI for repeated scans", SECOND INTERNATIONAL WORKSHOP ON SPARSITY TECHNIQUES IN MEDICAL IMAGING (STMI 2014), 14 September 2014 (2014-09-14), pages 1-9, XP055175868, the whole document</p> <p style="text-align: center;">-----</p>	1,14,15, 18-21, 24,25

# INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/IL2015/050071

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 9914616	A1	NONE	25-03-1999
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