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- (71) **Applicant:** THE UNITED STATES OF AMERICA, AS REPRESENTED BY THE SECRETARY, DEPARTMENT OF HEALTH AND HUMAN SERVICES [US/US]; Office of Technology Transfer, National Institutes of Health, 6011 Executive Blvd., Suite 325, Rockville, Maryland 20852-3804 (US).
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- (74) **Agents:** GALANT, Ron et al.; Polsinelli PC, 161 N. Clark Street, Suite 4200, Chicago, Illinois 60601 (US).
- (81) **Designated States** (*unless otherwise indicated, for every kind of national protection available*): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.
- (84) **Designated States** (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).
- Published:**
— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

(54) **Title:** SYSTEM AND APPARATUS FOR REAL-TIME PROCESSING OF MEDICAL IMAGING RAW DATA USING CLOUD COMPUTING

(57) **Abstract:** The present invention relates to a system and apparatus for managing and processing raw medical imaging data.



SYSTEM AND APPARATUS FOR REAL-TIME PROCESSING OF MEDICAL IMAGING RAW DATA USING CLOUD COMPUTING

[0001] The computing process (image formation from raw data) in medical imaging has become increasingly complex with high computational demands. The computational equipment (in general a single computer) deployed with clinical imaging systems is often inadequate for achieving clinically practical image reconstruction times. The hardware has to be specified and tested years before the imaging devices are deployed and the hardware is consequently obsolete before it is deployed. After the imaging data is acquired, one or more processing steps are performed to reconstruct an image using the imaging data. Conventional processing systems are located proximate to the image acquisition hardware (e.g., ultrasonic scanner, magnetic resonance imaging (MRI), and computed tomography (CT)). This processing raw image data may be quite intensive in nature, and may require significant processing capability.

[0002] Aspects of the present system and apparatus eliminate the need to deploy data processing hardware locally by deploying the image reconstruction hardware and software in a (remote) cloud computing system. The powerful computational resources available in commercial cloud systems can be leveraged directly in modern medical imaging devices and by doing so, the image processing hardware is replaced by a flexible software component, which can be scaled on-the-fly to match modern algorithms and which can be serviced and deployed remotely. For the end-user of imaging device, e.g. the physician or technician operating the scanner, they will feel no differences than if the computation was performed locally. We have demonstrated that this is possible with clinical MRI systems and using this paradigm, image reconstruction can be sped up by an order of magnitude for some applications.

[0003] Additional detail and description of the functionality of the system and apparatus for managing and/or processing of medical imaging raw, according to aspects of the present invention, is provided in the attached Appendices.

Appendix 1

Cardiac Function and Morphology Future Perspectives

Michael S. Hansen, PhD
Magnetic Resonance Technology Program
National Institutes of Health - NHLBI



U.S. Department of
Health and Human
Services



National Institutes
of Health



National Heart, Lung,
and Blood Institute

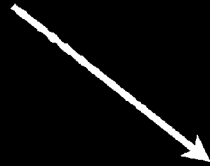
Appendix 1

No conflicts of interest to disclose

Mandav . January 27 14

Appendix 1

FREE BREATHING



True Real-Time
Function



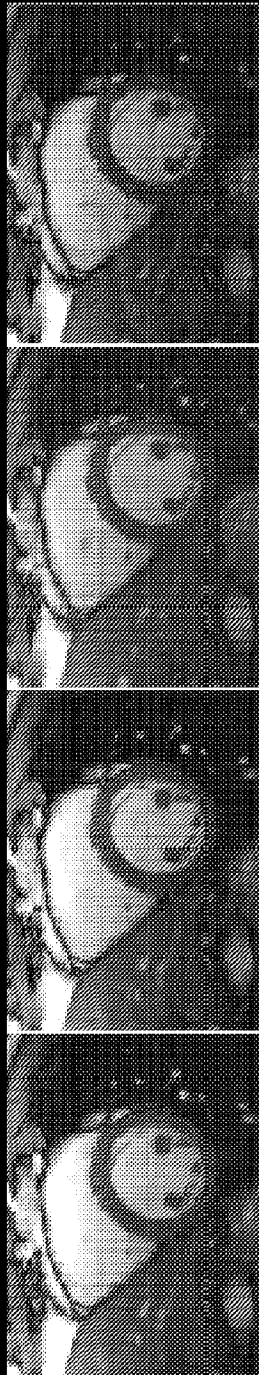
Real-Time
+ Motion Compensation

Mandav . January 27 14

The Future is Here: Parallel Imaging

Appendix 1

R=1 R=2 R=3 R=4



256x192

parallel
imaging
for
reduced
breath-hold

16 HB 8 HB 6 HB 4 HB



128x72

parallel
imaging
for
real-time
free-breathing
acquisition
with improved
temporal
resolution

158 ms 79 ms 53 ms 40 ms



192x108

280 ms 140 ms 94 ms 70 ms

Courtesy Peter Kellman, NHLBI, NIH

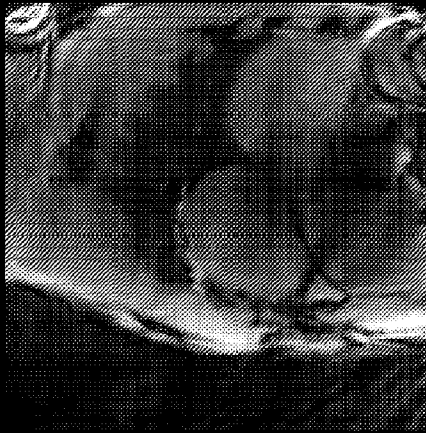
Real-Time Function Examples

Appendix 1

Real-Time Spiral SSFP
38ms/frame

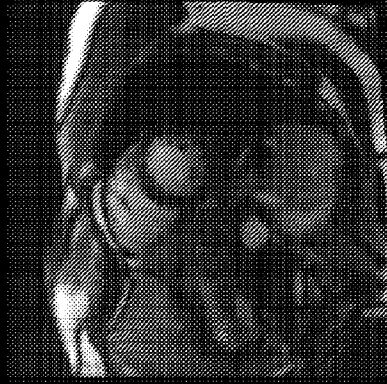
Joelle Barral, HeartVista

Real-Time Gold Angle Radial SSFP
192x192 matrix, 60ms/frame



"Off-the-shelf gadgetron recon"
Thomas Sorensen, Aarhus, Denmark

Real-Time Radial SSFP
192x192 matrix, 48ms/frame

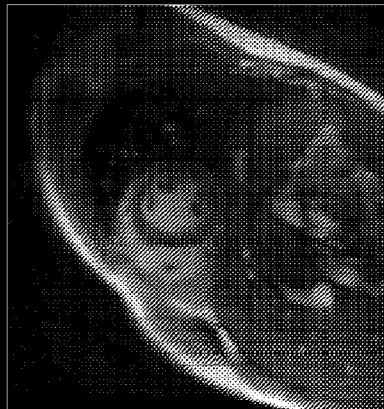


Haris Saybasily, Siemens
Nicole Steberlich, Case Western

Real-Time Function Examples

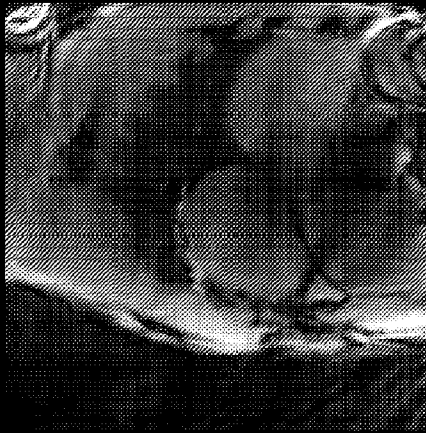
Appendix 1

Real-Time Spiral SSFP
38ms/frame



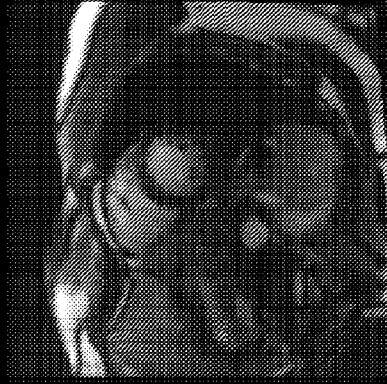
Joelle Barral, HeartVista

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192x192 matrix, 60ms/frame



"Off-the-shelf gadgetron recon"
Thomas Sorensen, Aarhus, Denmark

Real-Time Radial SSFP
192x192 matrix, 48ms/frame



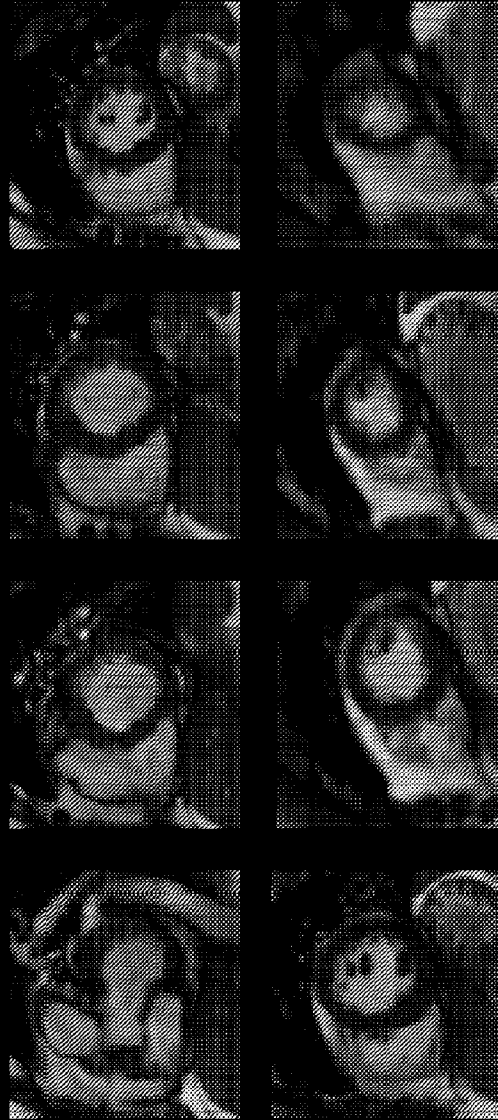
Haris Saybasily, Siemens
Nicole Steberlich, Case Western

Appendix 4

k-t Sparse: Cardiac Real-time CINE MRI*

SIEMENS

- Iterative k-t sparse reconstruction might become a key enabler for cardiac real-time CINE MRI
- Proposed Protocol
 - CINE TrueFISP, 1.5T
 - ECG triggered
 - Net Acceleration: 9.2
 - 16 heart-beats for 8 slices
 - Spatial resolution: 2.2 (2.6) x 2.2 x 8 mm³
 - Temp. resolution: 30 ms
- Aim: Recon. time: ~15 s per slice



Volunteer: 135 kg, 176cm, BMI:43

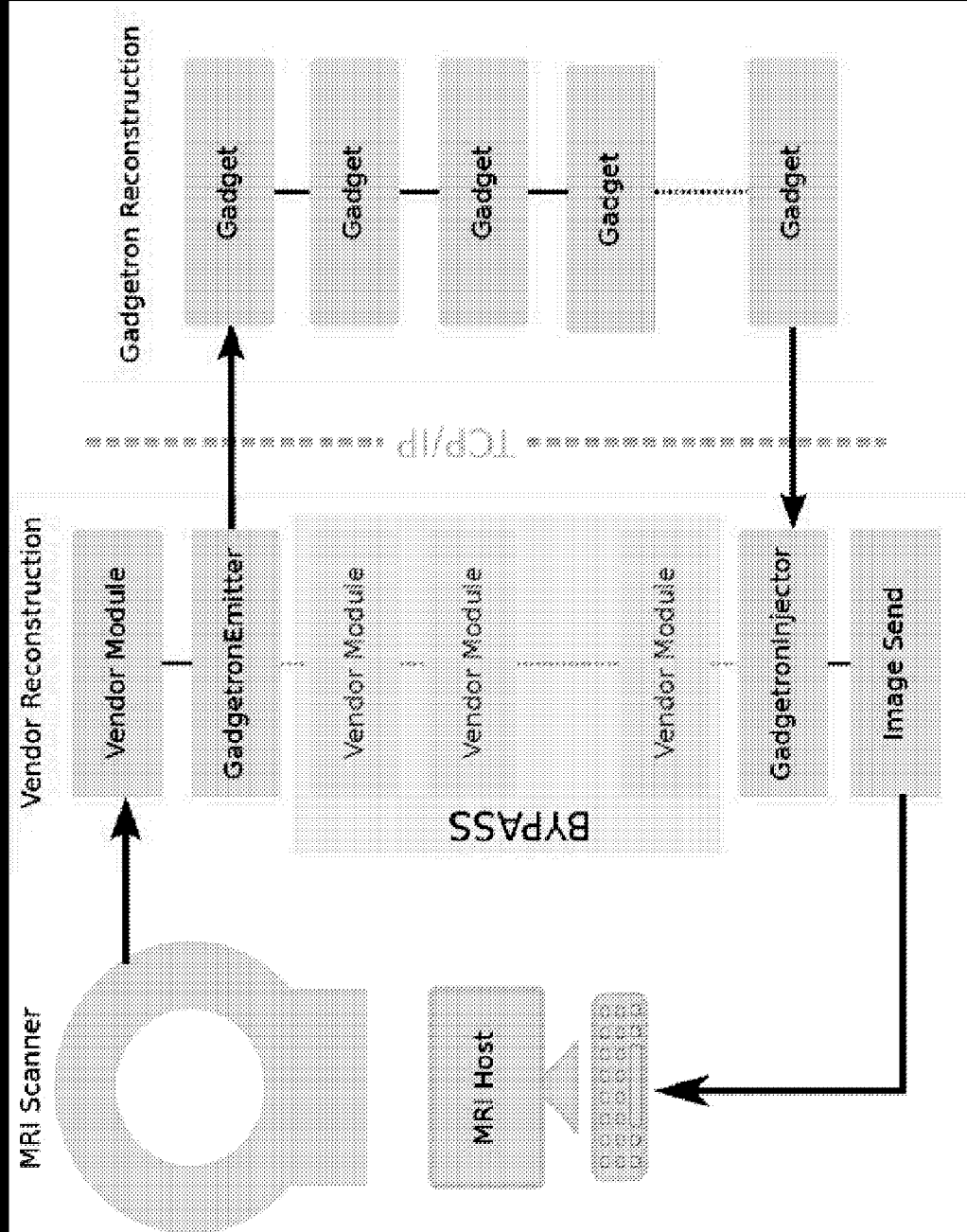
Unrestricted © Siemens AG 2013 All rights reserved.

* The product is currently under development; is not for sale in the U.S. and other countries. Its future availability cannot be guaranteed.

Slides provided by Michael Zenge, Siemens

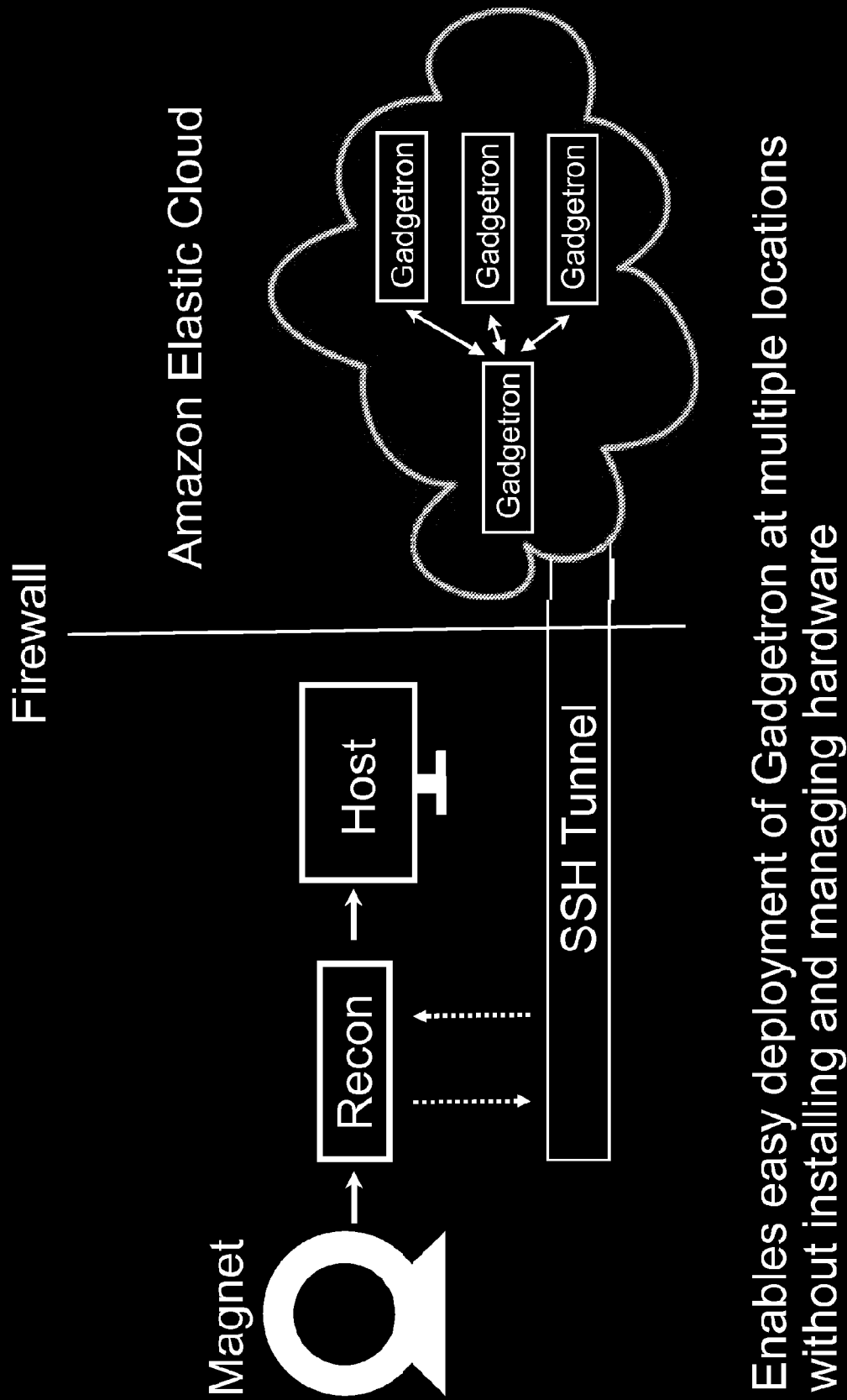
Magnetic Resonance

Appendix 1 Gadgetron Scanner Integration



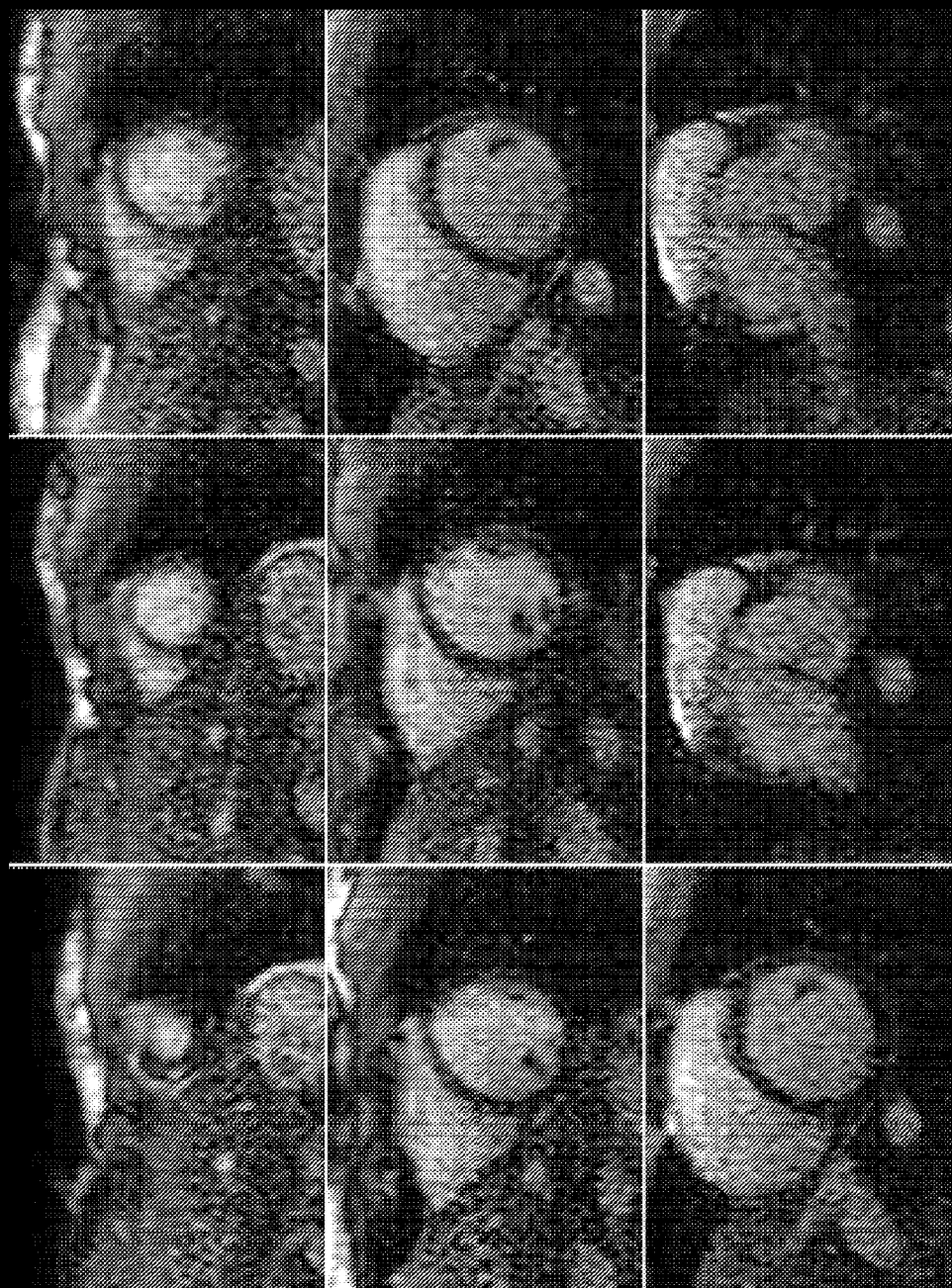
Appendix 1

Gadgetron in the Cloud



Cloud Based Gadgetron Reconstruction

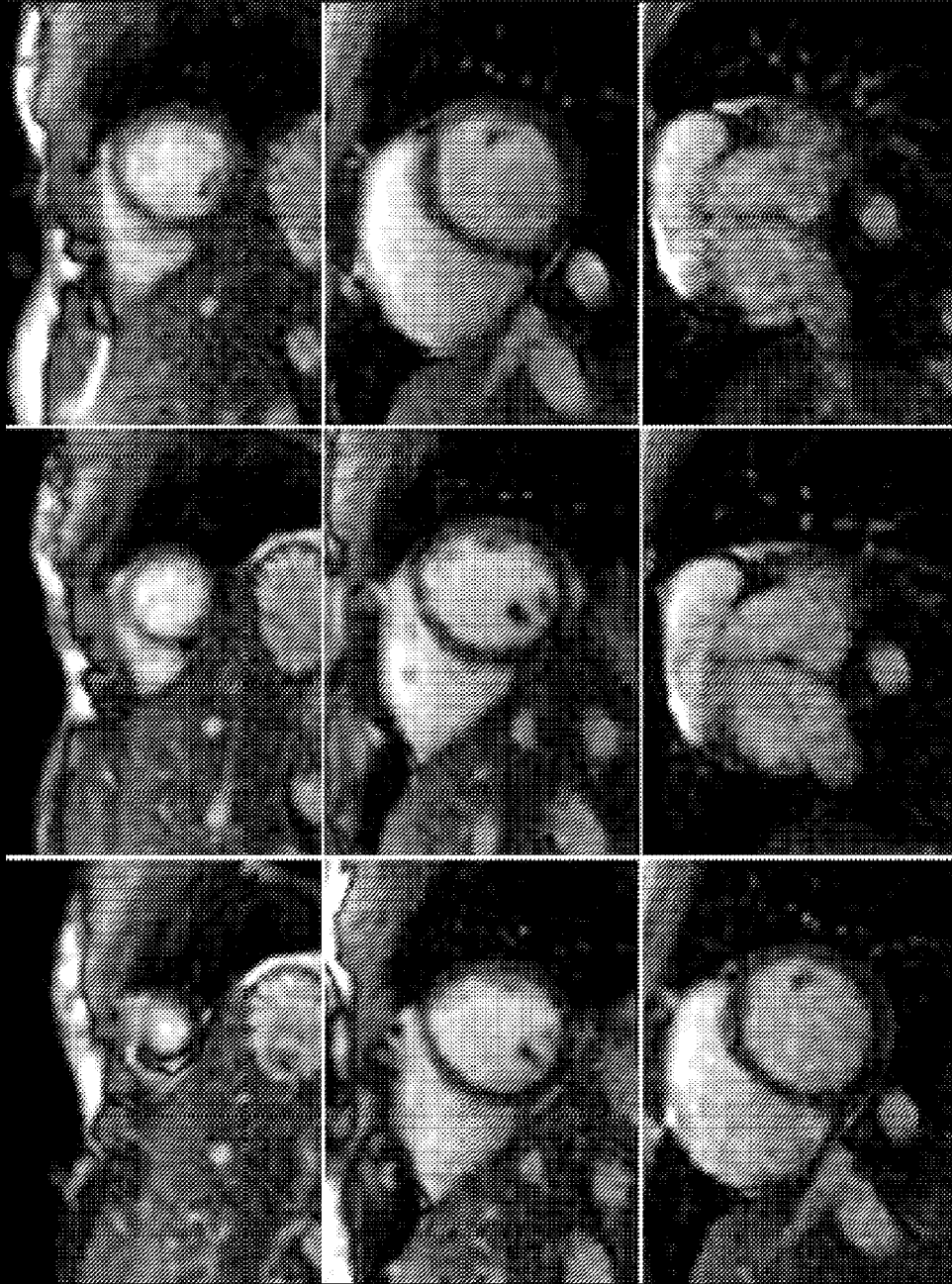
Appendix 1



Hui Xue, NHLBI, NIH

Cloud Based Gadgetron Reconstruction

Appendix 1



192x100 matrix
Rate 5
~50ms/frame

Acquired and
reconstructed
in <1min

Hui Xue, NHLBI, NIH

Improving Real-Time Cardiac MRI

Appendix 1

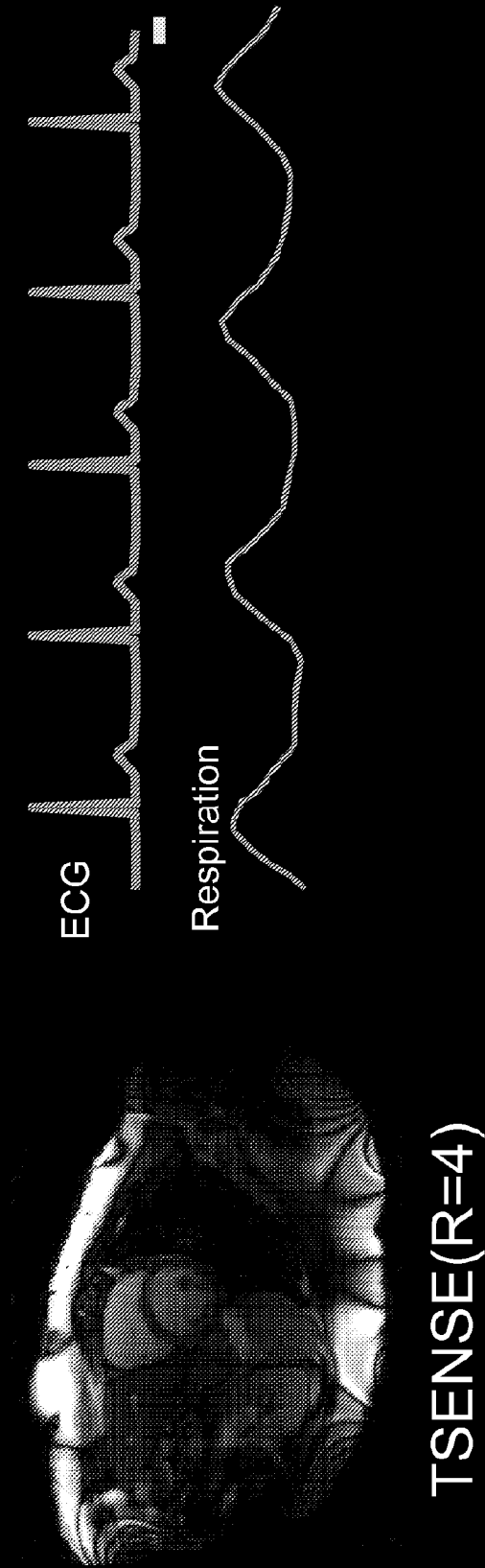


TSENSE(R=4)

Kellman et al. Magn Res Med. 2009, Hansen et al. Magn Reson Med 2012

Improving Real-Time Cardiac MRI

Appendix 1



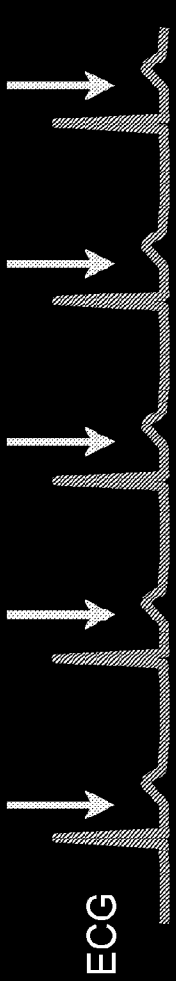
Kellman et al. Magn Res Med. 2009; Hansen et al. Magn Reson Med 2012

Improving Real-Time Cardiac MRI

Appendix 1



TSENSE(R=4)



Single Cardiac Phase

Non-Rigid Registration



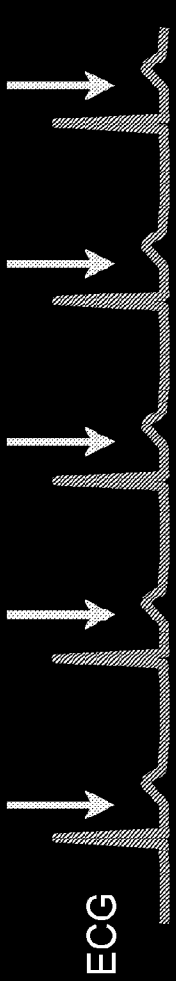
Kellman et al. Magn Res Med. 2009; Hansen et al. Magn Reson Med 2012

Improving Real-Time Cardiac MRI

Appendix 1



TSENSE(R=4)



Single Cardiac Phase



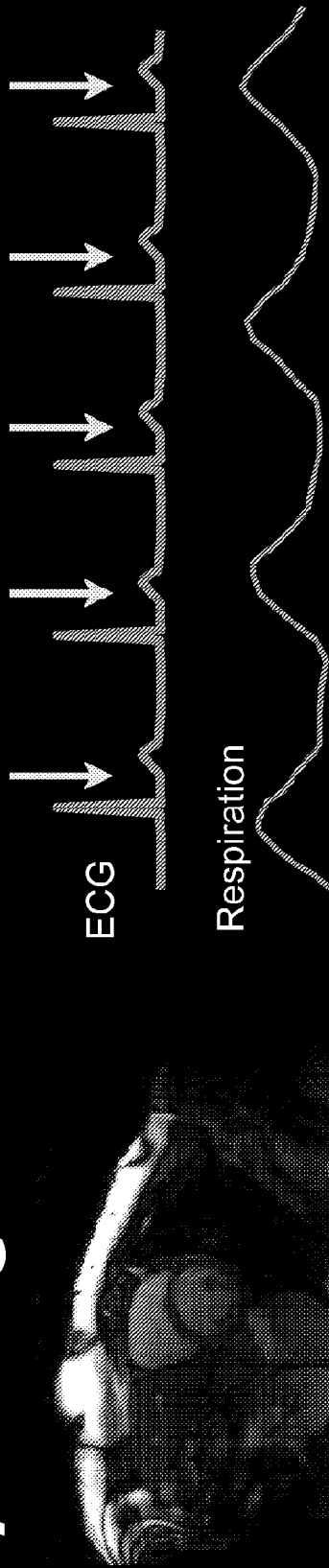
Non-Rigid Registration



Kellman et al. Magn Res Med. 2009; Hansen et al. Magn Reson Med 2012

Improving Real-Time Cardiac MRI

Appendix 1



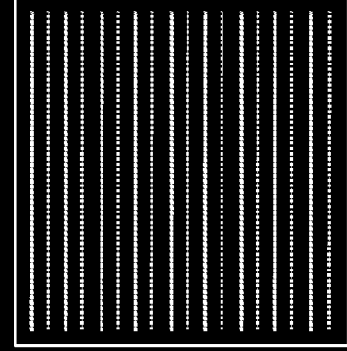
TSENSE(R=4)

k-space

FT

Non-Rigid Registration

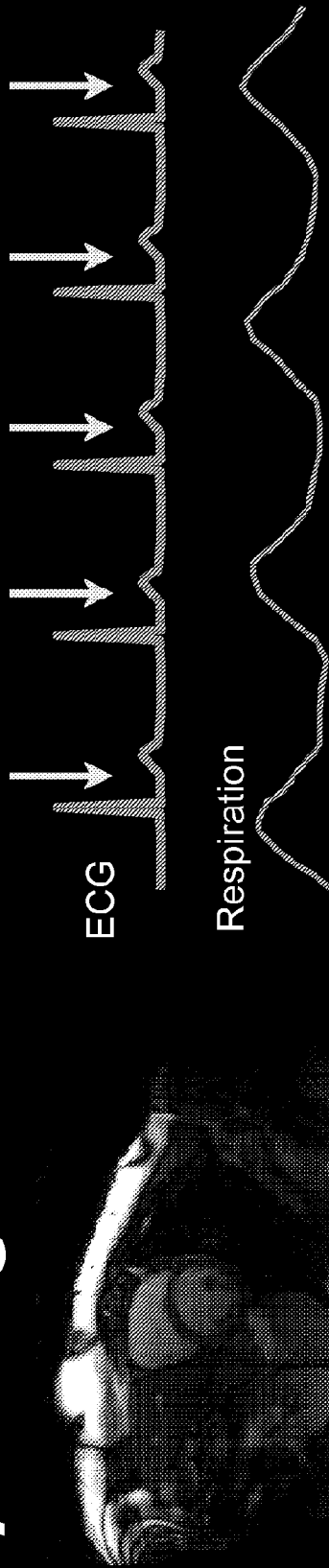
Single Cardiac Phase



Kellman et al. Magn Res Med. 2009, Hansen et al. Magn Reson Med 2012

Improving Real-Time Cardiac MRI

Appendix 1



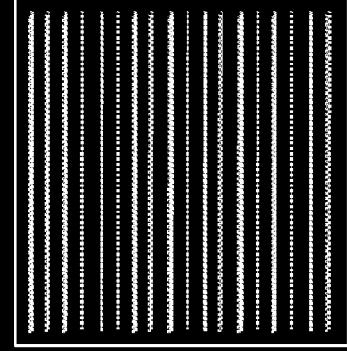
TSENSE(R=4)

k-space

FT

Non-Rigid Registration

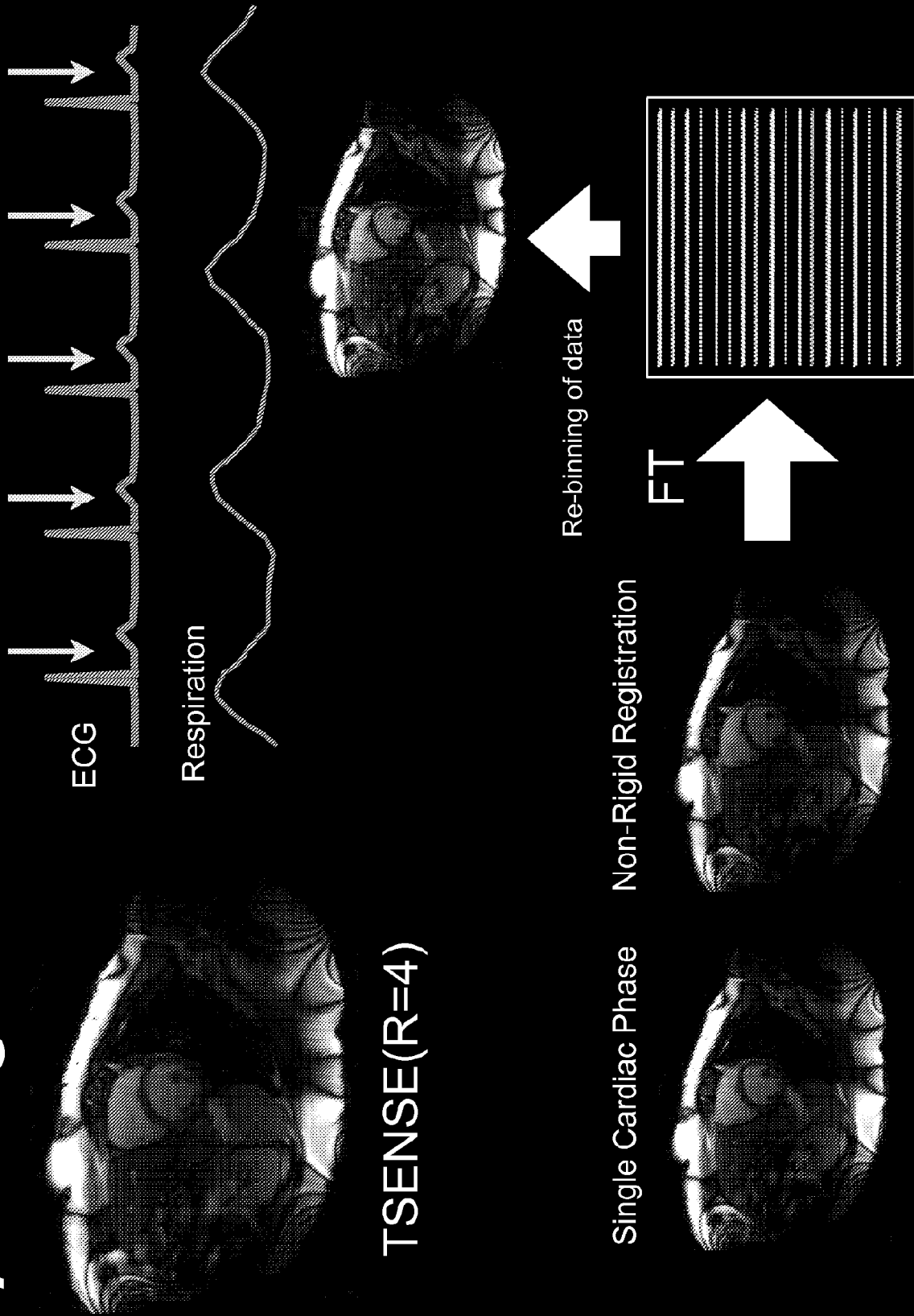
Single Cardiac Phase



Kellman et al. Magn Res Med. 2009, Hansen et al. Magn Reson Med 2012

Improving Real-Time Cardiac MRI

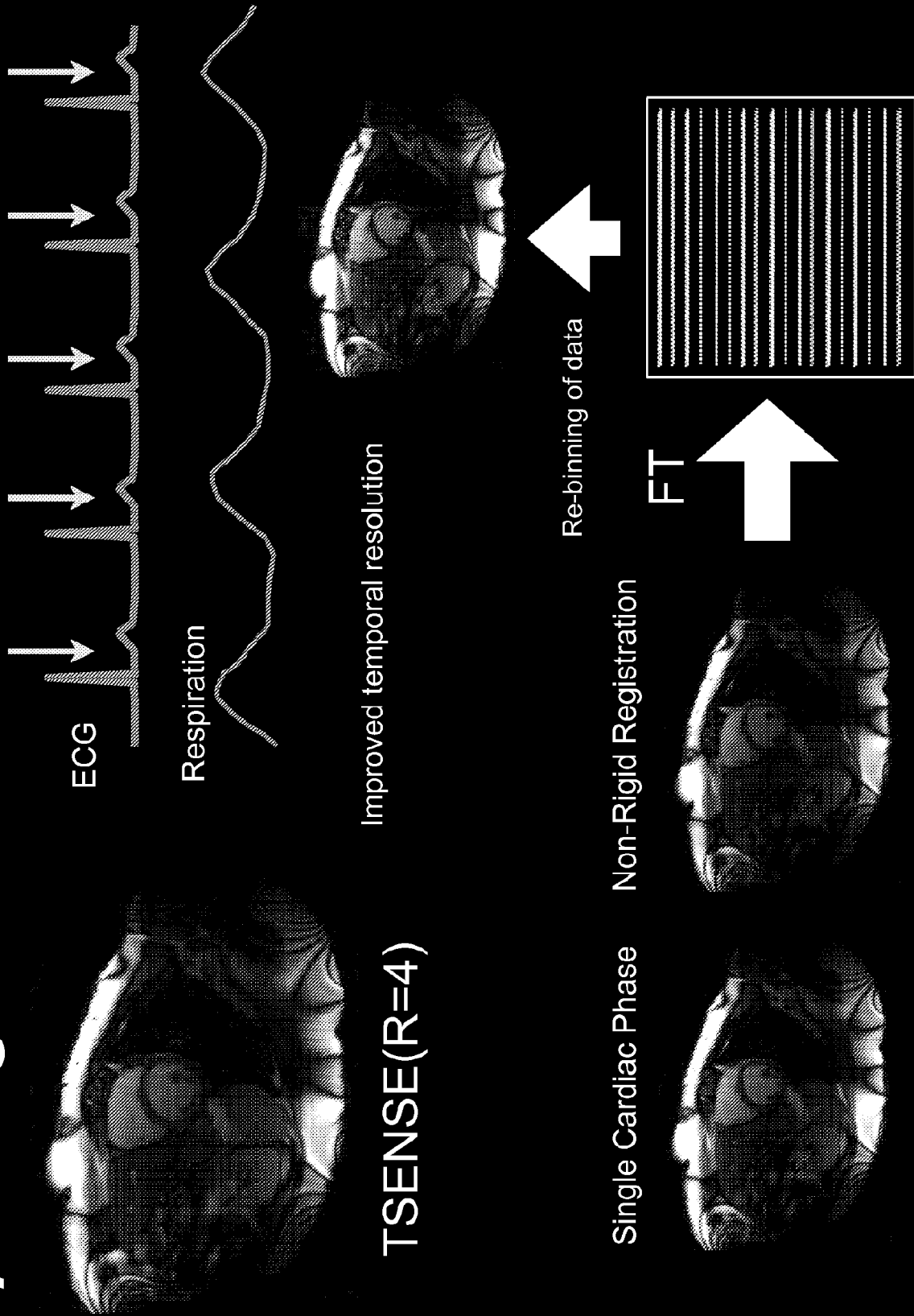
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Kellman et al. Magn Res Med. 2009, Hansen et al. Magn Reson Med 2012

Improving Real-Time Cardiac MRI

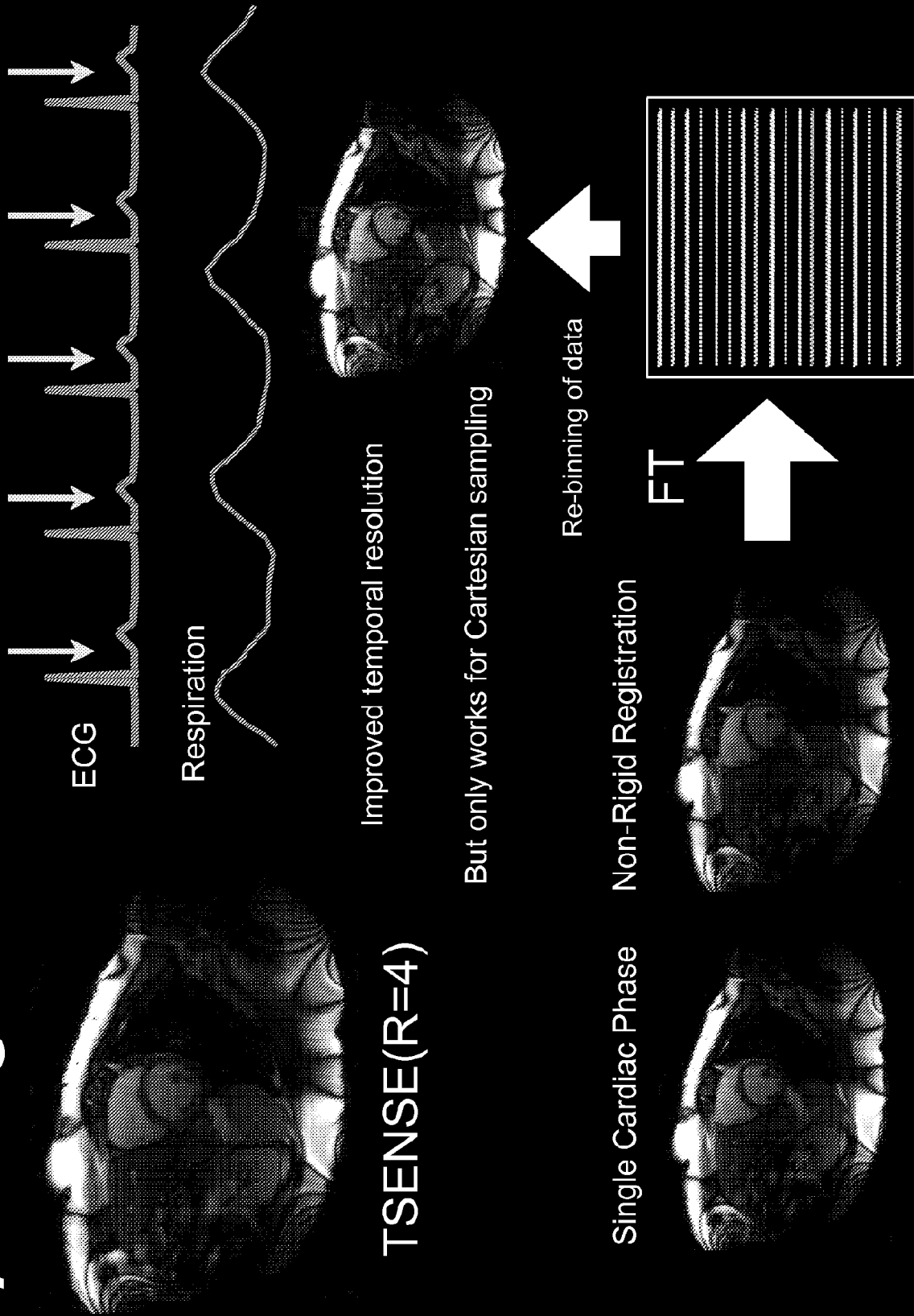
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Kellman et al. Magn Res Med. 2009, Hansen et al. Magn Reson Med 2012

Improving Real-Time Cardiac MRI

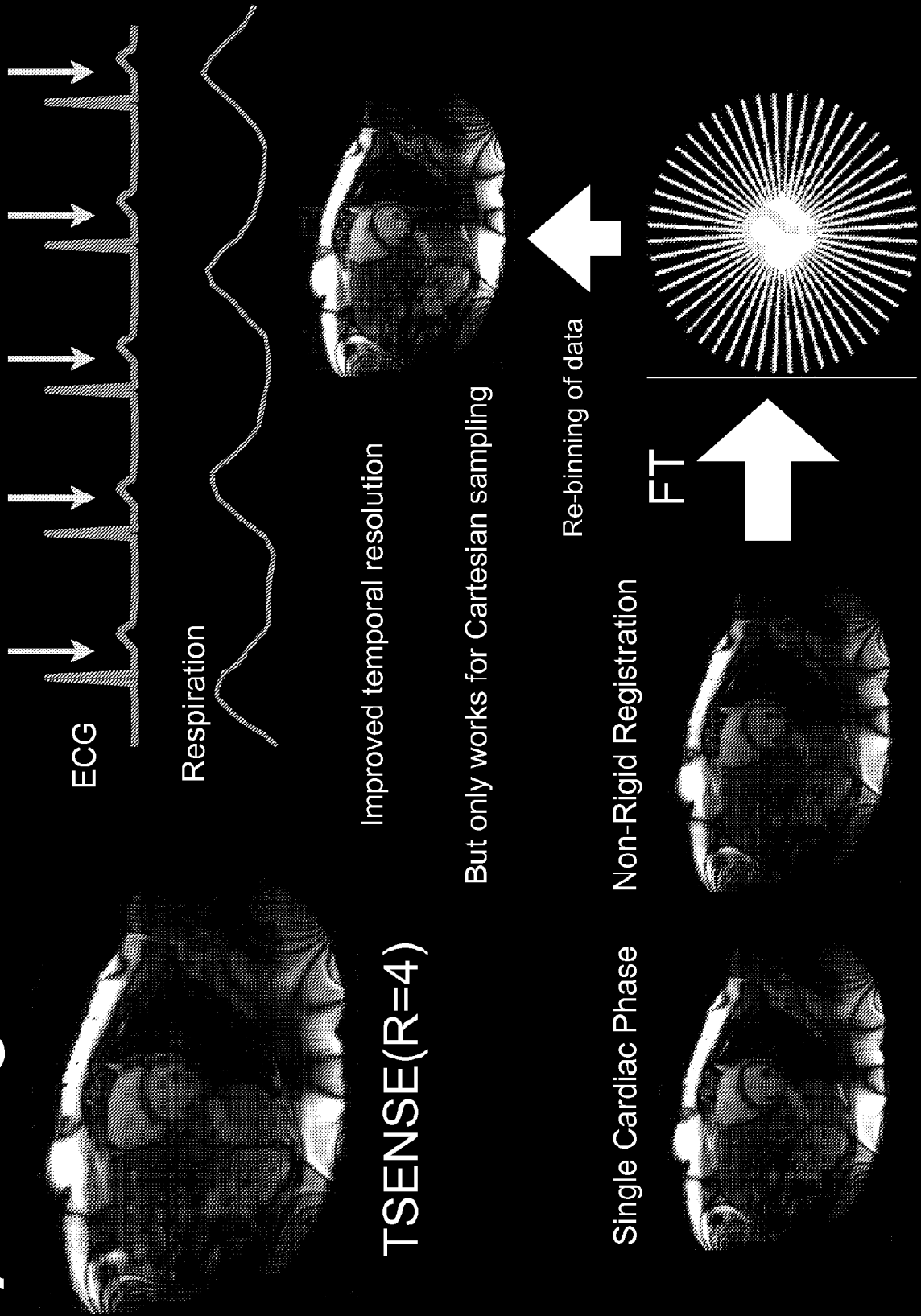
Appendix 1



Kellman et al. Magn Res Med. 2009, Hansen et al. Magn Reson Med 2012

Improving Real-Time Cardiac MRI

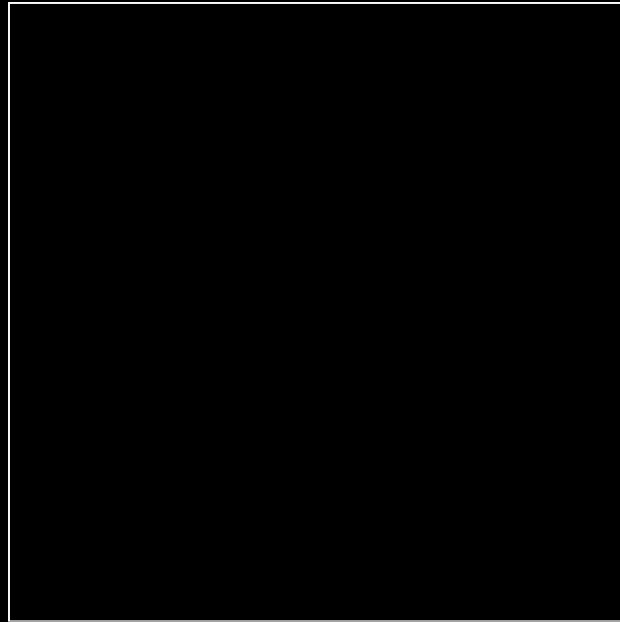
Appendix 1



Kellman et al. Magn Res Med. 2009, Hansen et al. Magn Reson Med 2012

Appendix 1 *Motivation for non-Cartesian Acquisition*

We would like to use the Golden Angle Trajectory



Each subsequent profile is rotated
111.23 degrees from previous

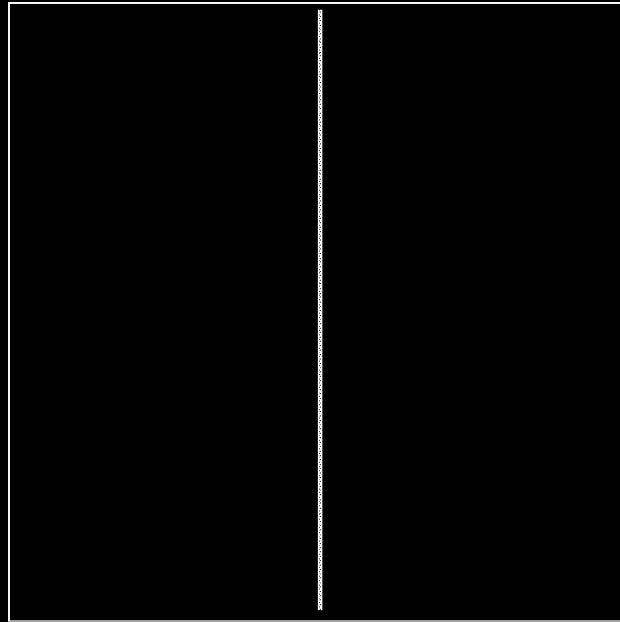
Temporal resolution can be adjusted
dynamically

Time



Appendix 1 *Motivation for non-Cartesian Acquisition*

We would like to use the Golden Angle Trajectory



Each subsequent profile is rotated
111.23 degrees from previous

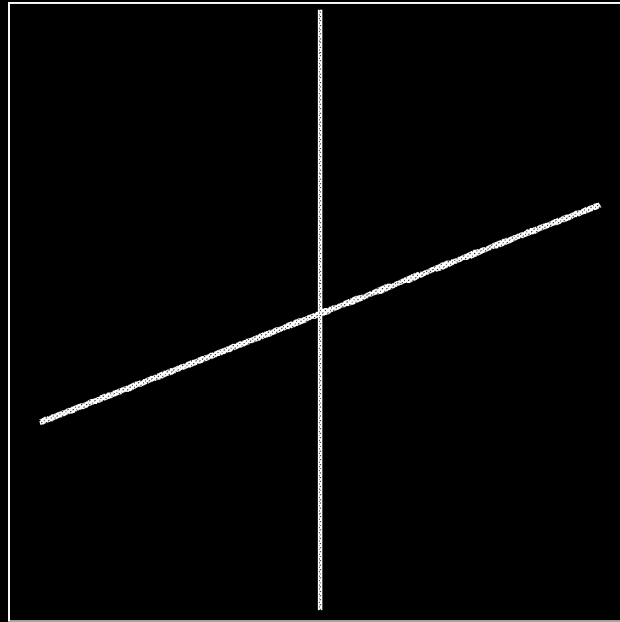
Temporal resolution can be adjusted
dynamically

Time

A horizontal arrow pointing to the right, with the word "Time" written above it.

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We would like to use the Golden Angle Trajectory



Each subsequent profile is rotated
111.23 degrees from previous

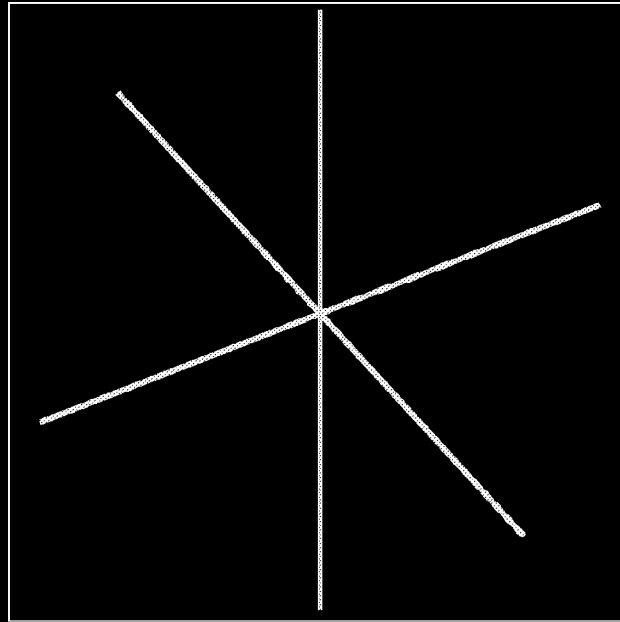
Temporal resolution can be adjusted
dynamically

Time

A white vertical arrow pointing upwards, starting from a small horizontal bar at the bottom and ending in a white arrowhead at the top.

Appendix 1 *Motivation for non-Cartesian Acquisition*

We would like to use the Golden Angle Trajectory



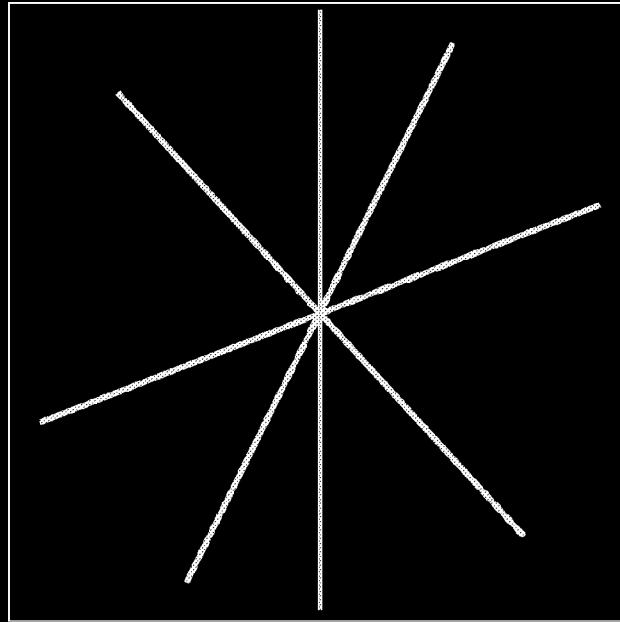
Each subsequent profile is rotated
111.23 degrees from previous

Temporal resolution can be adjusted
dynamically

Time

Appendix 1 *Motivation for non-Cartesian Acquisition*

We would like to use the Golden Angle Trajectory



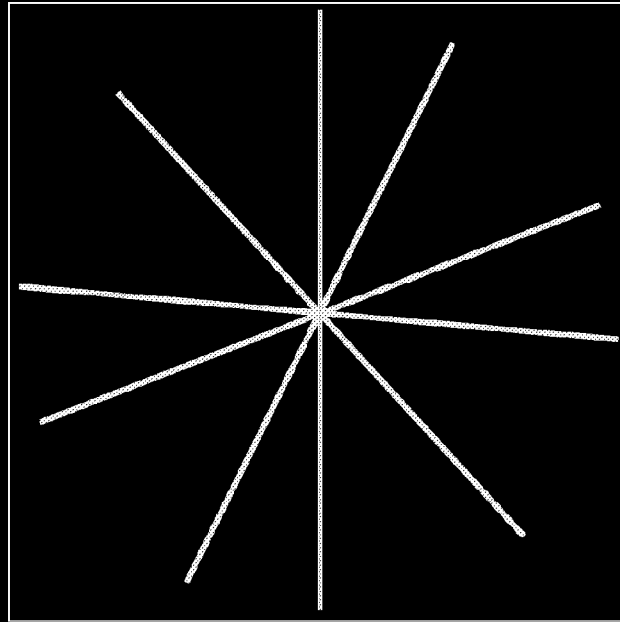
Each subsequent profile is rotated
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Temporal resolution can be adjusted
dynamically

Time

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We would like to use the Golden Angle Trajectory



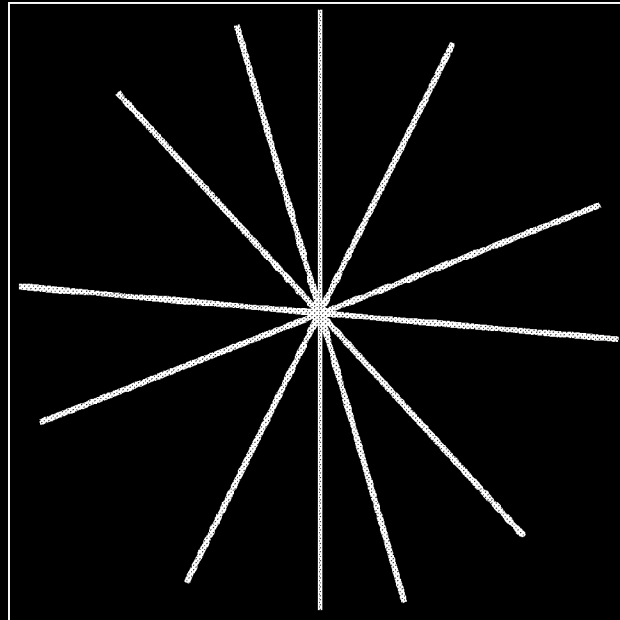
Each subsequent profile is rotated
111.23 degrees from previous

Temporal resolution can be adjusted
dynamically

Time

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We would like to use the Golden Angle Trajectory



Each subsequent profile is rotated
111.23 degrees from previous

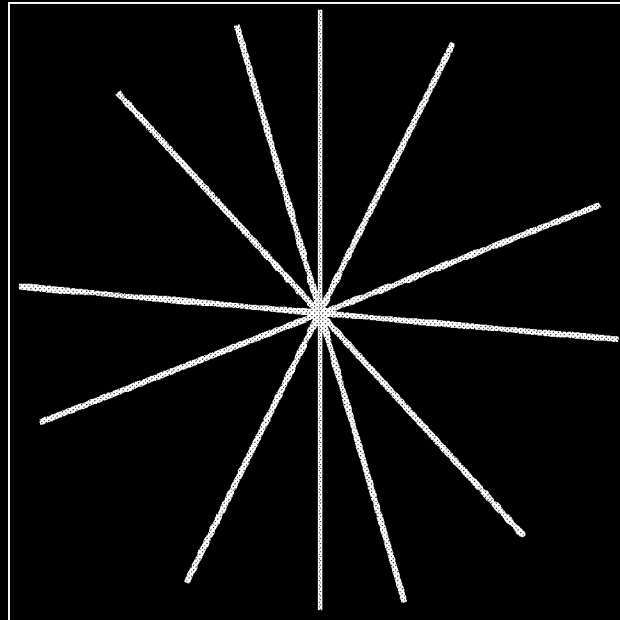
Temporal resolution can be adjusted
dynamically

Time

A vertical arrow pointing upwards, representing the progression of time.

Appendix 1 *Motivation for non-Cartesian Acquisition*

We would like to use the Golden Angle Trajectory



Each subsequent profile is rotated
111.23 degrees from previous

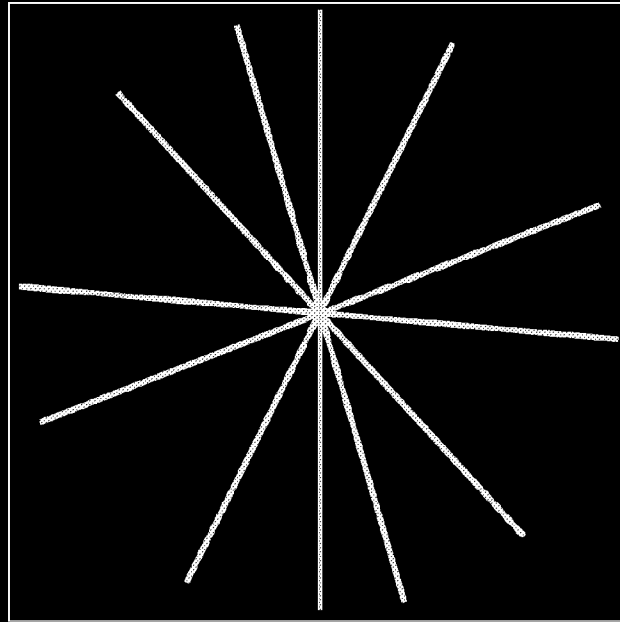
Temporal resolution can be adjusted
dynamically

Time

A vertical timeline with an arrow pointing upwards. The timeline is represented by a series of small vertical tick marks along a horizontal line, with the word "Time" written above the arrow.

Appendix 1 *Motivation for non-Cartesian Acquisition*

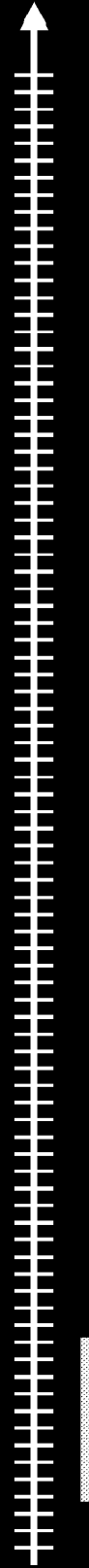
We would like to use the Golden Angle Trajectory



Each subsequent profile is rotated
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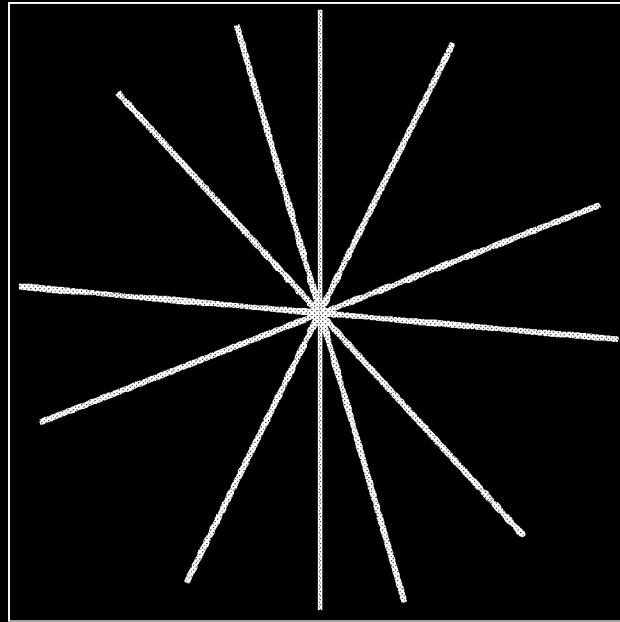
Temporal resolution can be adjusted
dynamically

Time



Appendix 1 *Motivation for non-Cartesian Acquisition*

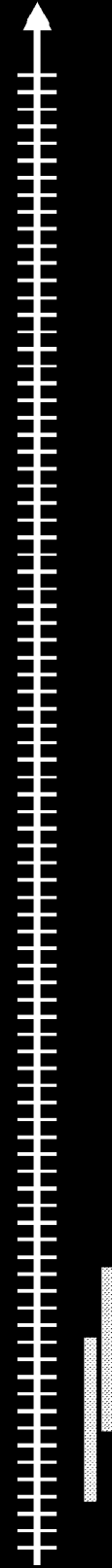
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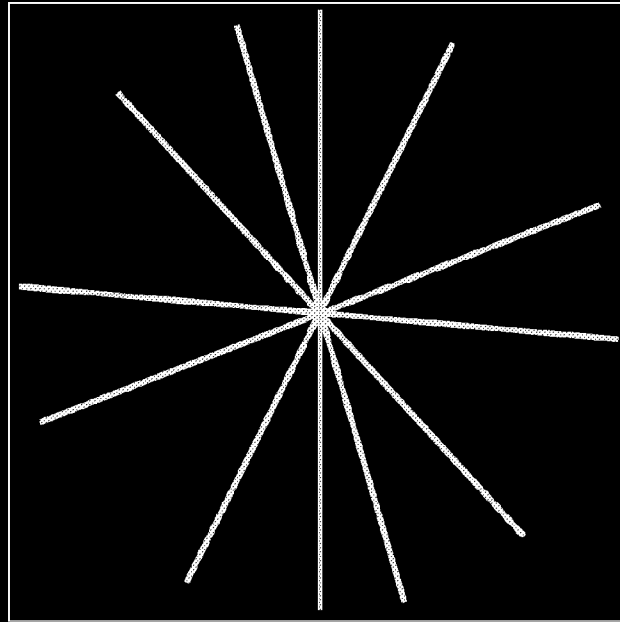
Temporal resolution can be adjusted
dynamically

Time



Appendix 1 *Motivation for non-Cartesian Acquisition*

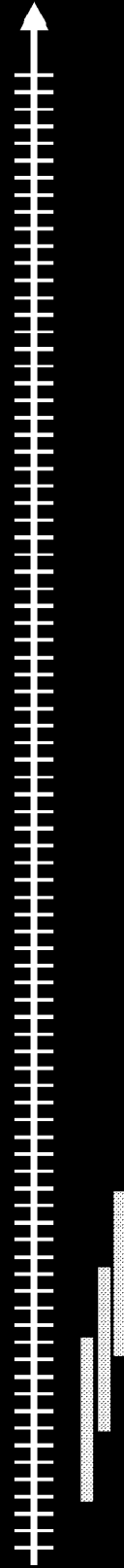
We would like to use the Golden Angle Trajectory



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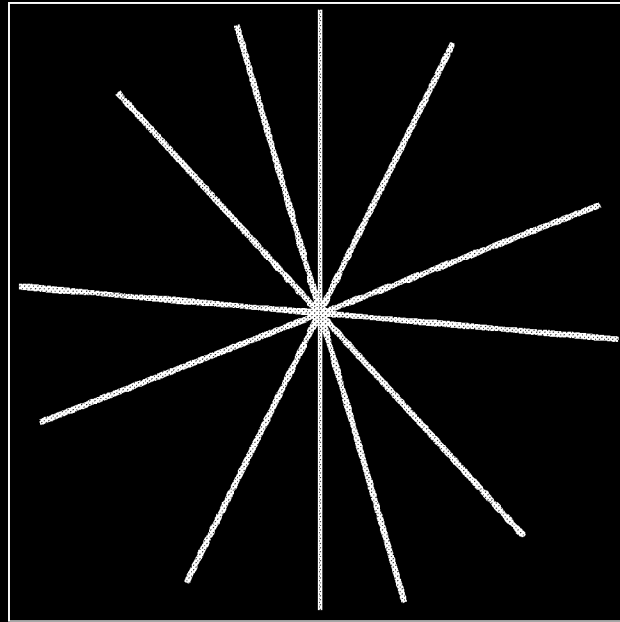
Temporal resolution can be adjusted
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Time



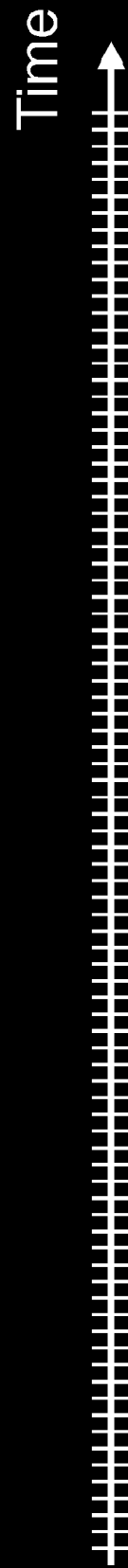
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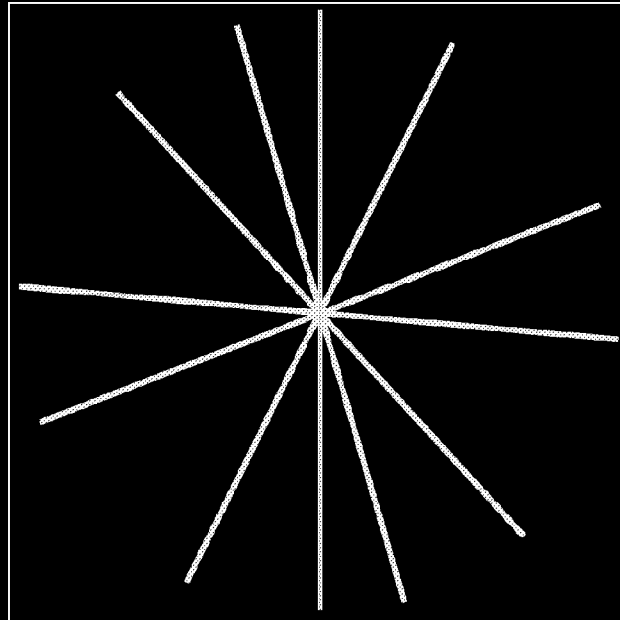
Each subsequent profile is rotated 111.23 degrees from previous

Temporal resolution can be adjusted dynamically



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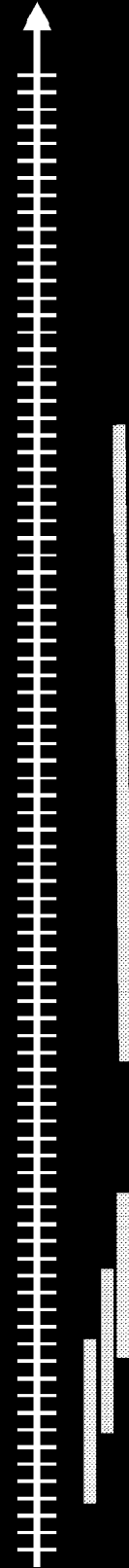
We would like to use the Golden Angle Trajectory



Each subsequent profile is rotated 111.23 degrees from previous

Temporal resolution can be adjusted dynamically

Time



Appendix 1 *Iterative Retro Motion Correction*

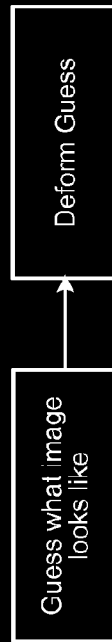
Reconstruction problem is solved by including motion into an iterative reconstruction algorithm:

Guess what image
looks like

Hansen et al. Magn Reson Med 2012

Appendix 1 *Iterative Retro Motion Correction*

Reconstruction problem is solved by including motion into an iterative reconstruction algorithm:



Appendix 1 *Iterative Retro Motion Correction*

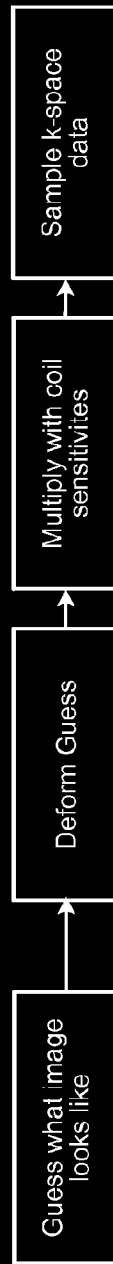
Reconstruction problem is solved by including motion into an iterative reconstruction algorithm:



Hansen et al. Magn Reson Med 2012

Appendix 1 *Iterative Retro Motion Correction*

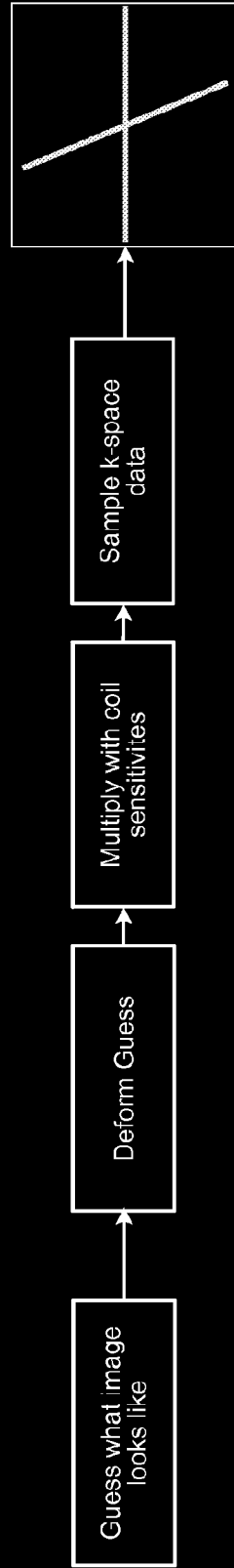
Reconstruction problem is solved by including motion into an iterative reconstruction algorithm:



Hansen et al. Magn Reson Med 2012

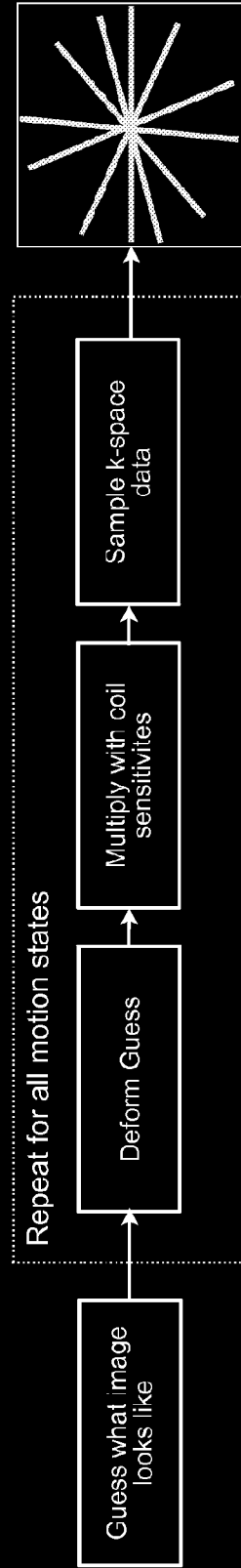
Appendix 1 *Iterative Retro Motion Correction*

Reconstruction problem is solved by including motion into an iterative reconstruction algorithm:



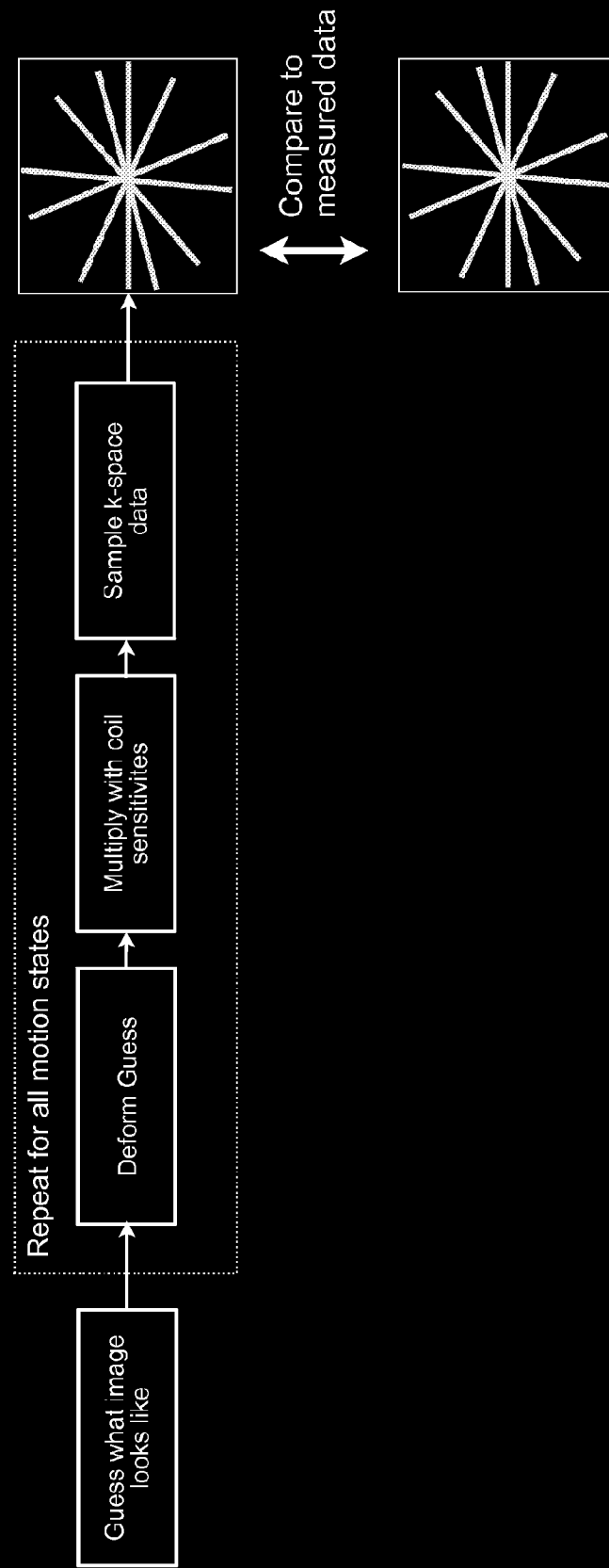
Appendix 1 *Iterative Retro Motion Correction*

Reconstruction problem is solved by including motion into an iterative reconstruction algorithm:



Appendix 1 Iterative Retro Motion Correction

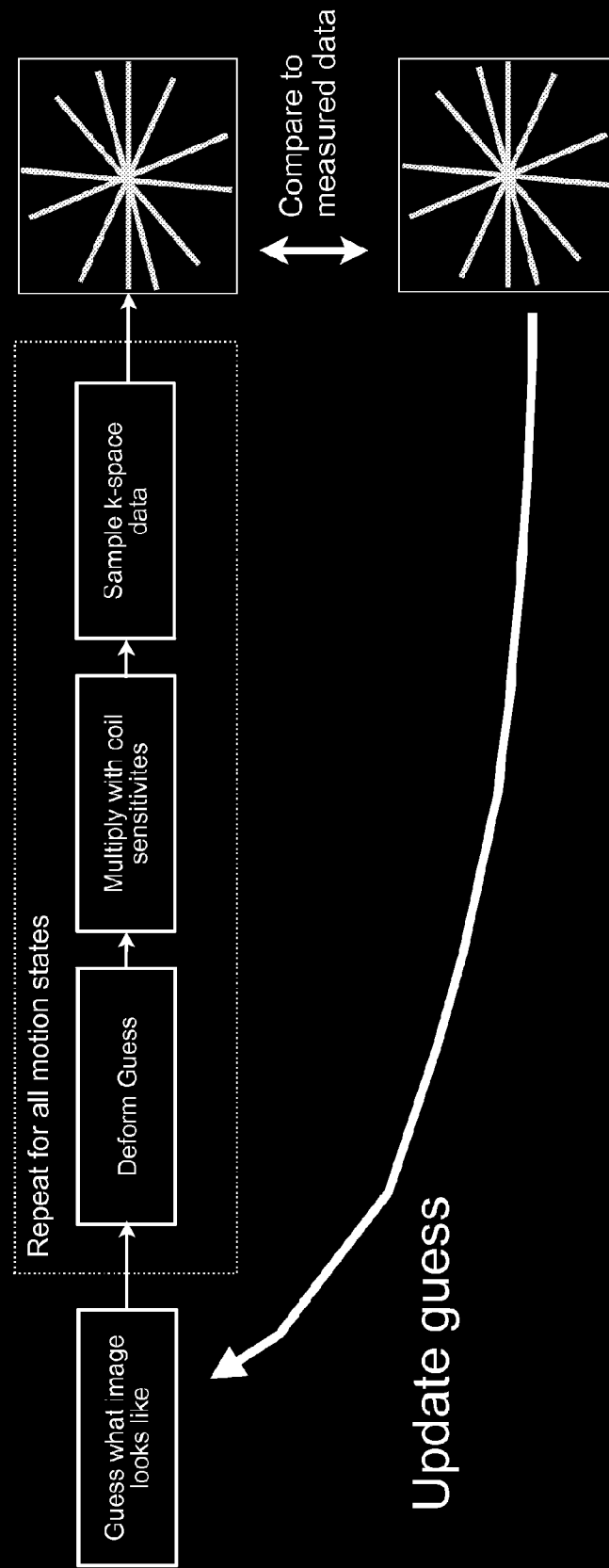
Reconstruction problem is solved by including motion into an iterative reconstruction algorithm:



Hansen et al. Magn Reson Med 2012

Appendix 1 Iterative Retro Motion Correction

Reconstruction problem is solved by including motion into an iterative reconstruction algorithm:



Hansen et al. Magn Reson Med 2012

Appendix 1 **Results: Cartesian and Non-Cartesian**

Reconstruction can be applied to Cartesian and Non-Cartesian trajectories:

Cartesian

Radial

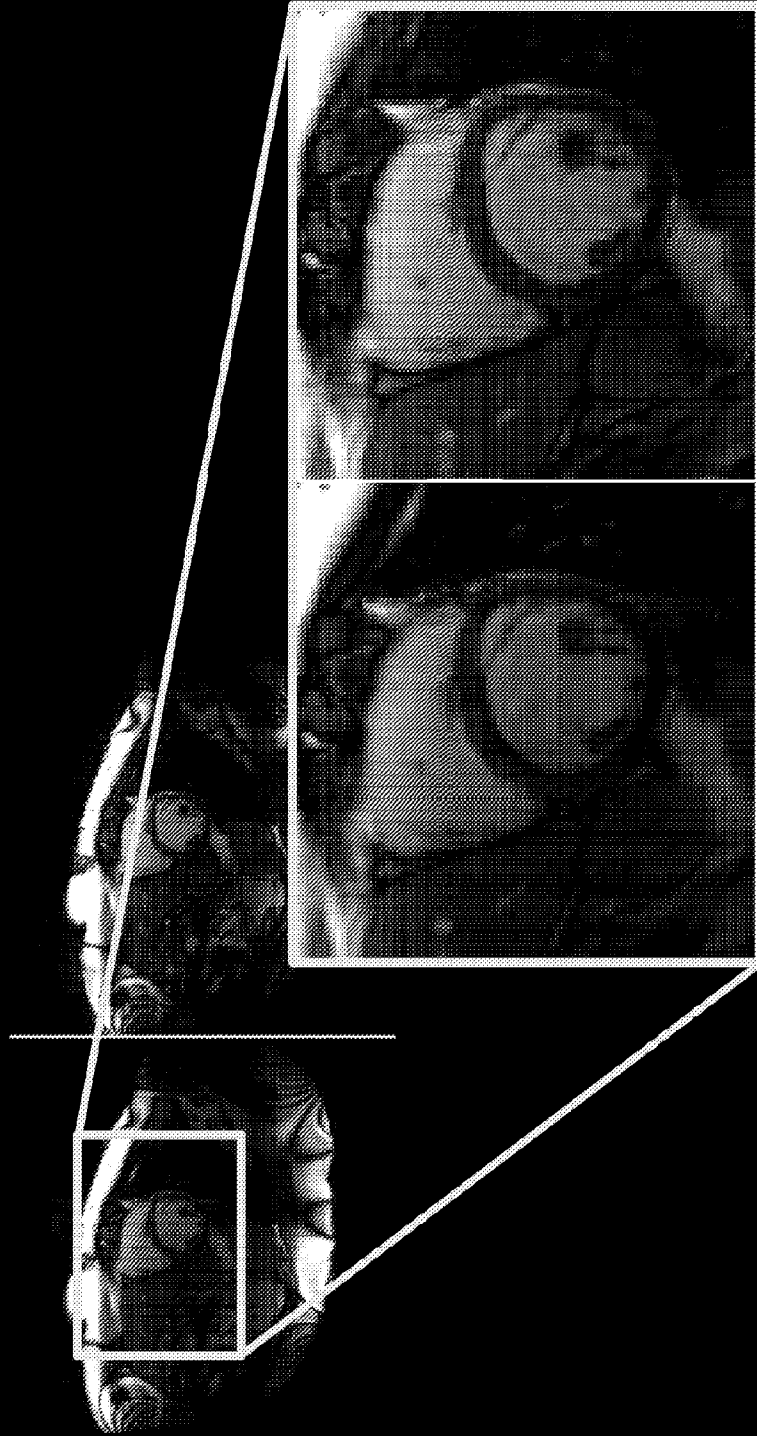


Appendix 1 **Results: Cartesian and Non-Cartesian**

Reconstruction can be applied to Cartesian and Non-Cartesian trajectories:

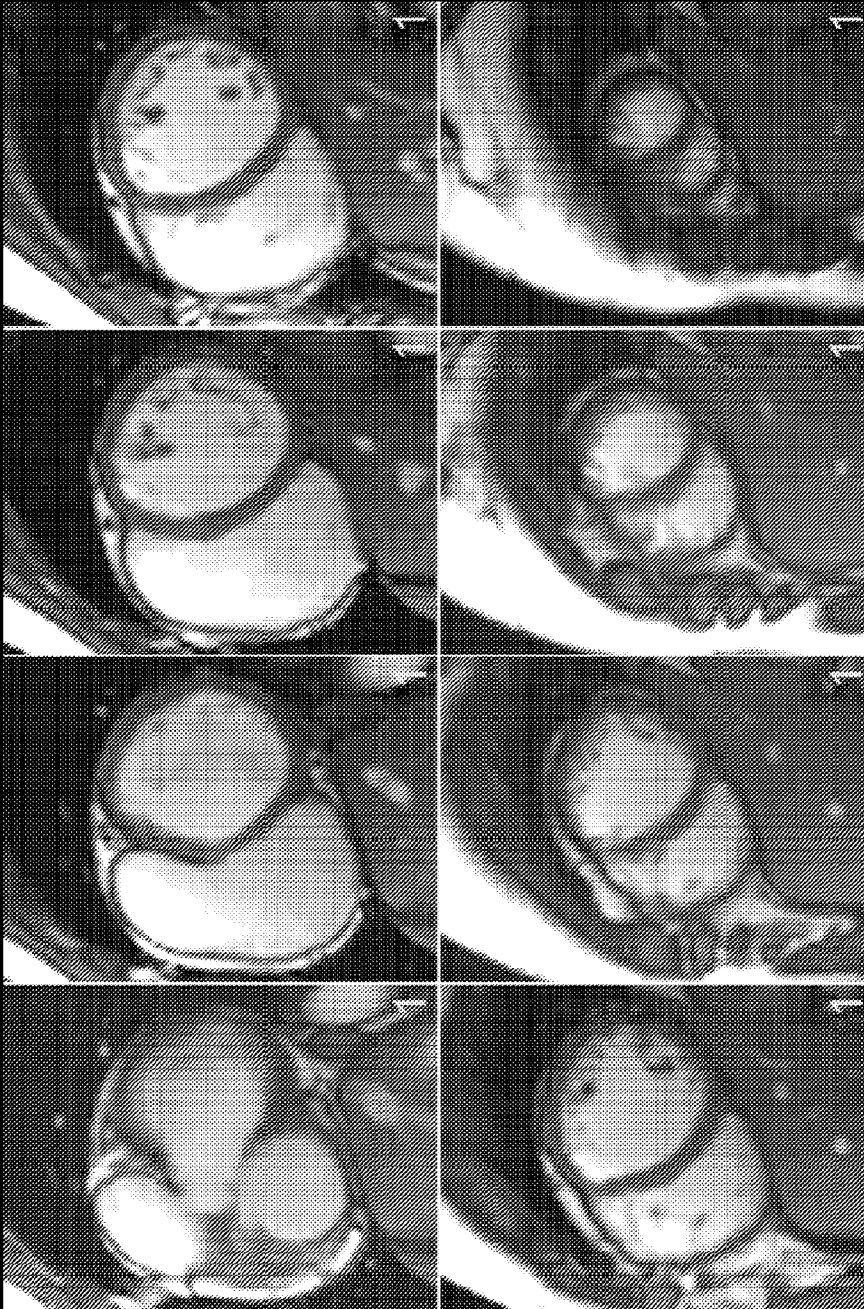
Cartesian

Radial



Non-Linear Binning Reconstruction

Appendix 1



192x128 matrix, 30 ms/frame, acquisition time 16s per slice

Xue et al. JCMR 2013, 15:102

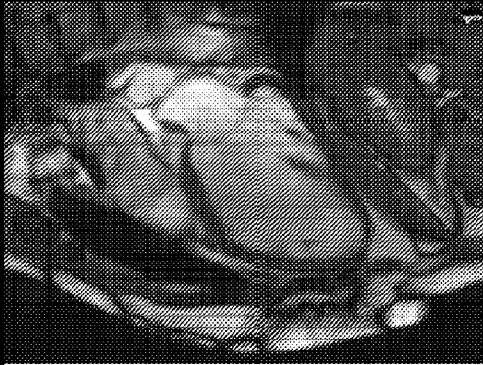
Non-Linear Binning Reconstruction

Appendix 1

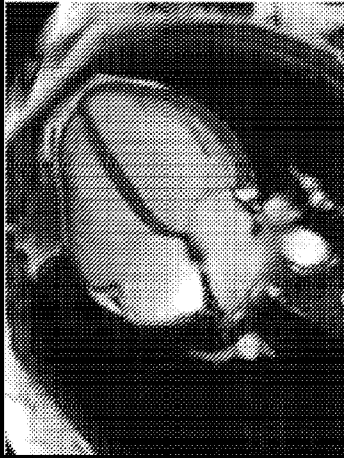
Free Breathing



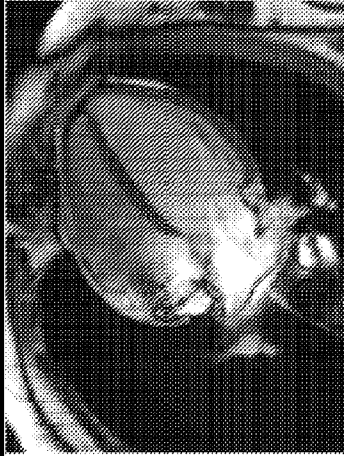
Breathhold



Free Breathing



Breathhold



Free Breathing



Breathhold

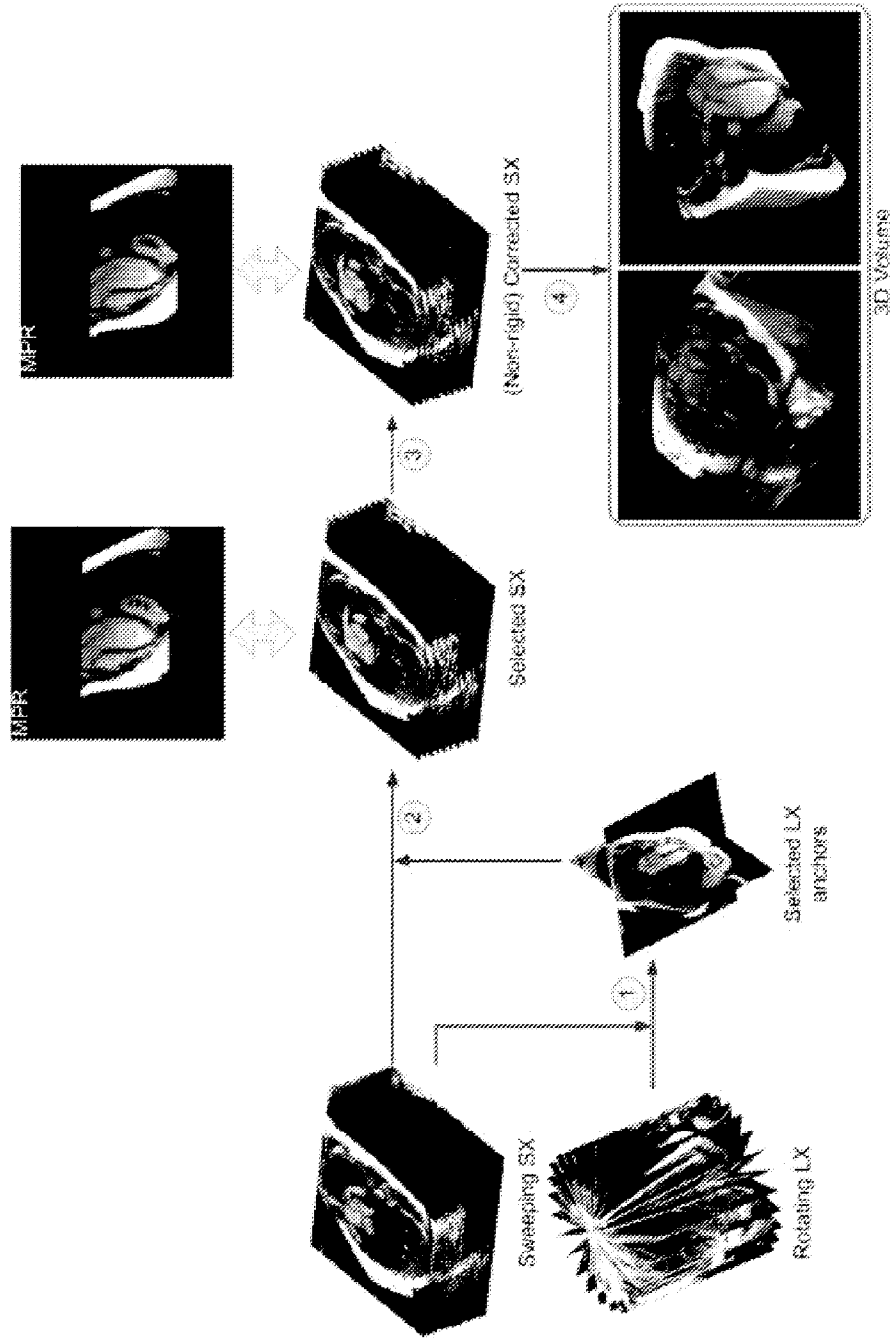


192x128 matrix, 30 ms/frame, acquisition time 16s per frame

Xue et al. JCMR 2013, 15:102

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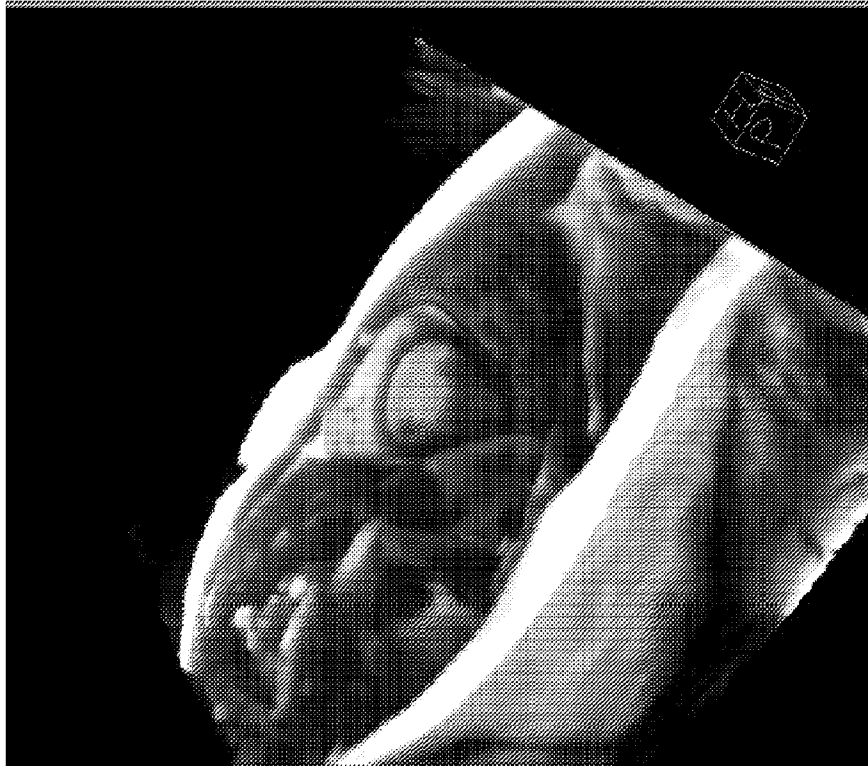
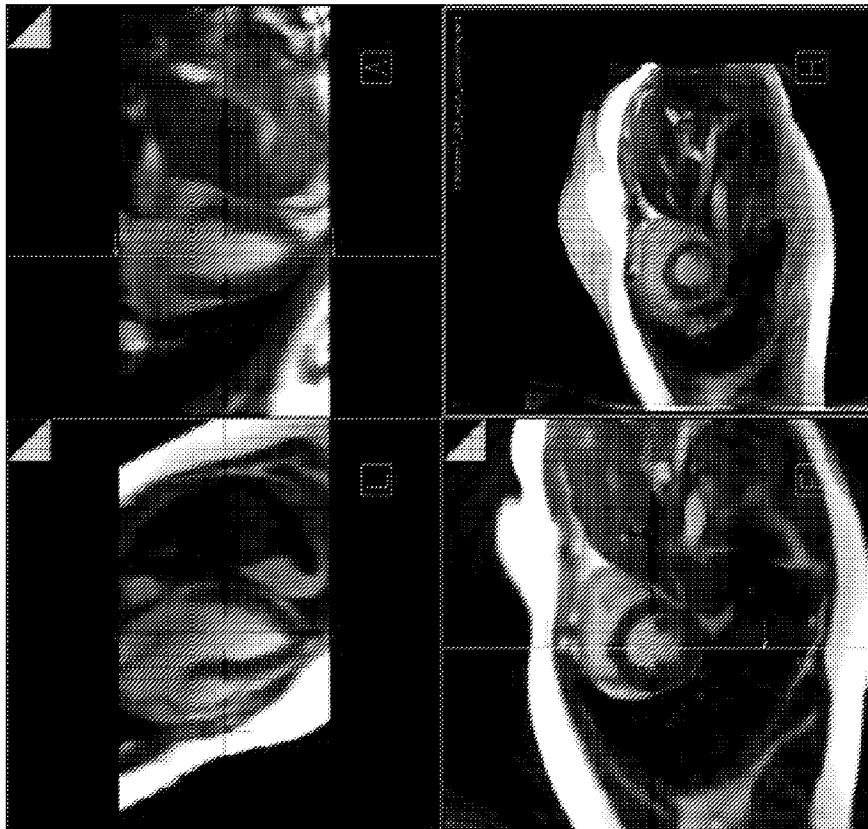
Assembly Principle



Volume reconstruction at one cardiac phase with four major steps: 1. Anchor selection; 2. Slice selection with anchors; 3. Non-rigid slice correction; 4. Scattered interpolation

Slides provided by Peter Speier, Siemens

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SIEMENS**4D Assembly (SX)**

Reconstruction from SX stack with LX slices as the anchors

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SIEMENS**4D Assembly (SX)**

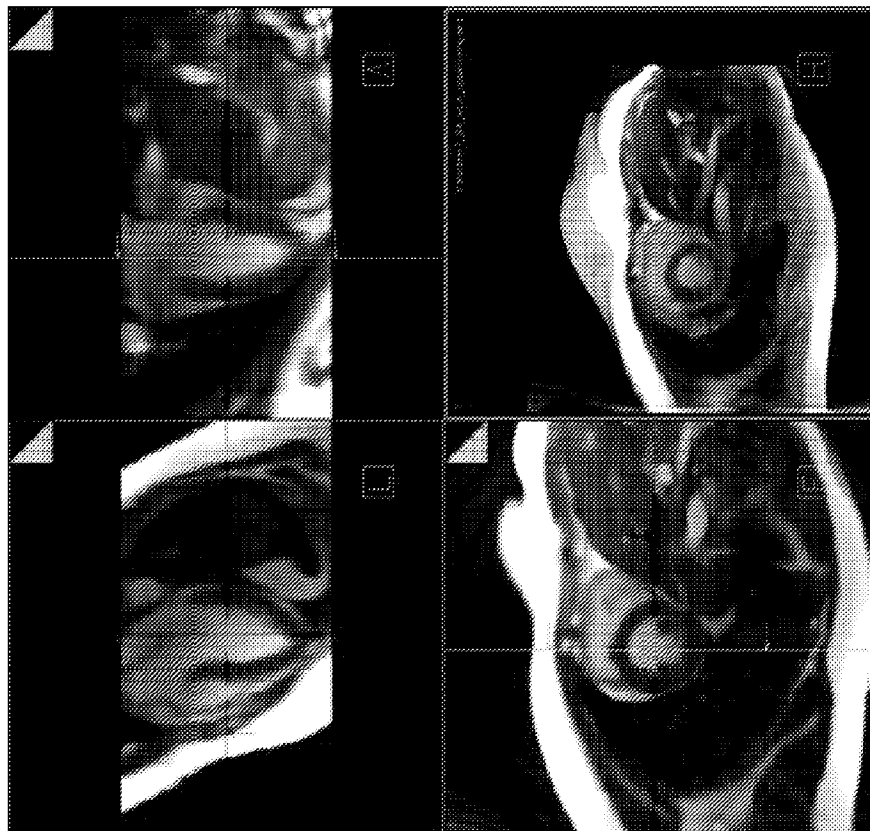
Reconstruction from SX stack with LX slices as the anchors

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4D Assembly (SX)



Reconstruction from SX stack with LX slices as the anchors

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Appendix 1

Summary

- Breath holds should not be necessary.
- Function can be evaluated with parallel imaging alone.
- More advanced techniques may be needed for higher resolution with high frame rate.
- Real-time series can be motion corrected and combined for improved temporal resolution.

Appendix 1

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Appendix 2



**Distributed MRI Reconstruction using Gadgetron based
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Research Focus:	Cardiovascular, Brain < Neurological
Note: The following files were submitted by the author for peer review, but cannot be converted to PDF. You must view these files (e.g. movies) online.	
Figure5a.avi Figure5b.avi	

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Magnetic Resonance in Medicine

Distributed MRI Reconstruction using Gadgetron based Cloud Computing

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Abstract**Purpose:**

To expand the Open Source Gadgetron reconstruction framework to support distributed computing and to demonstrate that a multi-node version of the Gadgetron can be used to provide non-linear reconstruction with clinically acceptable latency.

Methods:

The Gadgetron framework was extended with new software components that enable an arbitrary number of Gadgetron instances to collaborate on a reconstruction task. This cloud-enabled version of the Gadgetron was deployed on three different distributed computing platforms ranging from a heterogeneous collection of commodity computers to the commercial Amazon Elastic Compute Cloud. The Gadgetron cloud was used to provide non-linear, compressed sensing, reconstruction on a clinical scanner with low reconstruction latency for example cardiac and neuro imaging applications.

Results:

The proposed setup was able to handle acquisition and 11-SPIRiT reconstruction of nine high temporal resolution real-time, cardiac short axis cine acquisitions, covering the ventricles for functional evaluation, in under one minute. A three-dimensional high-resolution brain acquisition with 1 mm³ isotropic pixel size was acquired and reconstructed with non-linear reconstruction in less than five minutes.

Conclusion:

A distributed computing enabled Gadgetron provides a scalable way to improve reconstruction performance using commodity cluster computing. Non-linear, compressed sensing reconstruction can be deployed clinically with low image reconstruction latency.

For Peer Review

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Key words:

Gadgetron

Distributed computing

Non-linear MRI reconstruction

Open-source software

Running title:

Gadgetron Cloud Computing

Introduction

Image reconstruction algorithms are an essential part of modern medical imaging devices. The complexity of the reconstruction software is increasing due to the competing demands of improved image quality and shortened acquisition time. In the field of MR imaging, in particular, the image reconstruction has advanced well beyond simple fast Fourier transforms to include parallel imaging (1-5), non-linear reconstruction (6,7) and real-time reconstruction (8,9). The increased interest in 3D acquisitions and non-Cartesian sampling has increased the computational demands further. For applications where lengthy acquisition and reconstruction time is prohibited by physiological motion, biological processes, or limited patient cooperation, the reconstruction system is under further pressure to deliver images with low latency in order to keep up with the ongoing study.

While the need for fast image reconstruction is growing, most published reconstruction algorithms, especially those relying on iterative solvers, such as image domain compressive sensing (6,10-12) and k -space SPIRiT and its regularized versions (7,13,14), do not come with the efficient reference implementations that would enable clinical use. In many cases, the algorithms are not implemented for *online* use on clinical scanners. Even if the developers would like to integrate their reconstruction algorithms for *online* use, the vendor provided hardware and software platform may have inadequate specifications for a demanding reconstruction or the available programming window may be unsuited for integration of new reconstruction schemes. Consequently, there is a gap between the number of new algorithms being developed and published and the clinical testing and validation of these algorithms.

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Undoubtedly, this is having an impact on the clinical adoption of novel non-linear reconstruction approaches (e.g. compressed sensing).

We have previously introduced an open-source platform for medical imaging reconstruction algorithms called the Gadgetron (15), which aims to partial address the above-mentioned concerns. This platform is freely available to the research community and industry partners. It is platform independent and flexible for both prototyping and commercial development. Moreover, interfaces to several commercial MR platforms have been developed and are being shared in the research community. This simplifies the *online* integration of new reconstruction algorithms significantly and the new algorithms in research papers can be tested in clinical settings with less implementation effort. As a result, some groups have used Gadgetron for *online* implementation and evaluation of their reconstruction methods (16-18). Since the publication of the first version of the Gadgetron, the framework has adopted a vendor independent raw data format, the ISMRM Raw Data (ISMRMRD) format (19). This further enables sharing of reconstruction algorithms.

While this concept of an open-source platform and a unified ISMRMRD format shows great potential, the original Gadgetron framework did not support distributed computing across multiple computational nodes. Although the Gadgetron was designed for high performance (using multiple cores or GPU processors), it was originally implemented to operate within a single node or process. Distributed computing was not integral to the design. As reconstruction algorithms increase in complexity they may need computational power that would not be economical to assemble in a single node. The same considerations have led to the development of commodity computing clusters where a group of relatively modest

computers are assembled to form a powerful computing cluster. An example of such a cluster system is the National Institutes of Health Biowulf Cluster (<http://biowulf.nih.gov>). Recently commercial cloud based services also offer the ability to configure such commodity computing clusters on demand and rent them by the hour. The Amazon Elastic Compute Cloud (EC2) is an example of such a service (<http://aws.amazon.com/ec2>).

In this paper, we propose to extend Gadgetron framework to enable cloud computing on multiple nodes. With this extension (named “Gadgetron Plus or GT-Plus”), any number of Gadgetron processes can be started at multiple computers (referred to as ‘nodes’) and a dedicated inter-process controlling scheme has been implemented to coordinate the Gadgetron processes to run on multiple nodes. A large MRI reconstruction task can be split and run in parallel across these nodes. This extension to distributed computing maintains the original advantages of Gadgetron framework. It is freely available and remains platform independent. As demonstrated in this paper, the nodes can even run different operating-systems (e.g. Windows or different distribution of Linux) and have different hardware configurations.

The implemented architecture allows the user to set up a GT-Plus cloud in a number of different ways. Specifically, it does not require a dedicated professional cloud computing platform. The GT-Plus cloud can be deployed on setups ranging from an arbitrary collection of networked computers in a laboratory (we refer to this as a “casual cloud”) to high end commercial cloud systems, as demonstrated in the following. In this paper, we demonstrate the GT-Plus cloud set up in three different scenarios and demonstrate its flexibility to cope with variable computational environments. The first cloud setup is a “casual cloud”, consisting of seven personal computers situated in our laboratory at the National Institutes of

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Health. The second setup uses NIH's Biowulf Cluster (20). The last configuration is deployed on the commercial Amazon Elastic Compute Cloud (Amazon EC2) (21).

To demonstrate the benefits of this extension, we used the cloud enabled version of the Gadgetron to implement nonlinear l1-SPIRiT (7) for 2D time resolved (2D+t) and 3D imaging applications. We demonstrate that cardiac cine imaging with 9-slices covering the entire left ventricle (32 channels, acquired temporal resolution 50ms, matrix size 192×100, acceleration factor 5, ~1.5s per slice) can be reconstructed with l1-SPIRiT with a reconstruction time (latency <30s) that is compatible with clinical workflow. Similarly we demonstrate high resolution 3D isotropic brain scans (20 channels, matrix size 256×256×192, acceleration factor 3×2, 1mm³ isotropic acquired resolution), can be reconstructed with non-linear reconstruction with clinically acceptable latency (<2.5mins). For both cases, significant improvement of image quality is achieved with non-linear reconstruction compared to the linear GRAPPA results.

In the following sections, details of GT-Plus design and implementation are provided. The referral to specific source code components such as C++ classes, variables, and functions is indicated with monospaced font, e.g. `GadgetCloudController`.

Methods

Architecture and Implementation

In the following sections, we will first briefly review the Gadgetron architecture and the extensions that have been made to this architecture to enable cloud computing. Subsequently,

we will describe two specific types of MRI reconstructions (2D time resolved imaging and 3D imaging) that have been deployed on this architecture.

Gadgetron framework

The Gadgetron framework is described in detail in (15). Here we briefly review the dataflow for comparison to the cloud based dataflow introduced below. As shown in Fig. 1, A Gadgetron reconstruction process consists of three components: Readers, Writers and Gadgets. A Reader receives and de-serializes the incoming data sent from the client (e.g. a client can be the MR scanner). A Writer serializes the reconstruction results and sends the data packages to the client. The Gadgets are connected to each other in a streaming framework as processing chains.

The Gadgetron maintains the communication with clients using a TCP/IP socket based connection. The typical communication protocol of Gadgetron process is the following:

- a) The client issues the connection request to the Gadgetron server at a specific network port.
- b) The Gadgetron accepts the connection and establish the TCP/IP communication.
- c) The client sends an XML based *configuration* file to the Gadgetron server. This XML configuration outlines the Reader, Writers, and Gadgets to assemble a Gadget chain.
- d) The Gadgetron server loads the required Readers, Writers and Gadgets from shared libraries as specified in the configuration file.
- e) The client sends an XML based *parameter* file to the Gadgetron. The Gadgetron can initialize its reconstruction computation based on the parameters (e.g. acquisition

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matrix size, field-of-view, acceleration factor etc.). For MRI this XML parameter file is generally the ISMRMRD XML header describing the experiment.

- f) The client sends every readout data to the Gadgetron in the ISMRMRD format. These data are de-serialized by the Reader and passed through the Gadget chain.
- g) The reconstruction results are serialized by the Writer and send back to the client via the socket connection.
- h) When the end of acquisition is reached, the Gadgetron closes down the Gadget chain and closes the connection when the last reconstruction result has been passed back to the client.

Gadgetron Plus (GT-Plus): distributed computing extension of Gadgetron

A schematic outline of GT-Plus extension is shown in Fig. 2. A distributed Gadgetron process has at least one Gadgetron running on a specific port for each node (multiple Gadgetron processes can run within the same node at different ports). A software module, `GadgetCloudController`, manages the communication between nodes. Typically, the gateway node is receiving the readout data from the client and de-serializes them using a `Reader`. Depending on the reconstruction workflow, the gateway node may buffer the incoming readouts and perform some processing before sending reconstruction jobs to the connected nodes, or data can be forwarded directly to the client nodes. The `GadgetCloudController` maintains multiple TCP/IP socket connections with every connected node via a set of `GadgetronCloudConnector` objects (one for each connected node). Each `GadgetronCloudConnector` has a reader thread (`CloudReaderTask`) and a writer thread (`CloudWriterTask`) which are responsible for receiving and sending data (to the node) respectively. There is a Gadgetron Gadget chain running on every connected node.

The gateway node will send the XML configuration to the connected node to assemble the chain. For different cloud nodes, different Gadget chains can be assembled. In fact, the connected nodes can also be gateway nodes, thus creating a multi-tiered cloud. The typical protocol of GT-Plus distributed computing is as follows:

- a) The client issues the connection request to the GT-Plus gateway at a specific network port. Once the connection is established, the client will send the XML based configuration and parameter files to establish and initialize the gadget chain at the gateway node.
- b) The client starts sending readout data to the gateway node.
- c) The Gateway node establishes connection to cloud nodes and supplies them with XML configuration and parameter files. As mentioned, different connected nodes can be configured with different chains if needed.
- d) Job packages are sent to connected cloud nodes for processing via the corresponding `CloudWriterTask`.
- e) When all jobs are sent to nodes (the acquisition is done), the gateway Gadgetron either waits for reconstruction results or conducts extra computation. The `ReaderTask` objects, at the same time, listen for reconstruction results. Whenever the reconstruction results are sent back from a cloud node, the gateway Gadgetron is notified by the `ReaderTask` object and will take user-defined actions, e.g. passing the results downstream or waiting for the completion of all jobs. Finally the gateway node will proceed to finish other processing steps if any and send the images down the remaining part of the gateway Gadget chain and eventually back to the client.

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- f) If one or more connected nodes fail to complete a job successfully, the gateway node will be notified by either receiving an invalid result package or detecting a shutdown message on the socket. The `GadgetCloudController` on the gateway node will keep a record of uncompleted jobs and process them locally. In this way, the GT-Plus gains robustness against network instability.

The software modules mentioned above are implemented as C++ template classes and are capable of handling any type of custom job packages, i.e. the user is able to configure what data types are sent and received from the cloud nodes. The only requirement is to implement appropriate functions for serialization and de-serialization of work packages and results. This design is a straightforward extension of the Readers and Writers in the original Gadgetron.

In the current implementation, every computing node can be given an index indicating its computational power. This index is used to allow the gateway node to apply a scheduling algorithm where the workload is distributed to the cloud nodes in proportion to their computational capabilities. This can be important if the cloud consists of a heterogeneous set of hardware configuration.

To supply the network connection information of cloud nodes to the Gadgetron, user can specify IP addresses or hostnames of nodes in the gateway XML configuration file. Alternatively, the framework can read in a cloud structure definition file.

Gadgetron Plus (GT-Plus) for 2D time resolved (2D+t) Reconstruction Tasks

In addition to the software modules for cloud communication, the GT-Plus extensions also include a specific job type to support 2D+t reconstruction tasks, e.g. multi-slice cine imaging.

This workflow is used here to illustrate a cloud setup with a dual layer topology, as illustrated in Fig. 3. The gateway gadget chain will buffer readouts for a specified ISMRMRD dimension (e.g. for the multi-slice cine, it is usually the slice dimension). Once all data for a slice have arrived, the `GtPlusRecon2DTGadgetCloud` gadget will forward the job package to a first layer node to start the reconstruction.

For a 2D+t dynamic imaging task, one slice will have multiple 2D k -spaces. For example, for the cardiac cine acquisition, multiple cardiac phases are usually acquired. The first layer node responsible for the reconstruction of a given slice can choose to further distribute the dataset to a set of sub-nodes in the second layer. The first-layer nodes can serve solely to distribute jobs or they can perform computation as well. In principle, a given reconstruction job can utilize an arbitrary number of node layers to form a more complicated cloud topology.

Gadgetron Plus (GT-Plus) for 3D Reconstruction Tasks

For 3D acquisitions, a single layer cloud topology was used in this paper. The gateway node's `GtPlusRecon3DTGadget` receives the 3D acquisition and performs the processing such as coil compression and estimation of k -space convolution kernel for parallel imaging. It then splits the large 3D reconstruction problem by performing a 1D inverse FFT transform along the readout direction. Thus, the reconstruction is decoupled along the readout direction. Every chunk of data along the readout direction is then sent to a connect node for non-linear reconstruction. The gateway node will wait for all jobs to complete and results to return. It then reassembles the 3D volume from all chunks and continues to perform other post-processing, e.g. k -space filtering tasks and finally returns images to the client.

Toolbox Features

The Gadgetron is divided into Gadgets and *Toolbox* algorithms that can be called from the Gadgets or standalone applications. In addition to the toolbox features listed in (15), the GT-Plus extensions add additional toolboxes. Here is an incomplete list of key algorithm modules:

2D/3D GRAPPA. A GRAPPA implementation for 2D and 3D acquisition is added. It fully supports the ISMRMRD data format and different parallel imaging modes (embedded, separate or interleaved auto-calibration lines, as defined in (19)). For the 3D GRAPPA case, the implementation supports two-dimensional acceleration. To support parallel imaging in interactive or real-time applications, a real-time high-throughput 2D GRAPPA implementation using GPU is also provided in the Gadgetron.

2D/3D Linear SPIRiT. A linear SPIRiT (7) reconstruction is implemented in the Gadgetron toolbox. Specifically, if the k -space $\mathbf{x}$ consists of filled points $\mathbf{a}$ and missing points $\mathbf{m}$, then:

$$\mathbf{x} = \mathbf{D}^T \mathbf{a} + \mathbf{D}_c^T \mathbf{m} \quad (1)$$

Here $\mathbf{x}$ is a vector containing k -space points for all phase encoding lines for all channels; $\mathbf{a}$ stores the acquired points, and $\mathbf{m}$ is for missing points. $\mathbf{D}$ and $\mathbf{D}_c$ are the sampling pattern matrixes for acquired and missing points, Linear SPIRiT solves the following equation:

$$(\mathbf{G} - \mathbf{I}) \mathbf{D}_c^T \mathbf{m} = (\mathbf{G} - \mathbf{I}) \mathbf{D}^T \mathbf{a} \quad (2)$$

Here $\mathbf{G}$ is the SPIRiT kernel matrix, which is computed from a fully sampled set of auto calibration data.

2D/3D Non-linear II-SPIRiT. Equation 2 is extended by the L1 term:

$$\operatorname{argmin}_{\mathbf{m}} \{ \| (\mathbf{G} - \mathbf{I})(\mathbf{D}^T \mathbf{a} + \mathbf{D}_c^T \mathbf{m}) \|_2 + \lambda \| \mathbf{W} \Psi \mathbf{C}^H \mathbf{F}^H (\mathbf{D}^T \mathbf{a} + \mathbf{D}_c^T \mathbf{m}) \|_1 \} \quad (3)$$

Another variation of l1SPIRiT is to treat the full k -space as the unknowns:

$$\operatorname{argmin}_{\mathbf{x}} \{ \| (\mathbf{G} - \mathbf{I}) \mathbf{x} \|_2 + \lambda \| \mathbf{W} \Psi \mathbf{C}^H \mathbf{F}^H \mathbf{x} \|_1 + \beta \| \mathbf{D} \mathbf{x} - \mathbf{a} \|_2 \} \quad (4)$$

Here Ψ is the sparse transform and $\mathbf{W}$ is an extra weighting matrix applied on the computed sparse coefficients to compensate for non-isotropic resolution or temporal redundancy. $\mathbf{F}$ is the Fourier transform matrix. $\mathbf{C}$ is the coil sensitivity.

Redundant 2D and 3D wavelet transform. The redundant wavelet transform for 2D and 3D data arrays are implemented in the toolbox. It is used in the L1 regularization term. A fast implementation for redundant Harr wavelet is also provided.

Example Applications

Corresponding to the two types of cloud topologies described in the previous sections, two *in vivo* experiments were performed on healthy volunteers. The local Institutional Review Board approved the study, and all volunteers gave written informed consent.

Real-time multi-slice myocardial cine imaging using l1-SPIRiT

The aim was to make it clinically feasible to assess myocardial function using real-time acquisitions and non-linear reconstructions covering the entire ventricles. With conventional reconstruction hardware, the reconstruction time for such an application would prohibit clinical adoption. The dual layer cloud topology was used here and every slice was sent a separate node (first layer) which further split cardiac phases into multiple chunks. While processing one chunk itself, the first layer node also sent others to its sub-nodes for parallel processing. The algorithm workflow was as follows: a) Undersampled k -space data were

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acquired with the time-interleaved sampling pattern. b) The gateway node received the readout data and performed the on-the-fly noise pre-whitening (5). c) The data from one slice was sent to one first layer node. d) To reconstruct the underlying real-time cine images, the auto-calibration signal (ACS) data for a slice were obtained by averaging all undersampled k -space frames at this slice. e) The SPIRiT kernel was estimated on the assembled ACS data. f) The data for the slice was split into multiple chunks and sent to sub-nodes, together with the estimated kernel. The size of a data chunk for a node was proportional to its computing power index. f) Sub-nodes received the data package and solved equation 3. The linear SPIRiT problem (equation 2) was first solved to initialize the non-linear solver. g) Once the process for a slice was completed, the node sent the reconstructed frames back to gateway, which then returned them to the scanner. Note the reconstruction for a given slice started while acquisition was still ongoing for subsequent slices. Thus the data acquisition and processing was overlapped in time to minimize the overall waiting time after the data acquisition.

Fig. 4 outlines the 11SPIRiT reconstruction gadget chain for multi-slice cine imaging using the dual layer cloud topology. The raw data first went through the NoiseAdjustGadget, which performed noise prewhitening. After removing the oversampling along the readout direction, the data was buffered in the AccumulatorGadget. Whenever the acquisition for a slice was complete, the data package was sent to the GtPlusRecon2DTGadgetCloud gadget, which established the network connection to the first layer nodes and sent the data. The first layer node ran only the GtPlusReconJob2DTGadget gadget, which then connected to the second layer nodes. The CloudJobReader and CloudJobWriter were used to serialize and de-serialize the cloud job package.

Imaging experiments were performed on a 1.5T clinical MRI system (MAGNETOM Area, Siemens AG Healthcare Sector, Erlangen, Germany) equipped with a 32-channel surface coil. A healthy volunteer (female, 23.8yrs) was scanned. Acquisition parameters for free-breathing cine were as follows: balanced SSFP readout, TR = 2.53/TE = 1.04ms, acquired matrix size 192×100, flip angle 60°, FOV 320×240mm², slice thickness 8mm with a gap of 2mm, bandwidth 723 Hz/pixel, interleaved acquisition pattern with acceleration factor R=5. The whole left ventricular was covered by 9 slices and acquisition duration for every slice was ~1.5s with one dummy heartbeat between slices. The scan time (defined as the time to perform data acquisition) to complete all 9 slices was 22.6s.

High resolution neuro imaging using 11-SPIRiT

The second example aimed to use GT-Plus for non-linear reconstruction of a high resolution 3D acquisition. The algorithm workflow was as follows: a) Undersampled k -space data were acquired with the fully sampled center region. b) The gateway node received the readout data and performed the on-the-fly noise pre-whitening. c) When all data was received, the SPIRiT kernel calibration was performed on the fully sampled ACS region. The kernel was zero-padded only along the readout direction and Fourier transformed to the image domain. This was done to reduce the maximal memory needed to store the image domain kernel and decrease the amount of data transferred over the network to connected nodes. The k -space data was transformed to image domain along the readout as well. d) The gateway node split the image domain kernel and data into multiple chunks along the readout direction and sent them to multiple connected nodes. e) The connected nodes received the packages and zero-padded kernels along the remaining two spatial dimensions and transformed into image domain. The image domain kernel was applied to the aliased images by pixel-wise

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2
3 multiplication. This linear reconstruction was performed to initialize the non-linear
4 reconstruction. f) After receiving all reconstructed image from connected nodes, the gateway
5 assembled the 3D volume and performed some post-processing, such as *k*-space filtering and
6 then sent results back to the scanner.
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15 The imaging experiments were performed on a 3.0T clinical MRI system (MAGNETOM
16 Skyra, Siemens AG Healthcare Sector, Erlangen, Germany) equipped with a 20-channel head
17 coil. The acquisition parameters were as follows: GRE readout, TR = 10.0/TE = 3.11ms,
18 acquired matrix size 256×256×192, flip angle 20°, isotropic spatial resolution 1mm³,
19 bandwidth 130 Hz/pixel, two dimension acceleration factor R=3×2. The embedded parallel
20 imaging mode was used with the ACS signal acquired as a 32×32 fully sampled region. The
21 total acquisition time was 91.6s.
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Deployment and Scanner Integration

32
33 The cloud extension of Gadgetron (GT-Plus), can be deployed on different types of platforms.
34
35 Three setups have been tested here for *in vivo* experiments and the GT-Plus software can be
36 deployed on those setups without any code changes. The first setup (referred to as the “casual
37 cloud”) is a heterogeneous collection of computers, e.g. as one would find in many MRI
38 research laboratories. These computers have different hardware and operating system
39 configurations. The second setup is the NIH Biowulf cluster, which is a custom built cluster
40 with totally 2300 nodes (>12000 computing cores); it is a shared system and users request a
41 specific amount of resources for a given computational task. The third setup is the Amazon
42 Elastic Compute Cloud (EC2), where an arbitrary amount of computational power can be
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rented by the hour providing the flexibility to tailor the cloud configuration to suit a specific application.

“Casual” cloud

The first setup is a solution that almost any MRI research laboratory would be able to use by installing the Gadgetron on a set of networked computers and using one of these computers as the gateway node. No specific operating system or special hardware is needed. Here, six personal computers on the NIH intranet (1Gb/s connections) were used as the cloud nodes and two more computers were used as gateway nodes for 2D+t and 3D experiments respectively. The Gadgetron software was compiled and installed on all computers. The gateway node for 2D+t test was a desktop computer, running windows 7 Pro 64 bit (four core Intel Xeon E5-2670 2.60GHz processors, 48GB DDR3 RAM). The gateway node for 3D test also ran the same operating-system (two eight-core Intel Xeon E5-2670 2.60GHz processors, 192GB DDR3 RAM).

Among the six cloud nodes, two of them were running windows 7 Pro 64bit (each had four cores of Intel Xeon E5-2670 2.60GHz, and 48GB DDR3 RAM). Ubuntu linux 12.04 were running on other four nodes (two nodes each had six cores of Intel Xeon E5645 2.4GHz and 24GB DDR3 RAM; the other two had four cores of Intel Xeon X5550 2.67GHz and 24GB DDR3 RAM).

For the dual layer cloud test, one Windows and two Ubuntu computers served as first layer nodes. The other three nodes were on the second layer. Each of them was connected to one

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first layer node. For the 3D reconstruction test, all six nodes were connected directly to the gateway.

NIH Biowulf cloud

The second cloud setup tested in this study utilized the NIH Biowulf cluster. NIH Biowulf system is a GNU/Linux parallel processing system designed and built at the National Institutes of Health. Biowulf consists of a main login node and a large number of computing nodes. The computing nodes within Biowulf are connected by a 1Gb/ network. The MRI scanner used in this study was also connected to Biowulf system with a 1Gb/s network connection. For the 2D multi-slice cine experiments 37 nodes were requested from the cluster. The gateway node had 16 cores (two eight-core Intel Xeon E5-2670 2.60GHz processors) and 72GB DDR3 RAM. All other nodes had identical configurations (two six-core Intel Xeon X5660 2.80GHz, 24GB DDR3 RAM). For the dual layer cloud test, 9 nodes were used on the first layer to match the number of acquired slices. Each of them was connected to three sub-nodes on the second layer. For the 3D reconstruction test, the same gateway node and 23 connected nodes were requested.

The cloud topology was selected to balance the maximal parallelization and programming complexity. It is convenient to have dual layer structure for the multi-slice cine imaging, because this structure allows overlap between data acquisition and reconstruction computation. For the 3D acquisition, the reconstruction only starts when the data acquisition is completed; therefore, a simple one layer cloud is used to simplify the synchronization. The number of nodes used in the study was mainly limited by the available resources during the experiments. Although Biowulf system has a large number of nodes, hundreds of jobs from multiple users

can run in parallel at any given time. We also intentionally made number of nodes different between 2D+t and 3D tests, to challenge the scalability of Gadgetron based cloud software.

Amazon EC2 based cloud

The last setup utilized the Amazon Elastic Compute Cloud (Amazon EC2). Amazon EC2 cloud provides resizable computing capacity in the Amazon Web Services (AWS) cloud. User can configure and launch flexible number of computing nodes. Every node can have different hardware configuration and operating system. Amazon EC2 provides a broad selection of Windows and Linux operating systems. More details about Amazon EC2 can be found in (21).

For this study, 19 nodes were launched to build up a virtual cloud on Amazon EC2. Every node used the cc2.8xlarge instance type (two eight-core Intel Xeon E5-2670 2.60GHz processors, 20MB L3 cache per processor, 60GB DDR3 RAM), running Ubuntu Server 13.10. All nodes were connected 10Gb/s connections. For the dual layer test, one node was used as the gateway and 9 nodes were on the first layer. Each first layer nodes were connected to two other sub-nodes. Thus, data for every slice was processed by three nodes in total. For the 3D reconstruction test, all 18 nodes are connected directly to the gateway. At the time of the study, the price for the nodes used in this test was US \$2.4 per hour per node or US \$45.60 per hour for the complete cloud setup. In this case, the number of nodes was chosen as a reasonable balance between cost and performance.

The connection speed from the MRI scanner to the Amazon EC2 cloud was measured to be 49.8MB/s or 0.39Gb/s at the time of the experiments.

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Clinical scanner integration

As previously described, the Gadgetron enables direct integration with the MRI scanner for online reconstruction (15). The cloud extension of GT-Plus maintains this advantage of *online* processing. Effectively, this setup enables a seamless connection of cloud computing resources directly to the scanner. From the end-user perspective, the only noticeable difference between reconstruction in the cloud and locally (on the scanner's reconstruction hardware) is the improvement in reconstruction speed.

The integration of cloud computing resources with a clinical scanner raises questions about patient privacy. In this study multiple steps were taken to mitigate any risks. Firstly, all data being sent to the Gadgetron from the scanner was anonymized. Absolutely no identifying information that could be used to trace back to the patient were sent over the network. The only information sent was the MR raw data and protocol parameters such as field of view, matrix size, bandwidth, etc. Secondly, all data transfer between scanner and gateway node was encrypted via a secure shell (SSH) tunnel (22). All other nodes connected to the gateway were behind firewalls. Besides serving as a security measure, the use of SSH tunnels to connect to the Gadgetron was a convenient way to test multiple Gadgetron setups on the same scanner. The reconstruction could simply be directed to a different Gadgetron by changing the SSH tunnel pointing to a different Gadgetron instance.

Tests were performed on two clinical MRI scanners (Siemens Skyra 3.0T and Area 1.5T, Siemens Medical Solutions, Erlangen, Germany).

Results

Multi-slice myocardial cine imaging

Fig. 5 shows the reconstruction results generated by the GT-Plus cloud, illustrating the noticeable improved in image quality using non-linear reconstruction.

Table 1 shows the total imaging time and computing time. The imaging time is the time period from the start of data acquisition to the moment when images of all slices were returned to scanner. The computing time is defined as the time used to perform the reconstruction computation. On the described Amazon EC2 cloud, the total imaging time was 52.6s. The computing time was 48.9s because the computation was overlapped with the data acquisition. On the NIH's Biowulf cloud, imaging and computing times were 62.1s and 58.2s respectively. If only a single node was used, the computing time was 427.9s and 558.1s for two cloud setups. Therefore, the multi-slice cine imaging with entire ventricle coverage was completed within 1min using the non-linear reconstruction on the GT-Plus cloud. The casual cloud gave computing time of 255.0s and if only one node was used, the time went up to 823.7s. This speedup may be helpful to the development and validation of non-linear reconstruction in a MRI research lab.

High resolution 3D neuroimaging

Fig. 6 illustrates the cloud reconstruction results using 11-SPIRiT. Compared to the GRAPPA, the non-linear reconstruction shows noticeable SNR improvements. Table 2 gives the total imaging time and computing time for three cloud setups and the single node processing. The total imaging time on the Biowulf cloud was 278.5s which includes the computing time of 186.4s, since not all computational steps ran in parallel for this 3D reconstruction. As every

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computing node of the Amazon EC2 cloud setup had 16 cores and a newer CPU model, the total computing time was further reduced to 146.0s. Total imaging time on the Amazon cloud was 255.0s. Thus the latency following data acquisition was less than 2mins.

Availability and Platform support

The entire package is integrated with the currently available version of the Gadgetron, which is distributed under a permissive, free software license based on the Berkeley Software Distribution license. The licensing terms allow users to use, distribute and modify the software in source or binary form. The source code is supplied with this paper and documentation can be found at the Sourceforge Open Source distribution website for Gadgetron (<http://gadgetron.sourceforge.net/>). The software has been compiled and tested on Microsoft Windows 7 64bit, Ubuntu Linux, CentOS 6.4, and Mac OS X (Note this paper does not present examples running on CentOS and Mac OS X, but the software has been compiled and tested on those two operating systems).

Discussion

This work extends the previously published Gadgetron framework to support distributed computing, which makes it possible to distribute a demanding reconstruction task over multiple computing nodes and significantly reduce the processing time. This paper focused on reducing the processing time of non-linear reconstruction applications, which have so far been difficult to deploy clinically. As demonstrated in the examples, the increased computational power could make the processing time of non-linear reconstruction feasible for the regular clinical use.

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3 The Gadgetron Plus (GT-Plus) extension provides a set of utility functions to manage and
4 communicate with multiple nodes. Based on these functions, flexible cloud topologies can be
5 realized as demonstrated in this paper. In the current Gadgetron software release, the
6 discussed dual-layer and single layer cloud implementation are made available to the
7 community. They are designed and implemented for general-purpose use, although the
8 examples given are specific for cine and 3D neuroimaging. Based on the GT-Plus extensions
9 new cloud topologies will be explored in the future and users can design and implement their
10 own cloud structure.
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24 The Gadgetron based cloud computing was deployed on three different types of cloud
25 computing hardware. This demonstrates the flexibility both Gadgetron framework in general
26 and the GT-Plus extensions specifically. The casual cloud setup is the cheapest, most
27 accessible way of using Gadgetron cloud computing. It can be set up quickly and used for
28 algorithm development and validation in a research laboratory. The disadvantage of using
29 such a setup is the computing nodes may be very heterogeneous and optimal distribution of
30 the work among nodes may become non-trivial. If cloud computing is used in a production
31 type setting on a clinical scanner, it is also problematic that a node may be busy with other
32 tasks when it is needed by the scanner.
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48 The Amazon EC2 system, on the other hand, provides a professional grade cloud setup with
49 24/7 availability. The computational resources can be dedicated for a specific project or
50 scanner and the nodes can in general have the same configuration, which reduces the
51 complexity of scheduling. This setup is also easy to replicate and share among groups and
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scanners. There are other companies that provide the same type of cloud infrastructure service, e.g. Rackspace (<http://www.rackspace.com/>). With these vendors the users pay by hour to rent computers. In the setup we describe in this paper, the cost of running the cloud was on the order of US \$50 per hour. While this cost could be prohibitive if the cloud is enabled 24 hours per day, it is a relatively modest cost in comparison to the cost typical patient scans. Moreover, this cost is falling rapidly with more service providers entering into the market and more powerful computing hardware becoming available. The main downside of using a remote cloud service such as Amazon EC2 is the need for a high-speed Internet connection to the cloud provider. At large universities 1Gb/s connections (which are sufficient for the applications presented here) are becoming commonplace. However, this may not be the case for hospitals in general.

The third setup, the NIH's Biowulf, is a dedicated, custom built, cluster system. While not available to the entire MRI community, it represents a parallel computing platform often found at research institutions (such as universities) or large corporations. For large organizations aiming to provide imaging, reconstruction and processing service for a large number of scanners, this setup may be the most cost effective platform. It is, however, important to note that purchasing, configuration, deployment, and management of even modest cloud computing resources is a non-trivial task that requires significant resources.

Several software modules implemented in the Gadgetron framework are GPU accelerated, although the demonstrated examples in this paper are mainly using CPUs. The GT-Plus extension of distributed computing does not conflict with GPU based computational

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3 acceleration in any sense. Every computing node can be equipped with different hardware; for
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5 those with good GPU processors or CPU coprocessors (e.g. Intel Xeon Phi coprocessors
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7 <http://www.intel.com/content/www/us/en/processors/xeon/xeon-phi-detail.html>), the local
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9 processing can utilize those resources, since the Gadgetron framework allows every node to
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11 be configured with different Gadget chains. Heterogeneous computational hardware across
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13 nodes can be challenging for optimal load balancing. In the current framework, the user can
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15 supply computing power indexes for nodes to indicate its strength. But the framework does
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17 not presently implement more complicated approaches to help determine the computing
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19 ability of every node.
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27 The Gadgetron framework and its toolboxes are mainly programmed using C++ and fully
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29 utilize generic template programming. While efforts are made to provide documentation and
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31 examples in the Gadgetron distribution, developers who want to extend the toolboxes still
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33 need some proficiency with object oriented programming and C++ in particular.
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38 Conclusion

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40 We have developed the Gadgetron Plus extension for the Gadgetron framework to support
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42 distributed computing using various cloud setups. We have deployed the Gadgetron based
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44 distributed computing over three very different cloud environments. We have shown the
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46 increased computational power in the cloud significantly speeds up l1-SPIRIT reconstruction
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48 for 2D+t dynamic imaging and high-resolution 3D acquisitions.
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ACKNOWLEDGEMENTS

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For Peer Review

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List of Captions

FIG 1. A schematic presentation of Gadgetron architecture. The client application communicates with Gadgetron process via the TCP/IP connection. The Reader de-serializes the incoming data and passes them through the Gadget chain. The results are serialized by the Writer and sent back to client application. The Gadgetron process resides on one computer, the Gadgetron server. The client can be a MRI scanner or other customer processes. Note the algorithm modules implemented in the Gadgetron toolboxes are independent from the streaming framework; therefore, these functionalities can be called by standalone applications which are not using the streaming framework.

FIG 2. Example presentation of GT-Plus distributed computing architecture for Gadgetron. In this example, at least one Gadgetron process is running on a node (Multiple Gadgetron processes can run in one node on different ports). The gateway node communicates with the client application (e.g. MRI scanner). It manages the connections to each of the computing nodes via the software module `GadgetCloudController` and `GadgetronCloudConnector`. Whenever sufficient data is buffered on the gateway node, the package can be sent to the computing node for processing. Different computing nodes can run completely different reconstruction chain.

FIG 3. The dual layer topology of cloud computing for 2D+t applications. Every connected node contains its own `GadgetCloudController` and can split a reconstruction task for a slice to its sub-nodes. Compared to the basic cloud topology shown in Fig. 2, this dual layer example adds extra complexity. This example demonstrates the flexibility of GT-Plus architecture for composing different computing cloud topologies to fit different reconstruction tasks.

FIG 4. The gadget chain used in the multi-slice myocardial cine imaging. Here the `GtPlusRecon2DTGadgetCloud` gadget controls the connection to the first layer node where the data from a slice was reconstructed. The second layer sub-nodes were further utilized to speed up the reconstruction. The TCP/IP socket connections were established and managed by the cloud software module implemented in the GT-Plus.

FIG 5. Reconstruction results of multi-slice myocardial cine imaging on the GT-Plus cloud. Compared to the linear reconstruction (a), non-linear reconstruction (b) improves the image quality. With the computational power of Gadgetron based cloud, the entire imaging including data acquisition and non-linear reconstruction can be completed in 1min to achieve the whole heart coverage.

FIG 6. Reconstruction results of 1mm^3 brain acquisition on the GT-Plus cloud. The basic cloud topology shown in Fig. 2 was used here. Both GRAPPA linear reconstruction (a) and (the) I1SPIRIT results (b) are shown here. The single node processing time is over 20mins, which prohibits the clinical usage of non-linear reconstruction. With the Gadgetron based cloud, a computing time of <2.5mins can be achieved for this high resolution acquisition.

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Table 1

Total imaging time (from the start of data acquisition to the moment when all images are returned to the scanner) and computing time in seconds for the multi-slice myocardial cine imaging. The in vivo test was only performed with cloud setups. The single node computing time was recorded with the retrospective reconstruction on the gate-way node.

	Casual		Biowulf		Amazon EC2	
	Single	Cloud	Single	Cloud	Single	Cloud
Imaging time (s)	-	259.2	-	62.1	-	52.6
Computing time (s)	823.7	255.0	558.1	58.2	427.9	48.9

Table 2

Total imaging and computing time in seconds for the 3D neuro acquisition. The single node used for comparison is the gateway node for every cloud setup.

	Casual		Biowulf		Amazon EC2	
	Single	Cloud	Single	Cloud	Single	Cloud
Imaging time (s)	-	541.9	-	278.5	-	255.0
Computing time (s)	1054.3	449.1	1265.1	186.4	983.5	146.0

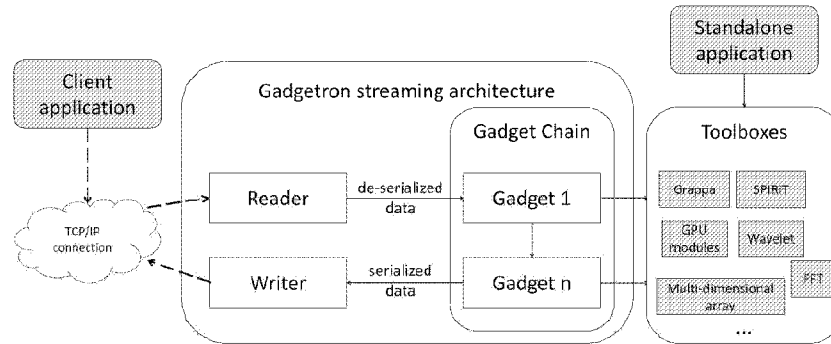
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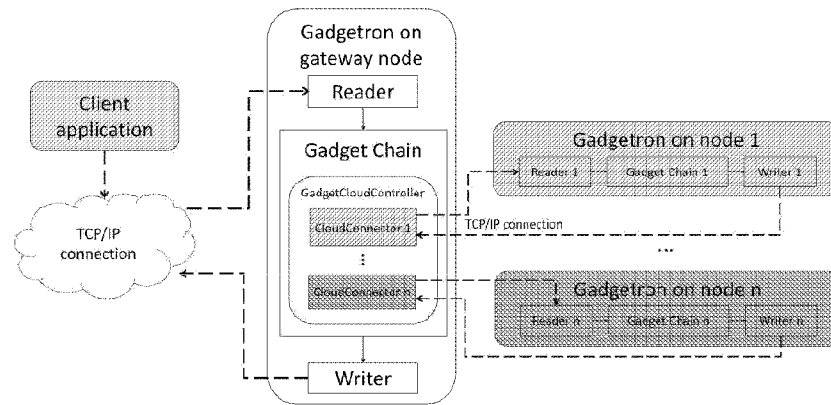


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999x643mm (120 x 120 DPI)

Review

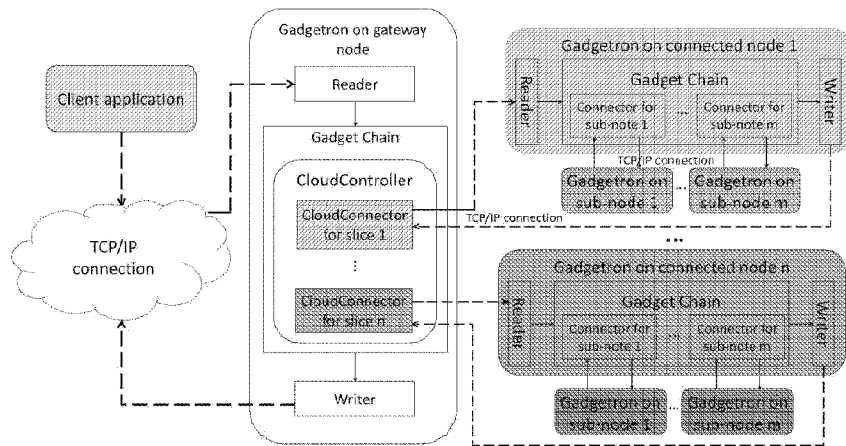


FIG 3. The dual layer topology of cloud computing for 2D+1 applications. Every connected node contains its own GadgetCloudController and can split a reconstruction task for a slice to its sub-nodes. Compared to the basic cloud topology shown in Fig. 2, this dual layer example adds extra complexity. This example demonstrates the flexibility of GT-Plus architecture for composing different computing cloud topologies to fit different reconstruction tasks.

661x458mm (120 x 120 DPI)

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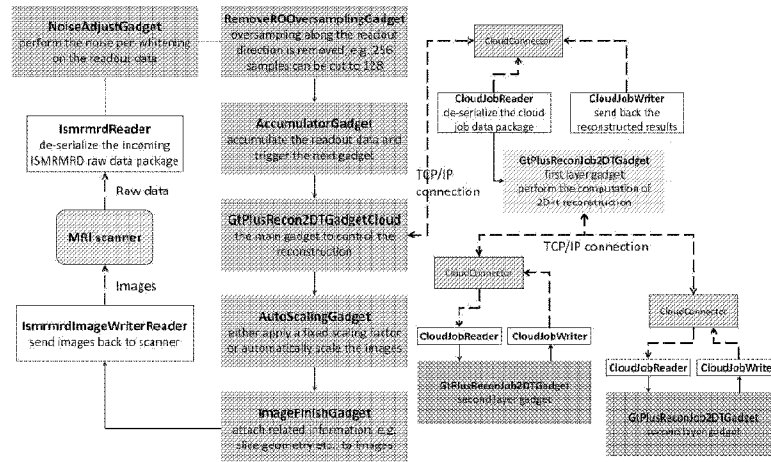


FIG 4. The gadget chain used in the multi-slice myocardial cine imaging. Here the *GtPlusRecon2DTGadgetCloud* gadget controls the connection to the first layer node where the data from a slice was reconstructed. The second layer sub-nodes were further utilized to speed up the reconstruction. The TCP/IP socket connections were established and managed by the cloud software module implemented in the GT-Plus.

931x648mm (120 x 120 DPI)

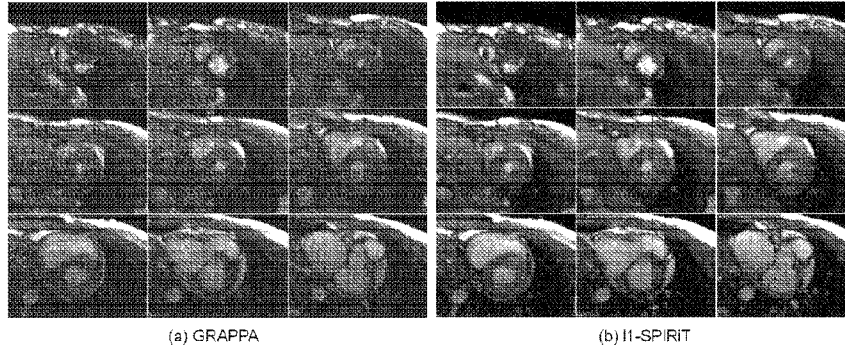


FIG 5. Reconstruction results of multi-slice myocardial cine imaging on the GT-Plus cloud. Compared to the linear reconstruction (a), non-linear reconstruction (b) improves the image quality. With the computational power of Gadgetron based cloud, the entire imaging including data acquisition and non-linear reconstruction can be completed in 1min to achieve the whole heart coverage.

388x197mm (120 x 120 DPI)

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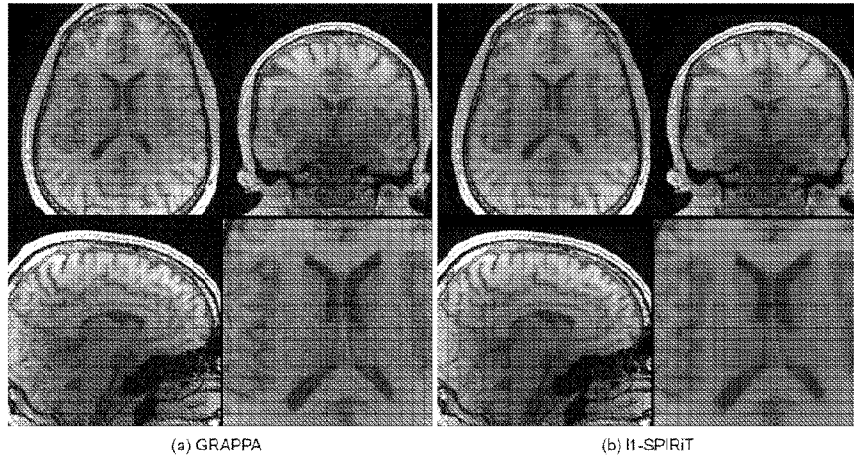


FIG 6. Reconstruction results of 1mm3 brain acquisition on the GT-Plus cloud. The basic cloud topology shown in Fig. 2 was used here. Both GRAPPA linear reconstruction (a) and the H1-SPIRiT results (b) are shown here. The single node processing time is over 20mins, which prohibits the clinical usage of non-linear reconstruction. With the Gadgetron based cloud, a computing time of <2.5mins can be achieved for this high resolution acquisition.

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41L-519

Appendix 3 Employee Discovery and Invention Report (EIR)

An EIR should be completed for each discovery or invention that is a) a novel innovation, b) a new or improved method or process; or c) believed to have potential commercial value (e.g. a new reagent, unique antibody, vaccine, medical device, or therapeutic compound); or d) a request from a commercial organization for use or resale of the new discovery or innovation.

If you are employed by PHS it is presumed that the invention was made as part your official duties as a Government employee. If this is not the case, you should still complete the EIR, but you must contact your Technology Development Coordinator (TDC) and provide the details pertaining to this particular discovery or invention so that a determination of rights can be made.

COMPLETION OF THE EIR

1. This is the WORD 2007 formatted version
http://www.ott.nih.gov/forms_model_agreements/forms_model_agreements.aspx
 - complete the form by filling in the shaded fields. For "check boxes" insert "X".
 - once completed, print the EIR and have each contributor sign their Contributor Information Sheet
 - questions regarding the completion of the EIR should be referred to your NIH/FDA Technology Development Coordinator (TDC)
 - email the completed electronic EIR template and any documents listed in questions 2.e., 5 or 6 to your NIH/FDA Technology Development Coordinator (TDC); and
 - Submit the signed EIR to your NIH/FDA Technology Development Coordinator (TDC)
2. The TDC will then forward the completed electronic report and the printed, signed EIR to the Office of Technology Transfer (OTT). If your IC in conjunction with the OTT decides not to file a patent application on your invention you may contact your Technology Development Coordinator (TDC) to request a waiver and, if granted, have an opportunity to obtain the rights to the invention by filing the patent application at your own expense.

Frequently Asked Questions: http://ottintranet.od.nih.gov/EIR/EIR_FAQS_20110915.htm

General questions regarding the form may be directed to the NIH Office of Technology Transfer (OTT). It is suggested, particularly if you leave government service and are receiving royalties, that you keep the Office of Financial Management apprised of changes in your official address.

Thank you for your cooperation

Privacy Act Notice: The PHS is collecting this information under authority of 45 CFR Part 7 "Employee Inventions". The information will be maintained as a part of the System of Records: 09-25-0168, "Invention, Patent and Licensing Documents." Provision of this information is mandatory and will be used as the initial step toward obtaining patent protection of inventions submitted by PHS employees, granting licenses to PHS inventions, administering and providing royalty payments to PHS inventors, and the intended "routine uses" of the information. Failure to provide complete information may adversely affect the Government's rights to future patent applications and licensing agreements.

Appendix 3

Employee Discovery and Invention Report (EIR)

IC Ref:	Date Received	OTT Reference #	Date Rcd 1/28/2014
		E-074-2014/0	via email

First Name	Hui	Middle Name		Last Name	Xue	Email	hui.xue@nih.gov
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1. **Title of Discovery:** (in 200 characters or less provide a title that is sufficiently descriptive to identify the discovery.)
Real-Time Processing of Medical Imaging Raw Data using Cloud Computing
2. **Please provide a clear and concise description of your discovery. Describe in terms that an individual in another field would understand.**

- a. Provide background information related to the discovery.

The computing process (image formation from raw data) in medical imaging has become increasingly complex with high computational demands. The computational equipment (in general a single computer) deployed with clinical imaging systems is often inadequate for achieving clinically practical image reconstruction times. The hardware has to be specified and tested years before the imaging devices are deployed and the hardware is consequently obsolete before it is deployed. This invention proposes to eliminate the need to deploy data processing hardware locally by deploying the image reconstruction hardware and software in a (remote) cloud computing system. The powerful computational resources available in commercial cloud systems can be leveraged directly in modern medical imaging devices and by doing so, the image processing hardware is replaced by a flexible software component, which can be scaled on-the-fly to match modern algorithms and which can be serviced and deployed remotely. For the end-user of imaging device, e.g. the physician or technician operating the scanner, they will feel no differences than if the computation was performed locally. We have demonstrated that this is possible with clinical MRI systems and using this paradigm, image reconstruction can be sped up by an order of magnitude for some applications.

- b. Describe how the discovery will be used and what product(s) could be made.

The proposed invention opens a new paradigm for imaging raw data processing. There are several potential uses.

1. A medical imaging equipment vendor can produce MRI (or other medical imaging modality) systems that are deployed with rudimentary image reconstruction equipment, which is only responsible for transmitting data to the cloud computing facility and receive images. Through this process, significant advantages are gain in terms of deployment cost, service complexity, and ability to adopt new technologies on existing systems.
2. Image reconstruction time can be significantly reduced for computationally intensive applications. Currently image reconstruction equipment is selected to provide reasonable performance over most applications. That means that the computationally demanding applications suffer because it would not be cost effective to deploy computing equipment that is sufficient for the high end applications since are not run that frequently (it may only be a single scan in some patients). With this solution a vendor can provide high performance for such applications by sharing the resources among multiple sites. The vendor can even have a scalable price/performance model.
3. Third party vendors can deploy an imaging application completely in software, i.e. small companies that provide high end imaging applications that rely on specialized reconstruction hardware without the need to deploy this hardware.

- c. Describe the unique features and advantages of this discovery that distinguishes it over the problems or limitations associated with the current science or existing products.

Current imaging devices, e.g. MRI scanners, perform the imaging computation locally on a computer connected to the scanner body. This computer has limited hardware resource and cannot deliver images faster enough for clinical usage for advanced imaging algorithms. Therefore, the current scanner vendors only provide relatively simple algorithms on their computers. The proposed invention will completely remove this limitation by leveraging a potentially unlimited computing resource in the cloud.

It is costly to deploy, service, and upgrade computing hardware in the field. With this invention the vendors can eliminate this part of the imaging system and service it remotely.

Appendix 3

Employee Discovery and Invention Report (EIR)

Currently, third party vendors have difficulty deploying novel raw data processing applications on clinical scanners because they can't select the hardware/software platform needed to deploy their application. They are forced to use the vendor provided hardware and programming window, which may be inadequate. This invention allows scanner vendors or third part companies to select hardware and software needed on a scan by scan basis.

Some current imaging systems, e.g. animal MRI scanner systems (used in pharmaceutical research) have very rudimentary image reconstruction systems. This invention has the potential to bring state-of-the-art imaging reconstruction functionalities to the animal MRI system and shall noticeably improve the imaging efficiency and image quality for those animal scans.

- d. (if applicable) If the discovery is or relates to a composition, describe the composition by providing sequence structures of amino acids or nucleic acids, provide chemical formulas for chemical compounds; if the discovery is a method, outline the particular steps of the method.

N/A

- e. Please list the most pertinent articles, presentations, other public disclosures, relevant patents or patent applications made by others that are related to your discovery?

No other inventions/papers/patents are related to this invention.

Attach copies of the publications cited; copies of U.S. Patents or published patent applications are not required.

3.

- a. **Current Stage of Development** (Please insert "X" for all the following states of development that currently best represent your discovery at this time)

☐ Conceptual	☐ Design	☐ Working	☐ Model/Prototype
☐ In-vitro testing	☒ In-vivo testing. Specify model	Normal human healthy volunteer study has been performed to testify this performance of this invention	
Model Organism Created: Specify			
☐ FDA submissions	☐ IND	☐ NCE/NME	☐ IDE
☐ Clinical Trial Phase	☐ Other		
☐ Research Material(s)			
☒ Software (beta or later) [please complete Attachment 2]			

- b. **Future Development Activities**

1. What activities related to this discovery will you be undertaking over the next 2 years?

- We will conduct plenty of research projects based on this invention to improve the imaging speed and image quality of MRI imaging.
- We will develop and deploy plenty of imaging computing software on the cloud system. Their usage may be made available to internal and external research collaborators.
- The system design and software implementation of this invention will be continuously improved over the time.

2. Would you consider working with a CRADA partner to further advance this discovery? If Yes,

NO

4. Potential Commercial Applications

- Does this disclosure include research material(s) that could be made available for licensing? If Yes, complete Attachment 1.
- Is this EIR being submitted based on an outside party's request for licensing a material?, If Yes, provide the name of the company's contact person and telephone number or email.
- Identify any company(s) or non-profit organizations that are conducting similar research.

We find NO other entities are conducting similar research or inventions.
- Have you been contacted by or are you in discussions with anyone interested in collaborating with you to develop this discovery?

Appendix 3

Employee Discovery and Invention Report (EIR)

NO

Thinking creatively, answer the following:

- e. Describe how the discovery or material may enhance the public health, i.e. therapeutic, diagnostic, drug screening, assay, research tool, medical imaging software, or other software.

- a) The clinical applicability of advanced imaging computing ability brought in by this invention will significantly speed up the imaging efficiency and improve image quality. It means the reduction of imaging costs, e.g. on MRI clinical scans for public, because the imaging time needed for each subject is reduced.
- b) Novel imaging application that currently cannot be used in patients can be deployed with the proposed methodology, which will enable testing of new techniques in patients and provide state-of-the-art technology to patients.
- c) The third-party entities can leverage this technology to compete for freely in the medical imaging market place, which may provide increase competition and lowered cost.
- d) The overall cost of an MRI system may be reduced. Effectively the vendor can provide the same (rudimentary) image reconstruction equipment to all customers and users that don't run very advanced imaging studies would simply pay for what they get and more advanced users would still be able to use the latest applications.

5. Public Disclosures/Presentations (Past and Future).

- a. List any disclosure of this discovery, including partial disclosures, made by you or anyone identified in 7.b. Examples of disclosures include, but are not limited to the following: abstracts, posters, oral presentations/seminars, NIH Annual Reports, theses/dissertations, grant applications, reports, journal publications, website postings, phone calls, emails, demonstrations, sales catalogs, news releases, and any public use, sale, or offer for sale of the technology.

Two abstracts were submitted to the Joint Annual Meeting ISMRM-ESMRMB 2014 which will be held on 10-16 MAY 2014, Milan, Italy. Abstract submission date was Nov 20, 2013.

One full length manuscript describing this invention is under preparation and will be submitted for publication in the near future.

- b. Has a manuscript(s) been prepared (or in the process of being prepared) or submitted for review? If Yes (attach a copy, *early first drafts are encouraged and will be kept confidential*)

i. Primary manuscript: -specify the (exact or expected) date of submission	Dec 10, 2013
-identify the journal's name; publisher's telephone number or email (if known)	Magnetic Resonance in Medicine http://onlinelibrary.wiley.com/journal/10.1002/(ISSN)1522-2594
-identify the date of publication (if known)	
ii. Additional manuscripts (draft and submitted) information:	

- c. Has an abstract or poster been prepared or is now in preparation for a future presentation or publication? If Yes attach a copy, (*early first drafts are encouraged and will be kept confidential*). For each presentation or publication: please identify, as appropriate, the following:

No.	Conference Symposium	Meeting Date (mm/dd/yy)	Date Abstract / Poster was submitted? (mm/dd/yy)	Abstract / Poster pre-published online or in catalogue?	Conference Organizer and Contact Information (Tab out of last cell to add additional row)
1.	Joint Annual Meeting ISMRM-	10-16 MAY 2014	Nov 20, 2013	May 10, 2014	http://www.ismrm.org/14/14pr

Appendix 3 Employee Discovery and Invention Report (EIR)

	ESMRMB 2014				ogram.htm
2	Joint Annual Meeting ISMRM-ESMRMB 2014	10-16 MAY 2014	Nov 20, 2013	May 10, 2014	http://www.ismrm.org/14/14program.htm

- d. Is anyone outside of the Public Health Service (NIH, FDA, and CDC) aware of your discovery? If Yes, please identify them, the date, and describe the circumstances. (e.g. formal or informal communications with colleagues, collaborators)

N/A

6. Collaborations, Material Transfers, Confidential Disclosure Agreements

The following questions are designed to answer whether any part of the research resulting in this discovery involved collaborations outside of your laboratory, used materials/software/equipment obtained from another party, and/or included outside funding. (Consult with your laboratory chief and/or your TDC if there is a question.)

- a. **CRADA:** Is the subject matter of your disclosure related to a PHS Cooperative Research and Development Agreement (CRADA or M-CRADA) involving you or your laboratory or IC? If Yes, please identify the collaborator, the NIH principle investigator, CRADA title and the Institute's CRADA reference number:

YES, we have access to programming (through the IDEA programming environment) the image reconstruction system through the Siemens MRI CRADA (Andrew Arai is the PI). This invention is, however, not related to a specific CRADA project and is NOT done in collaboration with Siemens.

- b. **Collaborations:** Is the subject matter based on research collaborations other than a CRADA? If Yes, please identify your collaborator and the name of their organization.

NO

- c. **Outside Materials/Information Transfer:** Is there subject matter in this discovery based on proprietary materials or confidential information obtained from an outside party or organization?

If Yes, please identify the third party contributor, their email or telephone number, and the organization's name.

NO

Please provide a copy of any document that records this transfer. This may include an email, Material Transfer Agreement, Confidential Disclosure Agreement, Clinical Trial Agreement, or Research Collaboration Agreement.

- d. **Non-NIH awards:** Did this discovery arise based on non-NIH support? (e.g. grants, fellowships) If Yes, please identify

NO

- e. **Human Subjects:** Does this discovery rely upon materials or information obtained from human subjects or from data involving human subjects as defined in and regulated under 45 CFR Part 46? If Yes, please provide the Protocol title, Institutional Review Board (IRB) protocol approval number and date or the OHSR exemption number, name or explain fully.

NO

7. Identification of Contributors

- a. Identify the individuals who could merit co-authorship credit for any associated publication.

Hui Xue, Peter Kellman, Michael S. Hansen, Thomas S. Soerensen, Souheil Inati

- b. List below the names and organizations of all people who participated in conceiving or continued development of the discovery/invention. Examples include those who made intellectual, theoretical, or innovative contribution to the discovery. In the case of software, those individuals who were involved in creating program code, manuals, flowcharts or any related items.

NOTICE: This may be fewer individuals than named in 7.a. above. Please be aware that inventorship is strictly defined in patent law. Accordingly, contributors you list in this section will be named on patent applications resulting from this EIR only if their contributions meet this legal standard. A co-author may or may not qualify based on the particular facts; if you have any questions, contact your TDC.

Appendix 3

Employee Discovery and Invention Report (EIR)

The following acknowledgement pertains to Government employees and those treated as employees. Under 45 CFR Part 7 "Employee Inventions", all employees of the Public Health Service have an obligation to report and assign inventions to the Government of the United States, as represented by the Department of Health and Human Services. Specifically, the Government shall obtain the entire right, title, and interest in inventions: (i) made during working hours; or (ii) made with a contribution by the Government of facilities, equipment, materials, funds or information or of time or services of other Government employees on official duty; or (iii) which bear a direct relationship or are made in consequence of the official duties of the inventor.

If you are employed by PHS to conduct or perform research, it is presumed that the invention was made under these circumstances. If this is not the case, you should still complete the EIR, but you must contact your Technology Development Coordinator (TDC) and provide the details pertaining to this particular discovery or invention so that a determination of rights can be made.

1. Submitting Contributor :	Hui Xue	: Org	NHLBI, NIH
2. Co-Contributor :	Michael S. Hansen	: Org	NHLB, NIH
3. Co-Contributor :	Peter Kellman	: Org	NHLB, NIH
4. Co-Contributor :		: Org	

5. Enter additional Co-Contributor's names and organizations as necessary.

--

An Additional Contributor Information document is to be completed for each additional contributor listed in 7b.5.

The form may be downloaded at: <http://www.ott.nih.gov/docs/EIR-Additional-Contributor.docx>

Contributor Information begins on next page

**Employee Discovery and Information Report (EIR)
Contributor Information Sheet**

♦ Indicates a required field

Contributor 1**Name**

♦ First	Michael	♦ Middle	S.	♦ Last	Hansen	Suffix	
Degree	PhD	♦ Citizenship	Denmark				
♦ Employee Identification No.:					♦ Associated project NIH Z01 Project Number(s)	HL004607-15	

♦ Describe this individual's contribution to the discovery.

Propose the system design, conduct the software development and perform the experiments

Current Organization Information:

♦ Organization Name	Magnetic Resonance Technology Program, National Heart, Lung and Blood Institute, National Institutes of Health, MD, USA						
Division/Branch/Laboratory							
♦ Title							
♦ Office Address	Building 10, B1D						
♦ City	Bethesda	♦ State	Maryland	♦ Zip code	20814	♦ Country	
♦ E-mail	michael.hansen@nih.gov	Telephone	+1-301-496-1457	FAX	+1 (301) 496-2389	Other contact number. (optional)	

♦ Has your organizational affiliation changed during the development of this discovery? Yes/No, if yes, explain

--

Home Information

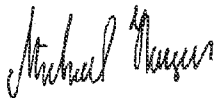
♦ City	Silver Spring	♦ State	MD	♦ Zipcode	20902	♦ Country	USA
Phone	301-412-9671	Email					

Please identify with a "X" if this individual falls under one or more of the following training or fellowship appointments or institutional partnerships.

☐	CRADA Personnel	☐	Howard Hughes Fellow	☐	ORISE Fellow	☐	NIH-ORAU
☐	Clinical Fellow	☐	Gates Foundation	☐	NRSA Fellowship	☐	Visiting Fellowship
☐	Fogarty Scholar	☐	IRTA Fellowship Program	☐	Postdoctoral Fellow	☐	Other (specify below *)
☐	Oxford-Cambridge Scholars Prog	☐	National Research Council Award	☐	Research or Clinical Fellowship	☐	NIH Contract Employee - specify employer name below *
☐	CNRM Personnel (HJF)	☐	Society Fellows specify below	☐	Graduate Partnership Program	☐	

* Note Section

Contributor: I have read and understand the information submitted in the EIR.

Signature

Date

Digitally signed by Michael S. Hansen
 DN: c=US, o=U.S. Government, ou=HHHS,
 ou=NIH, ou=People, cn=Michael S. Hansen,
 0.9.2342.19200300.100.1.1-0014806654
 Date: 2013.12.04 09:28:28 -05'00'

Employee Discovery and Invention Report (EIR)
Contributor Information Sheet

* Indicates a required field

Contributor 2

Name

*First	Hui	*Middle		*Last	Xue	Suffix	
Degree	PhD	*Citizenship	China				
*Employee Identification No.:				*Associated project	NIH Z01		
				Project Number(s)			

*Describe this individual's contribution to the discovery.

Propose the system design, conduct the software development and perform the experiments

Current Organization Information:

*Organization Name	Magnetic Resonance Technology Program, National Heart, Lung and Blood Institute, National Institutes of Health, MD, USA						
Division/Branch/Laboratory							
*Title							
*Office Address							
*City	Bethesda	*State	Maryland	*Zip code	20814	*Country	
*E-mail	hui.xue@nih.gov	Telephone	+1-301-496-3052	FAX	+1 (301) 496-2389	Other contact number. (optional)	

*Has your organizational affiliation changed during the development of this discovery? Yes/No, if yes, explain

Home Information

*City	Englewood	*State	New Jersey	*Zipcode	07631	*Country	USA
Phone	+1 609 712 3398	Email	hui.xue@nih.gov				

Please identify with a "X" if this individual falls under one or more of the following training or fellowship appointments or institutional partnerships.

☐	CRADA Personnel	☐	Howard Hughes Fellow	☐	ORISE Fellow	☐	NIH-ORAU
☐	Clinical Fellow	☐	Gates Foundation	☐	NRSA Fellowship	☐	Visiting Fellowship
☐	Fogarty Scholar	☐	IRTA Fellowship Program	☐	Postdoctoral Fellow	☐	Other (specify below *)
☐	Oxford-Cambridge Scholars Prog	☐	National Research Council Award	☐	Research or Clinical Fellowship	☒	NIH Contract Employee - specify employer name below *
☐	CNRM Personnel (HJF)	☐	Society Fellows specify below	☐	Graduate Partnership Program	☐	Kelly Government Service

* Note Section

Contributor: I have read and understand the information submitted in the EIR.

Hui Xue

Signature

Nov 29, 2013
Date

Employee Discovery and Invention Report (EIR) Contributor Information Sheet

♦ Indicates a required field

Contributor 3

Name

♦ First	Peter	♦ Middle		♦ Last	Kellman	Suffix	
Degree	PhD	♦ Citizenship	USA				
♦ Employee Identification No.					♦ Associated project NIH Z01 Project Number(s)		

♦ Describe this individual's contribution to the discovery.

Propose the system design, conduct the software development and perform the experiments

Current Organization Information:

♦ Organization Name	Medical Signal and Image Processing Program, National Heart, Lung and Blood Institute, National Institutes of Health, MD, USA						
Division/Branch/Laboratory							
♦ Title							
♦ Office Address							
♦ City	Bethesda	♦ State	Maryland	♦ Zip code	20814	♦ Country	
♦ E-mail	kellmanp@nhlbi.nih.gov	Telephone	+1-301-496-2513	FAX	+1 (301) 496-2389	Other contact number. (optional)	

♦ Has your organizational affiliation changed during the development of this discovery? Yes/No, if yes, explain

Home Information

♦ City		♦ State		♦ Zipcode		♦ Country	
Phone		Email					

Please identify with a "X" if this individual falls under one or more of the following training or fellowship appointments or institutional partnerships.

☐ CRADA Personnel	☐ Howard Hughes Fellow	☐ ORISE Fellow	☐ NIH-ORAU
☐ Clinical Fellow	☐ Gates Foundation	☐ NRSA Fellowship	☐ Visiting Fellowship
☐ Equity Scholar	☐ IRTA Fellowship Program	☐ Postdoctoral Fellow	☐ Other (specify below *)
☐ Oxford-Cambridge Scholars Prog	☐ National Research Council Award	☐ Research or Clinical Fellowship	☐ NIH Contract Employee - specify employer name below *
☐ CNRM Personnel (HJF)	☐ Society Fellows specify below	☐ Graduate Partnership Program	

* Note Section

Contributor: I have read and understand the information submitted in the EIR.

Signature

Date

Peter
Kellman -S

Digitally signed by Peter Kellman
-S
DN: c=US, o=U.S. Government,
ou=HHS, ou=NIH, ou=People,
cn=Peter Kellman -S,
0.9.2342.19200300.100.1.1=0010
050922
Date: 2013.12.04 11:23:49 -05'00'

Employee Discovery and Invention Report (EIR)
Contributor Information Sheet

♦ Indicates a required field

Contributor 4

Name

♦ First		♦ Middle		♦ Last		Suffix	
Degree		♦ Citizenship					
♦ Employee Identification No.:					♦ Associated project NIH Z01 Project Number(s)		

♦ Describe this individual's contribution to the discovery.

Current Organization Information:

♦ Organization Name							
Division/Branch/Laboratory							
♦ Title							
♦ Office Address							
♦ City		♦ State		♦ Zip code		♦ Country	
♦ E-mail		Telephone		FAX		Other contact number. (optional)	

♦ Has your organizational affiliation changed during the development of this discovery? Yes/No, if yes, explain

Home Information

♦ City		♦ State		♦ Zipcode		♦ Country	
Phone		Email					

Please identify with a "X" if this individual falls under one or more of the following training or fellowship appointments or institutional partnerships.

☐	CRADA Personnel	☐	Howard Hughes Fellow	☐	ORISE Fellow	☐	NIH-ORAU
☐	Clinical Fellow	☐	Gates Foundation	☐	NRSA Fellowship	☐	Visiting Fellowship
☐	Fogarty Scholar	☐	IRTA Fellowship Program	☐	Postdoctoral Fellow	☐	Other (specify below *)
☐	Oxford-Cambridge Scholars Prog	☐	National Research Council Award	☐	Research or Clinical Fellowship	☐	NIH Contract Employee - specify employer name below *
☐	CNRM Personnel (HUF)	☐	Society Fellows specify below	☐	Graduate Partnership Program	☐	

* Note Section

Contributor: I have read and understand the information submitted in the EIR.

Signature _____

Date _____

Employee Discovery and Invention Report (EIR)
Appendix B
Attachment 1

Supplemental Information Sheet for Research Materials

This attachment requests information regarding materials that may be available for potential licensing. The Set 1 questions are general information regarding specific materials required to practice the invention or ancillary materials created during the course development that may be potentially licensed.

The Set 2 questions SHOULD BE ANSWERED IF THIS EIR is being submitted based on an outside party's request for licensing a material.

Set 1. (not required if Set 2 Questions are completed) General material information.

- a) Identify those material(s) made during course of research that are specifically required to practice this invention. Please identify each unique material(s) or chemical compound(s) developed that are related to this EIR.

- b) Identify those material(s) made during course of research that may be available for licensing as a research material. Please identify each unique material(s) or chemical compound(s) developed that are related to this EIR.

- c) Material Citation or other source:

- d) Has material been deposited in the ATCC or similar repository? If Yes, please provide the repository and catalog reference number.

- e) Were any of the materials necessary to use or make the Material acquired from someone outside NIH? If Yes and not already listed in Question 6c, please provide contact information and a copy of any document that records this transfer.

Set 2. If a prospective licensee is interested in a material answer the following questions.

Provide a summary regarding the approximate difficulty/time/cost/effort for your laboratory to provide the material to an outside for-profit requestor. Is it a limited resource?

Identify and describe the Material Type

Examples of potential material types:

Antibodies: monoclonal, polyclonal | **Cell Lines:** uninfected cells, infected cells, hybridomas

DNA/RNA: genetic clones, expression vectors, PCR reagents:

Proteins/Peptides: | **Purified Proteins:** synthetic peptides

Viruses: virus isolates, drug resistant, virus isolates, recombinant vaccinia

Opportunistic Infections: Candida, Cryptococcus, cryptosporidium, cytomegalovirus, mycobacterium, mycoplasma, pneumocystis, toxoplasma

Model Organisms (e.g. strain, species) | **Chemical Compounds**

Designation: (Laboratory nomenclature)

Source of Material: (i.e. human, mouse, rat)

Reference Citation or other source

Has the material been deposited in the ATCC or similar repository? If Yes, please provide the repository and catalog reference number.

How can it be provided: (i.e. 2ml vial of frozen cells, plasmid)

Current quantities available for distribution: (i.e. 10 vials)

Recommended propagation medium and growth characteristics: (i.e. expression level, titer, temperature, passages)

Recommended freeze medium

Sterility: (i.e. negative for bacteria, fungi & mycoplasma)

Morphology: (i.e. epithelial-like, lymphoblast-like, fibroblast like)

Recommended Storage: (i.e. liquid nitrogen)

Appendix 3
Employee Discovery and Invention Report (EIR)
Attachment 2

Supplemental Information Sheet for Software

The purpose of this attachment is to provide information regarding evaluation of software for potential licensing. The following questions should be answered as completely as possible.

1. Does this software contain code obtained from a third-party or covered by any Open Source License (e.g., collaborator, under a software agreement, a vendor, purchased etc.)? If Yes, please explain
2. Has this software been previously copyrighted? If Yes, then by whom?
3. Did you use outsiders to beta-test code? If Yes, was this done under an agreement?
4. How would the lab generally classify the use of this software (e.g., imaging, array analysis, mapping etc.)?
5. From the lab's perspective, what would be the preferred way of distributing this software?
6. What are the operating system requirements to run this software?
7. In which computer language is the software code written?
8. What stage of development is the software? Select one of the following:

☐	Ready to use by anyone
☒	Usable with some effort or assistance
☐	Needs substantial further development
9. Is the lab willing to release the source code?
10. Is the lab willing to prepare a demonstration version of the software to give to prospective licensees?
11. Were the current or prior versions distributed? If Yes, explain and supply date of distribution and any distribution agreement (if any).

Yes
<http://gadgetron.sourceforge.net/>

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Appendix 3
Employee Discovery and Invention Report (EIR)
Attachment 2

Supplemental Information Sheet for Software

AUTHORS BE LIABLE FOR ANY CLAIM, DAMAGES OR OTHER LIABILITY, WHETHER
IN AN ACTION OF CONTRACT, TORT OR OTHERWISE, ARISING FROM, OUT OF OR
IN CONNECTION WITH THE SOFTWARE OR THE USE OR OTHER DEALINGS IN THE
SOFTWARE

12. Was a government contractor involved in the writing or development of any of the code? If yes, identify the individual.

Yes, Hui Xue is currently a contractor with NHLBI.

**Employee Discovery Appendix 8
Institute/Center Administration Section**

(To be completed by the IC Technology Transfer Office.)

Lead IC sponsoring this invention	NHLBI	Division/Lab/Branch (if applicable)	
Identify any other ICs (if necessary, include Division/Lab/Branch)			
Confirm the scientist who will serve as the key point of contact (Scientific Point of Contact (SPC)) to receive and respond to patent correspondence. This may be different from the person identified as the Submitting Contributor.			Michael Hansen

IC is requesting OTT to perform the following action regarding this EIR. Only 1 of the following option boxes should be checked.

Do Not File

☐	Do not file; EIR is being submitted due to a request for material(s) licensing. Requester's contact information is attached
☐	Do not file; market as a research material
☐	Do not file a patent application based on other patent and/or policy reasons

Evaluation/Searching

☐	Request OTT evaluation and recommendation, Outside search/opinion are authorized, if needed
☐	Request OTT evaluation and recommendation, Outside search/opinion is not authorized

Patent Application Filing

☒	Emergency Patent Filing - File immediate provisional patent application based on an imminent publication. Authorization for filing is provided. In the "Additional Information or Instructions" box enter the date, location of public release and any other instructions
☒	File Patent: File a fully enabled provisional patent application
☐	File Patent/Patent Opinion: File a fully enabled provisional patent application and conduct a patentability opinion/assessment immediately after the provisional patent application has been filed
☐	Patent Opinion/File Patent: Conduct a patentability opinion/assessment (Completed by contract law firm). If the patentability opinion/assessment is positive, proceed with the filing a fully enabled provisional patent application
☐	Third Party Filing Patent Lead: Third party has already filed or will be doing the filing. Please provide 3 rd Party contact information. Application number(s), filing date(s), and copy(ies) of application(s) should be provided as well as filing receipts or paperwork identifying the inventors as filed
☐	Other Filing Instructions

Additional Information or Instructions

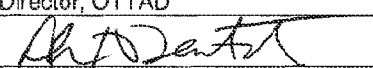
☒	Please see attached publications of interest
-------------------------------------	--

Is the IC submitting this EIR represented by a Service Center for this EIR? If Yes, please specify to whom the patent recommendations and patent correspondence are to be forwarded.

☐	Submitting IC, TDC only	☐	Service Center only	☐	Both the IC and Service Center
--------------------------	-------------------------	--------------------------	---------------------	--------------------------	--------------------------------

If documents are to be sent to the service center specify in "Additional Information or Instructions" box the individual to whom all patent recommendations and patent correspondence are to be directed.

The TDC, IC delegate, or Service Center Representative confirms receiving the EIR and acknowledges a complete EIR packet is being forwarded to OTT.

Name	Alan H. Deutch	Date	January 28, 2014
Title	Director, OTTAD		
Signature			

Authorized IC official for expenditure of IC funds for patent related expenses or attach authorization memo.

Name		Date	
Title			
Signature			

A complete EIR packet will be forwarded to the Director, DTDT, which comprises a single, non-stapled EIR packet containing the signed EIR containing all documents such as manuscripts, presentation, articles and citations referred to in the EIR, as well as any related IC reviews and authorization documents. The electronic version containing all the above information should be forwarded to OTT at ottfileroom@mail.nih.gov

Appendix 4

7403

3D High Resolution 11-SPIRiT Reconstruction on Gadgetron based Cloud

Hui Xue¹, Peter Kellman¹, Souheil Inati², Thomas Sorensen³, and Michael Schacht Hansen¹

¹Magnetic Resonance Technology Program, National Heart, Lung and Blood Institute, National Institutes of Health, Bethesda, Maryland, United States, ²National Mental Health Institute, National Institutes of Health, Bethesda, Maryland, United States, ³Department of Computer Science, Department of Clinical Medicine, Aarhus University, Aarhus, Denmark

Introduction Non-linear and iterative reconstruction algorithms have been the subject of intense study in the MR imaging community. Very promising algorithms have been published in the literature, including image domain compressive sensing [1] and k -space SPIRiT and its regularized versions [2]. Given the lengthy acquisition time of high resolution 3D MRI imaging, it is of great interest to apply non-linear reconstruction to shorten the imaging. The robustness against subject movement or uncooperative pediatric patients can be improved. However, the clinical usage of these techniques is often prohibited by the high demand for computational power and very long reconstruction time. To achieve practical reconstruction times for clinical usage of non-linear reconstruction, we have extended the previously published Gadgetron framework [3] to support the distributed computing across multiple computers. This extension is named "Gadgetron Plus" or "GT-Plus". A cloud version of 3D 11-SPIRiT reconstruction was implemented on the GT-Plus cloud framework and applied to high-resolution 3D neuroimaging. With the use of the computational power of the cloud, we demonstrate that a 3mins reconstruction can be achieved for 1mm³ isotropic neuro scans using 11-SPIRiT. Compared to the linear reconstruction, the image quality was significantly improved.

Architecture and Implementation At least one Gadgetron process was started at every node. The inter-node communication was managed by a software module GadgetCloudController using TCP/IP sockets. A gateway node was connected to the scanner and received readout data. It then sent buffered data package to computing nodes for processing. Every computing node was responsible for processing the received job via its processing chain and forwarded results back to the gateway. With all expected results received on the gateway, images were sent back to the scanner.

Cloud version of 3D 11-SPIRiT The gateway node was configured to receive the readouts for a 3D acquisition and perform k -space convolution kernel estimation. It then split the large 3D reconstruction problem by performing the 1D inverse FFT transform along the readout direction. Thus, the reconstruction was decoupled along the readout direction. Every chunk of data along the readout direction was sent to one computing node. The 11-SPIRiT algorithm was running on every node. The redundant Harr wavelet transform was used in the regularization term.

Deployment on cloud systems Two cloud setups were tested. **Amazon EC2 based cloud** 19 nodes were launched on the Amazon Elastic Compute Cloud (Amazon EC2). All nodes had two eight-core Intel Xeon E5-2670 2.60GHz processors, running Ubuntu Server 13.10. The gateway node had 240GB RAM and others had 60GB. **NIH Biowulf cluster** 23 nodes were requested from the Biowulf cloud (<http://biowulf.nih.gov>) which is a linux based parallel computing system (Red Hat Server 5.10) and built at National Institutes of Health, USA. The gateway node had 16 CPU cores (two eight-core Intel Xeon E5-2670 2.60GHz processors) and 256GB RAM. All other nodes had two six-core Intel Xeon X5660 2.80GHz processors and 24GB RAM. For both cloud setups, "online" reconstruction was achieved. That is, the acquired readout data was sent to cloud while the scan was proceeding. The reconstructed images were directly sent back to the scanner and stored in the clinical PACS.

In-vivo test Cloud based reconstruction was performed for high resolution neuro acquisition. A healthy volunteer was scanned on a 3.0T clinical MRI system (MAGNETOM Skyra, Siemens, 20-channel head coil). Acquisition parameters were: GRE readout, TR = 7.0/TE = 3.07ms, acquired matrix size 256x256x192, flip angle 20°, 1mm³ isotropic spatial resolution, bandwidth 120 Hz/pixel, two dimension acceleration R=3x2 and 3x3 with a 32x32 fully sampled k -space center. The total acquisition time was 65s and 46s for two acceleration levels.

Results Figure 1 shows the reconstruction results generated on the GT-Plus based cloud for R=3x2. Figure 2 is for R=3x3. Both cases indicate non-linear reconstruction noticeably improved image quality, compared to the linear GRAPPA reconstruction. The reconstruction time (defined as the computing time to perform the reconstruction algorithms) was 171s for R=3x2 and 170s for R=3x3 on the described Amazon EC2 cloud. On the Biowulf system, the reconstruction time was 239s and 242s. If only a single node was used, much longer reconstruction time was experienced: for R=3x2 and 3x3, the Amazon EC2 cloud recorded 1002s and 1022s and for the Biowulf system, computation took 1279s and 1338s respectively.

Conclusions The GT-Plus extension for Gadgetron framework was developed to support distributed computing across multiple nodes. The 3D 11-SPIRiT algorithm was implemented on the Gadgetron based cloud, giving significantly reduced reconstruction time for high resolution neuro scans. This speedup can enable the clinical usage of advanced non-linear reconstruction algorithms on 3D MR applications.

References [1] Lustig M, et al., MRM 58:1182-1195 [2] Lustig M, et al., MRM 64:457-471 [3] Hansen MS, et al., MRM 69:1768-1776 (2013)

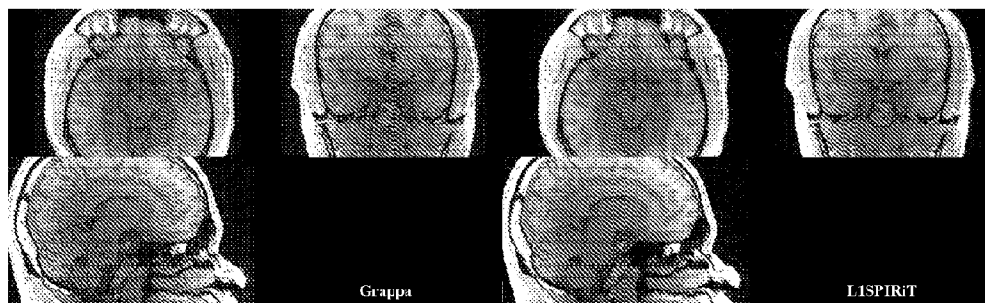


Figure 1. Reconstruction results of 3D neuro scan on the GT-Plus cloud for two dimensional acceleration R=3x2. Compared to the Grappa linear reconstruction on the left, non-linear reconstruction on the right gives noticeable improvement in signal to noise. For this 1mm³ protocol, the cloud version of non-linear reconstruction was completed within 3mins after the end of data acquisition, while on a single-node reconstruction took >15mins. This reduction of computing time could be crucial for clinical usage of advanced image reconstruction techniques.

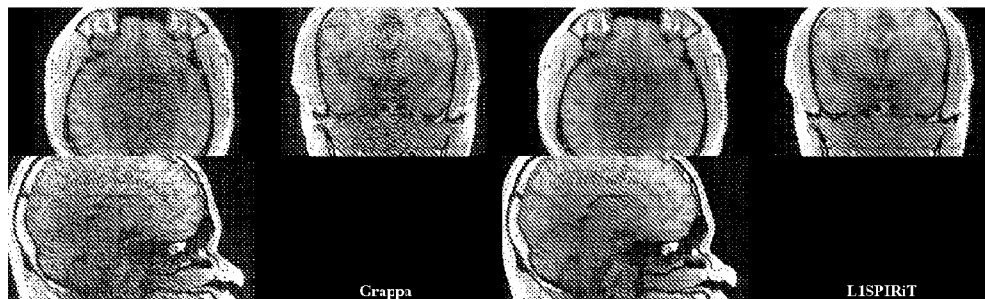


Figure 2. Reconstruction results of 3D neuro scan on the GT-Plus cloud for two dimensional acceleration R=3x3. Compared to the Grappa linear reconstruction shown on the left and results shown in Figure 1, the improvement in image quality is even more substantial for higher acceleration. Since the head coil used for this test has 20 channels, the R=3x3 acceleration severely degrades the Grappa reconstruction because of the elevated g-factor, while 11-SPIRiT reconstruction is much more robust in this case.

Appendix 5

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Distributed Computing on Gadgetron: A new paradigm for MRI reconstructionHui Xue¹, Peter Kellman¹, Souheil Inati², Thomas Sorensen³, and Michael Schacht Hansen¹¹Magnetic Resonance Technology Program, National Heart, Lung and Blood Institute, National Institutes of Health, Bethesda, Maryland, United States, ²National Mental Health Institute, National Institutes of Health, Bethesda, Maryland, United States, ³Department of Computer Science, Department of Clinical Medicine, Aarhus University, Aarhus, Denmark

Introduction MRI reconstruction has moved beyond the simple Fast Fourier Transform, towards more complicated parallel imaging and non-linear reconstruction algorithms. Often, developers who wish to implement and deploy their advanced algorithms on clinical scanners, find the vendor supported reconstruction hardware is inadequate for advanced algorithms or the provided programming environment is not suitable for clinical integration. The open-source framework, the Gadgetron, which was published recently, aims to address some of these concerns [1]. With this framework, algorithms can be implemented on suitable hardware selected by the user and subsequently connected to the scanner. While this is a valuable step-forward, the original Gadgetron was designed to run the reconstruction task within one process residing on a single computer and does not provide explicit support for cloud computing across multiple computational nodes. Although multiple CPU or GPU cores on one computer can contribute to the computation, single computer may not carry sufficient computing power to achieve clinical usage of non-linear reconstruction. To remove this limitation, we have extended the Gadgetron framework to support cloud computing. With this extension (named “Gadgetron Plus or GT-Plus”), any number of Gadgetron processes can run across multiple computers (hereafter referred as ‘nodes’) and a dedicated inter-process controlling scheme is implemented to multiple nodes. We demonstrate that with the GT-Plus cloud non-linear reconstruction of real-time cardiac cine imaging can be deployed in a clinical setting with acceptable reconstruction latency. Specifically, a multi slice real-time cine acquisition covering cardiac ventricles and non-linear reconstruction can be completed within 1min.

Architecture and Implementation Schematic outline of GT-Plus is shown in Fig. 1, representing a typical setup of Gadgetron based cloud where at least one Gadgetron running on a specific port at each node. A software module GadgetCloudController is implemented to manage the communication between nodes via TCP/IP sockets. Typically, a gateway node receives readout data from the scanner and distributes them through the cloud. For every connected node, a reader thread (CloudReaderTask) and a writer thread (CloudWriterTask) is spawned as active objects. There is a Gadgetron processing chain running on every connect node and for different cloud nodes, different processing chains can be performed. Whenever the reconstruction results are sent back from a cloud node, the gateway is notified and will take actions defined by the user, e.g. forwarding images back to the scanner or waiting for other jobs to complete.

Deployment The GT-Plus package can be deployed on various platforms. Two cloud setups were tested here. **Amazon EC2 based cloud** 19 nodes were launched to build up a virtual cloud on the Amazon Elastic Compute Cloud (Amazon EC2). Every node had two eight-core Intel Xeon E5-2670 2.60GHz processors and 60GB RAM, running Ubuntu Server 13.10. **NIH Biowulf cluster** The Biowulf system (<http://biowulf.nih.gov>) is a GNU/Linux parallel processing system built at the National Institutes of Health, USA. A total of 38 nodes were requested from the Biowulf. The gateway node had two eight-core Intel Xeon E5-2670 2.60GHz processors and 72GB RAM. All other nodes have two six-core Intel Xeon X5660 2.80GHz processors and 24GB RAM. For both setups, the “online” reconstruction was achieved.

In-vivo test Cloud based reconstruction was performed for multi-slice free-breathing myocardial cine imaging with non-linear I1-SPiRiT reconstruction [3]. A healthy volunteer (female, 23.8yrs) was scanned on a 1.5T clinical MRI system (MAGNETOM Aera, Siemens, 32-channel surface coil). Acquisition parameters were: balanced SSFP readout, TR = 2.53/TE = 1.04ms, acquired matrix 192x100, flip angle 60°, FOV 320x240mm², slice thickness 8mm with a gap of 2mm, bandwidth 723 Hz/pixel, interleaved acquisition pattern with acceleration factor R=5. The ventricles of the heart were covered by 9 slices and for every slice the acquisition lasted 1.5s with one dummy heartbeat between slices.

Results Figure 2 shows the reconstruction results generated on the GT-Plus based cloud, illustrating noticeable improvement in image quality using non-linear reconstruction. The scan time (defined as the time to perform data acquisition) for this test was 22.6s. On the described Amazon EC2 cloud, the total imaging time (defined as the time from the start of data acquisition to the moment when images of all slices were sent back to scanner) was 52.6s. The computing time (defined as the time used to perform the reconstruction computation) was 48.9s. Note the reconstruction started once the first slice was acquired, rather than waiting for the completion of all 9 slices. On the NIH’s Biowulf cloud, imaging and computing times were 62.1s and 58.2s. If only the single gateway node was used, the computing time was 427.9s and 558.1s for two cloud setups respectively.

Conclusions The GT-Plus extension for the Gadgetron framework was developed to support cloud computing over multiple computing nodes. As a demo, the increased computational power significantly speeds up the I1-SPiRiT reconstruction for multi-slice cine imaging, enabling the 1min imaging time for whole left ventricular coverage with significant improvement in image quality. On the other hand, the framework is independent from specific use cases and can be applied to other MRI applications.

References [1] Hansen MS, et al., MRM 69:1768–1776 (2013) [2] Lustig M, et al., MRM 64:457–471

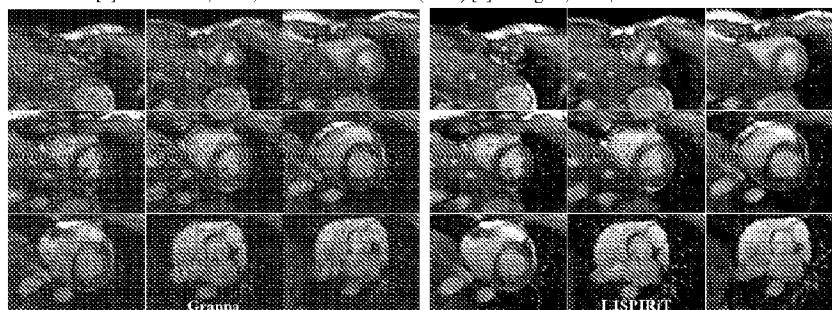


Figure 2. Reconstruction results of multi-slice myocardial cine imaging on the GT-Plus cloud. Compared to the Grappa linear reconstruction shown on the left, non-linear reconstruction on the right gives noticeable improvement in image quality. For this 9-slice cine protocol with entire ventricular coverage, the cloud version of non-linear reconstruction was completed within 30s after the end of data acquisition, while the single-node reconstruction took ~9mins. This significant reduction of computing time could be crucial for clinical usage of advanced image reconstruction techniques.

CLAIMS

What is claimed is:

1. A system for generating reconstructed images comprising:
a client computing device for generating raw image data for a subject, the raw image data comprising one or more image parameters;
at least one database comprising:
a list of modeling rules for selecting a target computational model based on image parameters included in the raw image data ; and
a network address location for each of a plurality of the reconstruction systems, each reconstruction system executing at least one different computation model to generate a reconstructed image data from the raw image data; and
at least one processor;
an application executable by the at least one processor to:
process received raw image data from the image scanner to identify a target computational model based on the list of modeling rule and the image parameters include in the received raw image data;
identify a corresponding network address location for one of the plurality of the reconstruction system executing the target computational model;
transmit the received image data to the corresponding network address location for the reconstruction system to generate reconstructed image data; and
retrieve the reconstructed image data for display.
2. The system of claim 1 wherein the client computing device is a magnetic resonance image (MRI) scanner.
3. The system of claim 1 wherein the client computing device is a computed tomography (CT) scanner.

4. The system of claim 1 wherein the client computing device is an ultrasound scanner.

5. The system of claim 1 wherein the identified network address location corresponds to Uniform Resource Locator (URL) address on the Internet.

6. The system of claim 1 wherein the reconstruction system comprises:
a reader to de-serialize the raw image data received from the client computing device;
at least a second processor to execute the target computational model in response to the raw image data and generate the reconstructed image data; and
a writer to serialize the reconstructed image data for transmission to the at least one processor.

7. The system of claim 1 wherein:
the database further comprises an computation power index associated with each of the plurality reconstruction systems, the computation power index indicating computational capabilities of each reconstruction systems;
the application executable by the at least one processor is further configured to:
determine a computation load based on image parameters included in the received raw image data;
identify the corresponding network address location for the reconstruction system based on the associated computation power index and the computational load required for reconstructing the raw image data;
transmitting the received raw image data to the corresponding network address location for the reconstruction system associated with a computation power index capable of accommodating the required computation load .

8. The system of claim 1 wherein the one or more image parameters specify a two-dimensional image type or a three-dimensional image type.

9. The system of claim 8 wherein the application executable by the at least one processor is further configured to:

transmit the received raw image data to a first corresponding network address location for a first reconstruction system to generate the reconstructed image data when the image parameters specify a two-dimensional image type; and

transmit the received raw image data to a second corresponding network address location for a first reconstruction system to generate the reconstructed image data when the image parameters specify a three-dimensional image type.

10. The system of claim 1 wherein the application executable by the at least one processor is further configured to transmit the received raw image data to the corresponding network address location over a communication network selected from one of a group consisting of a wide area network and a local area network.

11. The system of claim 1 wherein the one or more image parameters are selected from the group consisting of a spatial dimension parameter, a time parameter, a flow/velocity parameter, an experiment timing dimension parameter, a diffusion encoding parameter, a functional/physiological testing dimension parameter, and physiologic gating index parameter.

12. An apparatus for processing system raw image data for image reconstruction comprising:

at least one processor;

a memory comprising:

a list of modeling rules identifying a target computational model based on image parameters included in raw image data ; and

an network address location for each of a plurality of the reconstruction systems, each reconstruction system executing a different computation model to generate reconstructed image data from the raw image data; and

an application comprising modules executable by the at least one processor to control routing of the raw image data to a reconstruction system for processing, the application comprising:

- an input module to receive raw image data from an image scanner;
- a computation identification module to identify a target computational model based on the list of modeling rules image parameters include in the received raw image data;
- an address module to identify a corresponding network address location for the reconstruction system executing the target computational model;
- a communication module to:
 - transmit the received raw image data to the corresponding network address location for the reconstruction system to generate reconstructed image data; and
 - retrieve the reconstructed image data for display.

13. The apparatus of claim 12 wherein the input module receives the raw image data from a magnetic resonance image (MRI) scanner.

14. The apparatus of claim 12 wherein the input module receives the raw image data from a computed tomography (CT) scanner.

15. The apparatus of claim 12 wherein the input module receives the raw image data from an ultrasound scanner.

16. The apparatus of claim 12 wherein the identified network address location correspond to Uniform Resource Locator (URL) address on the Internet.

17. The apparatus of claim 12 wherein the reconstruction system comprises:
a reader to de-serialize the raw image data received from the image scanner;
at least a second processor to:
 execute the target computational model in response to the raw image data;
 and
 generate the reconstructed image data; and
a writer to serialize the reconstructed image data and transmit transmission to the
at least one processor.

18. The apparatus of claim 12 wherein:
the memory further comprises an computation power index associated with each
of the plurality reconstruction systems, the computation power index
indicating computational capabilities of each reconstruction systems
the computation identification module is further configured to:
 identify a computation load based on image parameters included in the
 received raw image data;
the address module is further configured to:
 identify the corresponding network address location for the reconstruction
 system based on the associated computation power index and the
 computational load required for reconstruction the raw image data;
 and
the communication module is further configured to:
 transmit the received image data to the corresponding network address
 location for the reconstruction system associated with a
 computation power index capable of accommodating the required
 computation load .

19. The apparatus of claim 12 wherein the one or more image parameters specify
a two-dimensional image type or a three-dimensional image type.

20. The apparatus of claim 19 wherein:

the communication module is further configured to:

transmit the received raw image data to a first corresponding network address location for a first reconstruction system to generate the reconstructed image data when the image parameters specify a two-dimensional image type; and

transmit the received raw image data to a second corresponding network address location for a first reconstruction system to generate the reconstructed image data when the image parameters specify a three-dimensional image type.

21. The apparatus of claim 12 wherein the communication module is further configured to transmit the received raw image data to the corresponding network address location over a communication network selected from one of a group consisting of a wide area network and a local area network.

22. The apparatus of claim 12 wherein the one or more image parameters are selected from the group consisting of a spatial dimension parameter, a time parameter, a flow/velocity parameter, an experiment timing dimension parameter, a diffusion encoding parameter, a functional/physiological testing dimension parameter, and a physiologic gating index parameter.