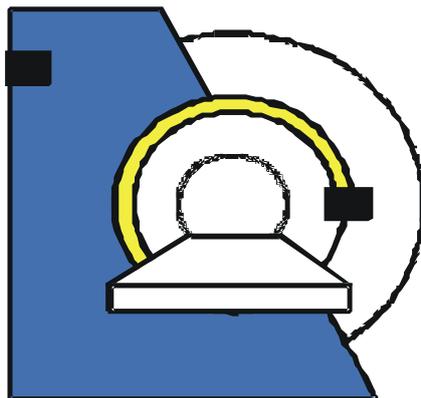


2D / 3D CINE PC-MRI Flow Sensitive 4D MRI Tissue Phase Mapping

Customer to Customer C²P Package, Version 2.1

For the
SIEMENS Magnetom Espree/Avanto/TRIO



Installation and User's Guide NUMARIS/4 VB17

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Nov 29, 2011

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1 General Remarks

1.1 Preface

This package being a substantial commitment from our side is provided free of charge for everybody to benefit. In order to encourage the continued development of the package feel free to reference the following paper(s) in your publications:

Markl M, Harloff A, Bley TA, Zaitsev M, Jung B, Weigang E, Langer M, Hennig J, Frydrychowicz A. Time-resolved 3D MR velocity mapping at 3T: Improved navigator-gated assessment of vascular anatomy and blood flow. *J Magn Reson Imaging* 2007;25:824–831.

Jung B, Stalder A, Bauer S, Markl M. On the undersampling strategies to accelerate time-resolved 3D imaging using k-t-GRAPPA. *Magn Reson Med* 2011;66:966–975.

1.2 Disclaimer

The software and the associated documentation (the “Software”) is provided “as is”, without warranty of any kind, express or implied, including but not limited to the warranties of merchantability, fitness for a particular purpose and noninfringement. In no event shall the authors or copyright holders 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.

1.3 Revision History

V 1.0	07.09.2007	Original release.
V 1.1	08.07.2008	Bug Fix Navigator Gating Added Maxwell correction Bug fix 'sum of squares' multi-coil reconstruction
V 1.2	06.05.2009	Added low SAR rf-pulse option
V 1.2.1	21.05.2010	Upgrade to VB17
V 1.2.2	18.10.2010	Added non-adaptive navigator gating for TPM
V 1.2.2	12.01.2011	Added complex averaging
V. 1.2.3	22.3.2011	Enforce 'sum of squares' as coil combine mode
V. 2.1	29.11.2011	k-t parallel imaging PEAK-GRAPPA added

2 Method Principles and Implementation

ECG synchronized time-resolved 2D or 3D MR-velocity mapping (also termed phase contrast MRI) offers the opportunity to assess 3D blood flow characteristics with true 3D and temporal coverage of a cardiovascular region of interest. Alternatively, the technique can be used for the assessment of tissue motion, e.g. left ventricular myocardial motion.

The VB 17 implementation of this method provides the possibility to acquire time-resolved 2D or 3D phase contrast MRI data. Supported features include:

- 2D or 3D CINE MRI using prospective ECG gating
- 2D or 3D CINE phase contrast MRI using prospective ECG gating
- Flexible adjustment of temporal resolution
- Parallel imaging using GRAPPA
- Parallel imaging using k-t parallel imaging PEAK-GRAPPA
- 1, 2, or 3-directional velocity encoding
- Independent adjustment of in-plane and through plane venc
- Adaptive respiratory navigator gating with real-time adjustment of the navigator acceptance window
- Black blood saturation for 2D CINE and Tissue Phase Mapping
- Optimized gradient wave forms for velocity encoding with minimal TE and TR

A more detailed description of the MR methodology and applications can be found in the following references:

MR Methods:

Jung B, Stalder A, Bauer S, Markl M. On the undersampling strategies to accelerate time-resolved 3D imaging using k-t-GRAPPA.
Magn Reson Med 2011;66:966–975.

Markl M, Harloff A, Bley TA, Zaitsev M, Jung B, Weigang E, Langer M, Hennig J, Frydrychowicz A. Time-resolved 3D MR velocity mapping at 3T: Improved navigator-gated assessment of vascular anatomy and blood flow.
J Magn Reson Imaging 2007;25:824–831.

Assessment and analysis of 3D blood flow in the thoracic aorta:

A. Frydrychowicz, A. Harloff, B. Jung, M. Zaitsev, E. Weigang, T. A. Bley, M. Langer, J. Hennig, M. Markl. Time-Resolved 3D MR Flow Analysis at 3T: Visualization of Normal and Pathological Aortic Vascular Hemodynamics.
J Comput Assist Tomo, 2007;31:9-15

Assessment and analysis of 3D blood flow in intra-cranial arteries

Wetzel S, Meckel S, Frydrychowicz A, Bonati L, Radue EW, Scheffler K, Hennig J, Markl M. In Vivo Assessment and Visualization of Intracranial Arterial Hemodynamics with Flow-Sensitized 4D MR Imaging at 3T.
AJNR Am J Neuroradiol 2007;28(3):433-438.

Assessment and analysis of 3D blood flow in peripheral vessels

Frydrychowicz A, Winterer JT, Zaitsev M, Jung B, Hennig J, Langer M, Markl M. Visualization of iliac and proximal femoral artery hemodynamics using time-resolved 3D phase contrast MRI at 3T. *J Magn Reson Imaging* 2007;25(5):1085-1092.

Assessment and analysis of 3D blood flow in the carotid arteries

Harloff A, Albrecht F, Spreer J, Stalder AF, Bock J, Frydrychowicz A, Schöllhorn J, Hetzel A, Schumacher M, Hennig J, Markl M. 3D Blood Flow Characteristics in the Carotid Artery Bifurcation by Flow Sensitive 4D MRI at 3T. *Magn Reson Med* 2009, 61:65-74.

Tissue Phase Mapping - assessment and analysis of myocardial motion

Jung B, Foll D, Bottler P, Petersen S, Hennig J, Markl M. Detailed analysis of myocardial motion in volunteers and patients using high-temporal-resolution MR tissue phase mapping. *J Magn Reson Imaging* 2006;24(5):1033-1039.

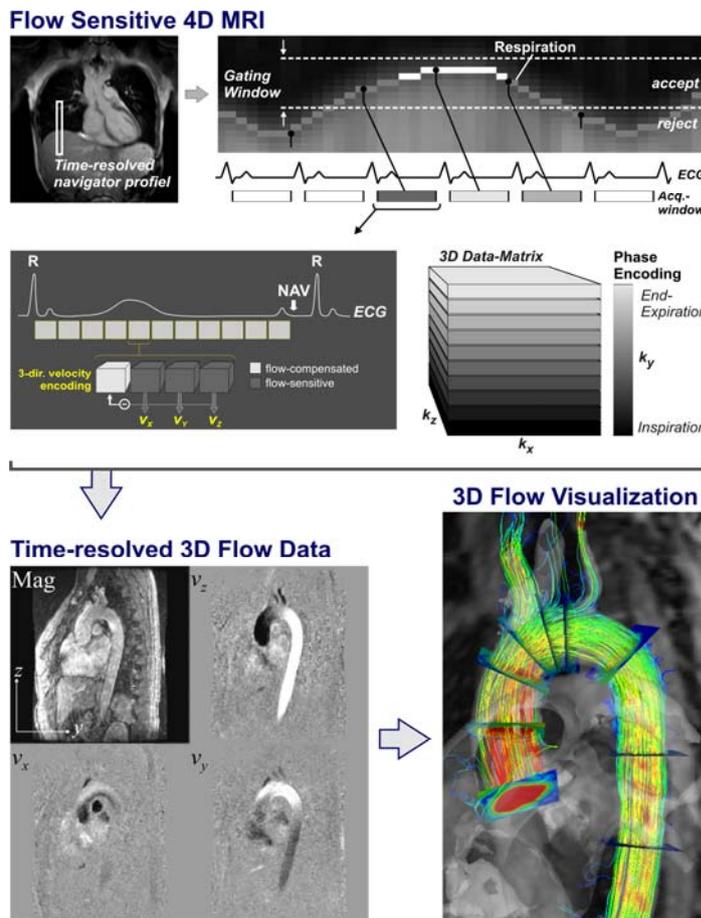


Figure 1. Flow sensitive 4D MRI in the thoracic aorta: Schematic illustration of the respiration control by adaptive navigator gating and prospective ECG gating. For each time frame a flow compensated reference data set (Ref.) as well as three separate flow sensitive 3D volumes (flow sensitization in x, y and z) were successively collected. Three-directional blood flow velocities (v_x , v_y , and v_z) are

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calculated by subtracting the flow sensitized data from the reference volumes. The late diastolic navigator signal (NAV) of the lung-liver interface is used for prospective respiration estimation. Data within the acceptance range are sorted into k-space according to their respiratory position as schematically indicated for differently gray shaded sections of 3D k-space (lower right). The resulting magnitude and velocity data provides the opportunity to evaluate 3D blood flow within the entire aorta. Note that extensive post-processing (data correction 3D visualization, flow quantification) is necessary to derive images as exemplary illustrated in figure 1 from the acquire data.

Post-processing and 3D visualization tools are **not** part of this package.

2.1 Implementation

The sequence is based on Siemens FLASH prototype sequence and on Siemens Navigator sources Version VA25.

The 2D / 3D CINE PC MRI package is implemented as a set of the following program modules:

- 2D / 3D CINE PC MRI sequence, based on rf-spoiled 3D CINE Phase Contrast gradient echo imaging
- ICE program for 2D / 3D CINE PC MRI reconstruction,

The flow-sensitive 4D MRI sequence is based on a basic product FLASH sequence and product navigator sequence building block which has been extensively modified.

The modified ICE program for flow-sensitive 4D MRI reconstruction performs phase difference calculations and magnitude averaging.

For each measurement, the ICE program produces 2 image series, which are stored in the image database on the host. One series contains all 3D CINE magnitude images while the second series contains all phase difference images.

3 Software Installation Procedure

The package consists of several 9 file types:

- 2D / 3D CINE PC MRI sequence file for the host
- 2D / 3D CINE PC MRI sequence file for the MPCU
- ICE program
- Installation script (install.bat)

An installation script, install.bat, is provided to automate the installation procedure. In case automatic installation fails, it is possible to proceed with manual installation, as described below.

3.1 Automatic Installation

Automatic installation of on the scanner includes the following steps:

Start SDE shell or command shell (CMD).

Change into the directory, where the package archive was unpacked.

Start the installation script by typing:

```
install.bat
```

Make sure that the script completed successfully without error or warning messages.

3.2 Manual Installation

Manual installation of on the scanner includes the following steps:

Start SDE shell or command shell (CMD).

Change into the directory, where the package archive was unpacked.

Copy the 2D / 3D CINE PC MRI sequence file for the host to the customer sequence directory:

```
copy bj_fs4DMRI.dll %CustomerSeq%
```

Copy the correct 2D / 3D CINE PC MRI sequence file for the MPCU to the corresponding sequence directory by execution the following command:

```
copy bj_fs4DMRI.ia86 %CustomerSeq%
```

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Copy files for the 2D / 3D CINE PC MRI ICE program to the MedHome/bin directory:

```
copy mm_IceProgramNav.dll %MedHome%\bin
copy mm_IceProgramNav.evp %MedHome%\bin
copy IceGGRAPPA.dll %MedHome%\bin
copy IceGGRAPPA.evp %MedHome%\bin
```

Copy a file for the 2D / 3D CINE PC MRI ICE program to the MRIRHOME\lib directory:

```
copy libmm_IceProgramNav.so %MRIRHOME%\lib
copy libIceGGRAPPA.so %MRIRHOME%\lib
```

Copy a file for the 2D / 3D CINE PC MRI ICE program to the CustomerIceProgs directory (don't forget to change into a different 'IceConf' directory and back).

```
cd IceConf
copy mm_IceProgramNav.evp %MRIRHOME%\lib
copy IceProgramGGRAPPA.evp %MRIRHOME%\lib
cd ..
```

Copy the external rf-file file to the customer sequence directory:

```
copy blackblood.dat %MEASDAT%
```

3.3 Create Protocol

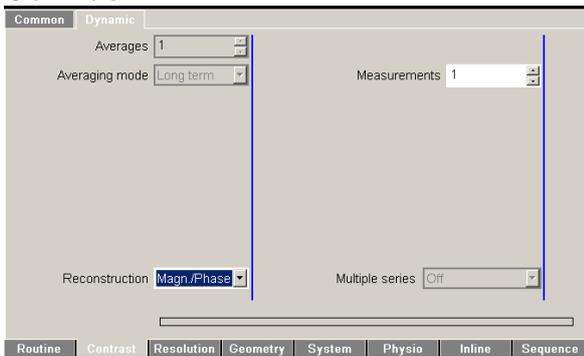
Create the new default protocols:

Open the Exam Explorer, select a protocol location, select 'Insert ... Sequence', select 'Folder: USER', select 'bj_fs4DMRI', click 'Insert'. Double click the new protocol and adjust the parameters as desired.

4 Sequence and Protocols

Features regarding the protocol card:

Contrast

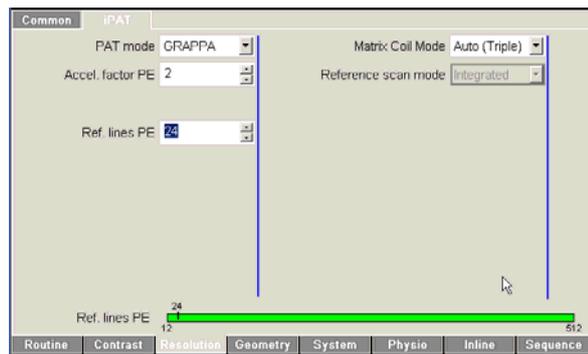
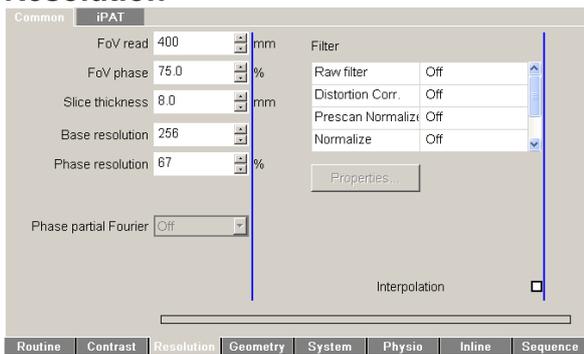


Reconstruction: Magn./ Phase is set automatically if velocity encoding is selected

Averages is not supported

Measurements: is not supported

Resolution



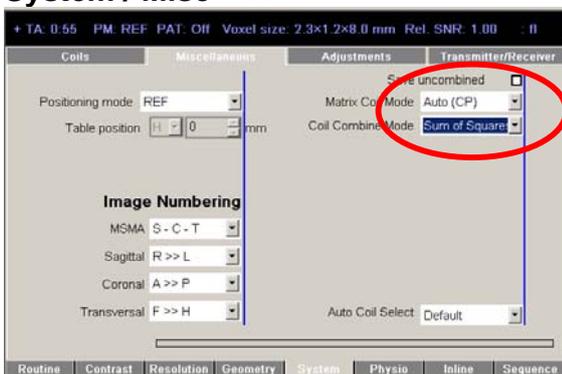
Phase resolution: flexible, but is adjusted to the number of heartbeats to acquire, (phase matrix divided by the segments has to be an integer)

Slice resolution (appears for 3D scans): not flexible, must be always 100%.

iPAT mode GRAPPA: Parallel imaging using GRAPPA along the PE direction.

iPAT mode mSENSE: is not supported

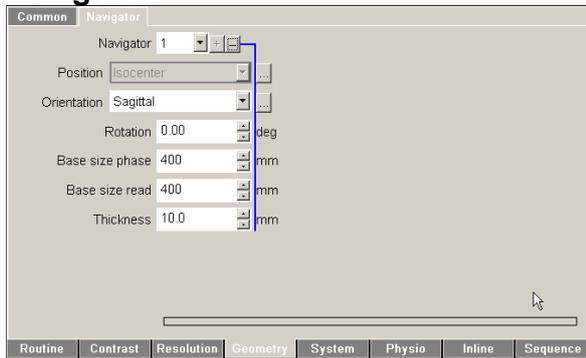
System / Misc



Important: 'Coil Combine Mode' should be automatically switched to **Sum of Squares**

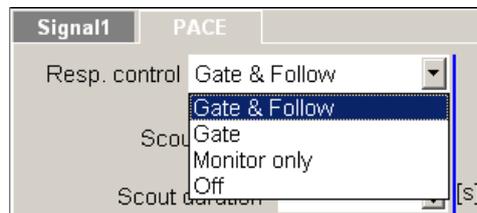
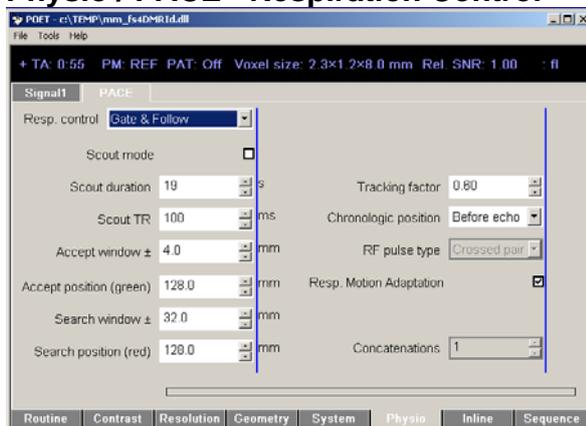
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Navigator



Standard Crossed pair navigators are used to track the position of the lung liver interface

Physio / PACE - Respiration Control



Respiration Control:

Gate & Follow: Motion-adapted gating technique based on k-space weighting. The navigator is played out at the end of the cardiac cycle, and dependent on the current breathing position, corresponding k-space lines are acquired during the next cardiac cycle. The position of the gating window (for *Gate* and *Gate & Follow*) is shifted automatically according to the maximum (i.e. the expiration position) of the last 20 navigator echoes and is updated online during the measurement. This avoids a significant prolongation of measurements due to a change in the breathing pattern during a scan.

Gate: The navigator is played out at the end of the cardiac cycle. No adaptation to the current respiration position. Standard k-space segmentation. Useful for 2D PC or 2D TPM to avoid steady state effects

Resp. Motion Adaptation: should be switched on

Monitor only: not supported

Off: switch off navigator-tracking, for breath-held or non-thoracic applications

Scout mode: acquisition of breathing pattern for determination of navigator reference position.

Known bug: scout mode may not run due to SAR limitations.

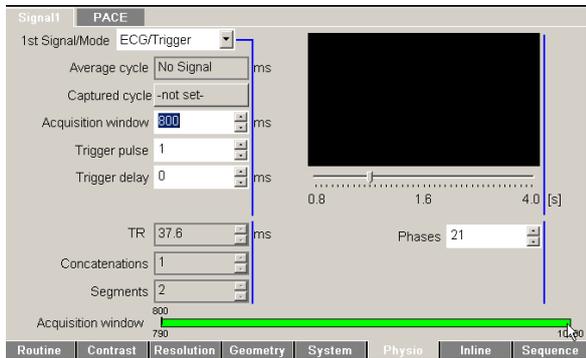
Solution: Increase 'Scout TR' to 150-200ms

or

use Navigator scout of any product sequence and copy parameters

Tracking factor / Chronologic position: not supported.

Physio / Signal 1 - ECG gating



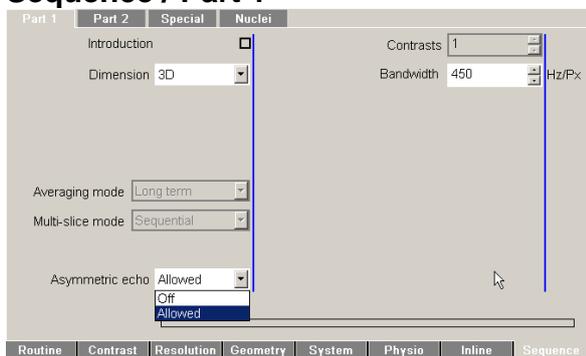
TR: temporal resolution (same as Sequence / Special / Temporal resolution)

Segments: number of k-space lines per cardiac phase and cardiac cycle.

For interleaved *n-D Velocity Encoding*:
 $TR = Segments * (n+1) * Echo\ spacing$

Phases: should cover approximately 80-90% of the RR-interval. For TPM high temporal resolution measurements with 60 possible phases set only to 50 (i.e. ~100-150 ms less than the average cycle for TPM measurements and ~50 ms for flow measurements). The reason is that the additional time for the black blood pulses is needed (which are played out about every 100 ms) as well as for the navigators and their evaluation time is not considered for the calculation of the number of possible phases.

Sequence / Part 1

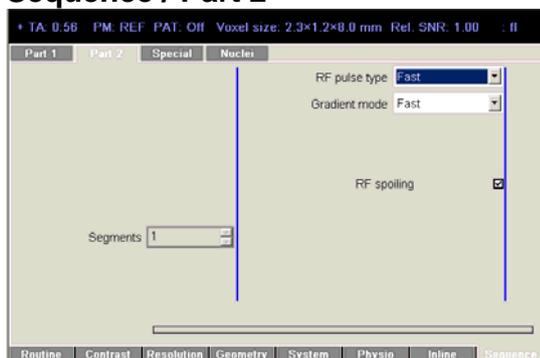


2D – 3D: 2D CINE PC and 3D CINE both implemented

Bandwidth: flexible

Asymmetric echo: can be switched on / off, it is recommended to use the asymmetric echo for optimized TE / TR and thus temporal resolution

Sequence / Part 2

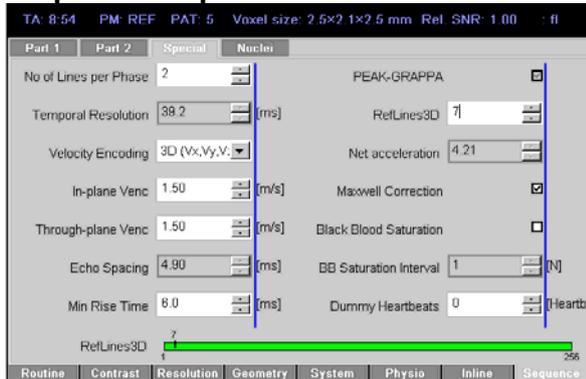


Gradient Mode: fast, normal and whisper selectable

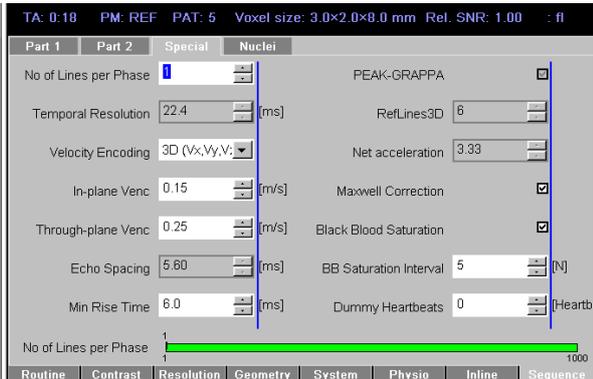
RF pulse type: fast & low SAR selectable

Rf-spoiling: should be switched on

Sequence / Special



Example of the sequence special card for flow sensitive 4D MRI protocol



Example of the sequence special card for a 2D high temporal resolution TPM protocol

Number of Lines per Phase: Number of k-space lines that are acquired per phase, i.e. cardiac time-frame.

Temporal resolution: not editable, corresponds to TR and is determined by the number of k-space lines per phase and the velocity encoding. Number of k-space lines that are acquired per phase, i.e. cardiac time-frame.

For *n*-D Velocity Encoding: $TR = Segments * (n+1) * Echo\ spacing$

Velocity Encoding: The sequence can be operated in GE mode (no velocity encoding, simple 2D or 3D CINE MRI) or using through-plane (1D, Vz), in-Plane (2D, Vx,Vy) or full three-directional velocity encoding (3D Vx,Vy,Vz). Note that changing the settings in 'Velocity Encoding' will considerably affect the temporal resolution and total scan time.



In-plane Venc and Through-plane Venc: can be adjusted independently

Echo spacing: not editable, true underlying TR of the pulse sequence

Min Rise Time: Adjust the minimum gradient rise time used for the calculation of the gradient waveforms. Increasing the min rise time may help to overcome peripheral nerve stimulation problems.

PEAK-GRAPPA: Allows higher reduction factors compared to conventional GRAPPA for time-resolved imaging. It can be used for 2D and 3D imaging. Possible reduction factors are 2, 3, 4, 5, 8, and 10. For TPM scans R=5 with 10 reference lines are recommended, for 4D flow scans R=5 with 20 reference lines in ky and about 8-10 (depending on the slice matrix) reference lines in kz – the net acceleration factor should not exceed a value of about 4.2. If protocol wanted to be switched back to conventional GRAPPA, the reduction factor should be set to R<=4 with 24 reference lines, otherwise the PEAK-GRAPPA toggle remains not editable (see screen shot examples for sequence/special card).

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RefLines3D: The number of reference lines in kz-direction for 3D measurements using PEAK-GRAPPA. About 15-20% of the slice number is recommended.

Net acceleration: not editable, displays the nominal acceleration factor for PEAK-GRAPPA considering the reference lines in ky and kz direction.

Maxwell Correction: Switch on / off Maxwell correction to reduce background errors.

Black Blood Saturation: only needed for TPM measurements.

BB Saturation interval: for TPM measurements, determines how often the black blood pulse is played out during one RR-interval. N determines the number of phases between 2 successive black blood pulses. A *BB interval* = $N * TR$ of about 100 ms are recommended.

Dummy Heartbeats: Additional heartbeats to reach the gradient echo steady state without data acquisition.

Remarks for PEAK-GRAPPA:

Note that reconstruction times for PEAK-GRAPPA are inherently longer compared to conventional GRAPPA. Using a 12-channel coil the reconstruction time for a TPM scan takes about 20 seconds, for a 4D flow scan about 4-8 minutes. With a 32-channel coil the time increases dramatically, i.e. reconstruction times can take up to 1 hour for a 4D flow scan depending on the matrix size and the number of time frames.

Starting any other measurement (even navigator gated measurement such as the 4D flow scan) while still reconstructing a data set works; however, any other image reconstruction is blocked due to the current PEAK-GRAPPA reconstruction.

It is possible to stop the reconstruction process and perform it later – this can be useful if the PEAK-GRAPPA 4D flow scan is not the last scan within an entire exam. Do the following steps to stop the reconstruction after the scan has been finished:

1. Go to “System - Control” to start the System Manager
2. Choose the card “Image Reconstruction System”
3. Hit the button “Restart Image Calculation”

Do the following steps to retrospectively reconstruct the rawdata:

1. Hit the Windows Start button and chose “Run”
2. Enter “twix”
3. Select the not-reconstructed data set in the left side of the new window
4. Press the reconstruction button
5. Start reconstruction via the Start button in the lower part of the Twix window.

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To check if the reconstruction is still running, do the following steps:

1. Hit the Windows Start button and chose "Run"
2. Enter "logviewer"
3. If the message "Peak Grappa Recon is finished" appears the image reconstruction has finished in a few seconds, otherwise the recon is still running.

The screenshot shows the LogViewer application window titled "LogViewer - [MrParcTraceSrv.log]". The window displays a log of MRI scan events. The columns are MeasID, Date/Time, ProcName, and a detailed description of the event. The event at 15:19:24.033 is highlighted with a red box and contains the message "PEAK Grappa Recon is finished".

MeasID	Date/Time	ProcName	Description
12098	2011-11-30 15:05:29.489	MrIrisContainer	sourceN 768 targetN 256
12099	2011-11-30 15:06:32.209	MrIrisContainer	sourceN 768 targetN 256
12100	2011-11-30 15:07:37.145	MrIrisContainer	sourceN 768 targetN 256
12101	2011-11-30 15:08:41.723	MrIrisContainer	sourceN 768 targetN 256
12102	2011-11-30 15:09:44.164	MrIrisContainer	sourceN 768 targetN 256
12103	2011-11-30 15:10:16.451	MrIrisContainer	sourceN 768 targetN 256
12104	2011-11-30 15:10:48.976	MrIrisContainer	sourceN 768 targetN 256
12105	2011-11-30 15:11:20.252	MrIrisContainer	sourceN 768 targetN 256
12106	2011-11-30 15:12:24.598	MrIrisContainer	sourceN 768 targetN 256
12107	2011-11-30 15:12:55.875	MrIrisContainer	sourceN 768 targetN 256
12108	2011-11-30 15:13:28.404	MrIrisContainer	sourceN 768 targetN 256
12109	2011-11-30 15:14:00.659	MrIrisContainer	sourceN 768 targetN 256
12110	2011-11-30 15:15:03.977	MrIrisContainer	sourceN 768 targetN 256
12111	2011-11-30 15:16:08.269	MrIrisContainer	sourceN 768 targetN 256
12112	2011-11-30 15:17:13.114	MrIrisContainer	sourceN 768 targetN 256
12113	2011-11-30 15:18:15.680	MrIrisContainer	sourceN 288 targetN 192
12114	2011-11-30 15:18:21.708	MrIrisContainer	sourceN 288 targetN 192
12115	2011-11-30 15:18:27.747	MrIrisContainer	sourceN 384 targetN 320
12116	2011-11-30 15:18:38.860	MrIrisContainer	sourceN 384 targetN 320
12117	2011-11-30 15:18:49.974	MrIrisContainer	sourceN 288 targetN 192
12118	2011-11-30 15:18:55.965	MrIrisContainer	sourceN 288 targetN 192
12119	2011-11-30 15:19:01.957	MrIrisContainer	sourceN 384 targetN 320
12120	2011-11-30 15:19:12.994	MrIrisContainer	sourceN 384 targetN 320
12121	2011-11-30 15:19:24.033	MrIrisContainer	PEAK Grappa Recon is finished
12122	2011-11-30 15:19:24.270	MrIrisContainer	mode = 2 outputLimit = -1 srcAs = - AccSpecDia: 15 First var dia: 9 First iterator c
12123	2011-11-30 15:19:43.261	MrIrisContainer	gGrappaImageReconFuncior::FirstCall End
12124	2011-11-30 15:19:43.264	MrIrisContainer	getTReff() failed, continue using TR from protocol ...->>>.-ImageControl - Boundaries:
12125	2011-11-30 15:19:51.671	CoCos	Send event string 'MEAS IR SERIESUPDATE 92 Local 6.0.58520419' to 'NCAP_MRC20506\Measureme
12126	2011-11-30 15:19:51.671	CoCos	Send event string 'MEAS IR SERIESUPDATE 92 Local 6.0.58516372' to 'NCAP_MRC20506\Measureme
12127	2011-11-30 15:20:02.687	CoCos	Send event string 'MEAS IR SERIESUPDATE 92 Local 6.0.58520419' to 'NCAP_MRC20506\Measureme
12128	2011-11-30 15:20:02.687	CoCos	Send event string 'MEAS IR SERIESUPDATE 92 Local 6.0.58516372' to 'NCAP_MRC20506\Measureme
12129	2011-11-30 15:20:11.515	CoCos	Send event string 'MEAS IR SERIESUPDATE 92 Local 6.0.58520419' to 'NCAP_MRC20506\Measureme
12130	2011-11-30 15:20:11.515	CoCos	Send event string 'MEAS IR SERIESUPDATE 92 Local 6.0.58516372' to 'NCAP_MRC20506\Measureme
12131	2011-11-30 15:20:21.703	CoCos	Send event string 'MEAS IR SERIESUPDATE 92 Local 6.0.58520419' to 'NCAP_MRC20506\Measureme
12132	2011-11-30 15:20:21.703	CoCos	Send event string 'MEAS IR SERIESUPDATE 92 Local 6.0.58516372' to 'NCAP_MRC20506\Measureme
12133	2011-11-30 15:20:31.671	CoCos	Send event string 'MEAS IR SERIESUPDATE 92 Local 6.0.58520419' to 'NCAP_MRC20506\Measureme
12134	2011-11-30 15:20:31.687	CoCos	Send event string 'MEAS IR SERIESUPDATE 92 Local 6.0.58516372' to 'NCAP_MRC20506\Measureme
12135	2011-11-30 15:20:41.718	CoCos	Send event string 'MEAS IR SERIESUPDATE 92 Local 6.0.58520419' to 'NCAP_MRC20506\Measureme
12136	2011-11-30 15:20:41.718	CoCos	Send event string 'MEAS IR SERIESUPDATE 92 Local 6.0.58516372' to 'NCAP_MRC20506\Measureme
12137	2011-11-30 15:20:51.890	CoCos	Send event string 'MEAS IR SERIESUPDATE 92 Local 6.0.58520419' to 'NCAP_MRC20506\Measureme
12138	2011-11-30 15:20:51.890	CoCos	Send event string 'MEAS IR SERIESUPDATE 92 Local 6.0.58516372' to 'NCAP_MRC20506\Measureme
12139	2011-11-30 15:20:58.312	Spice	Received AcqEnd message.
12140	2011-11-30 15:20:58.312	CoCos	IRIS Pipe: MeasUID: 92. State: Ready

"logviewer" window