SIEMENS

Applications Guide

Pre-saturation based B1 mapping

(Works-in-Progress)

MAGNETOM 7T, TX array Step 2.2

syngo MR B17A

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Version 2.1

WIP 543B

Pre-saturation based B1 mapping

Important Note

This document provides a description of techniques developed by Siemens. Siemens has tested the software provided with this works-in-progress package in combination with the proposed clinical application. However, each user should be aware of the fact that incorrect use of this software may produce unknown results.

The sequences contained in this software package do not exceed the FDA safety performance parameter guidelines for MRI exams. Specifically, there is no change to patient risk as compared to routine operation of the MAGNETOM with regard to: static magnetic field; the time rate of change of the gradient magnetic fields; the rate at which RF power is deposited into the body (SAR); or the acoustic noise created by the MAGNETOM. However, when using this package on a Tim TX array system, the user is responsible for appropriate SAR supervision.

The software has been tested internally but not yet in a clinical environment. For routine applications, its functionality may not be complete, and use of this software will remain investigational.

In general, the clinical user will, in its sole responsibility, decide on the use of this application package or on subsequent therapeutic or diagnostic techniques and shall apply such techniques in its sole responsibility.

Siemens will not take responsibility for the correct application of, or consequences arising from use of, this applications package.

The software in this package may change in the future, or may not be available in future software versions. Siemens has the right to remove this software at any point. In case of any questions that are related to the use of this package please contact one of the WIP authors listed on the next page.

Authors

Dr. Hans-Peter Fautz
Siemens AG, Healthcare Sector
H IM MR TR PRM
91052 Erlangen, Germany
Hans-Peter.Fautz@siemens.com

Dr. Rene Gumbrecht
H IM MR TR
91052 Erlangen, Germany
rene.gumbrecht@siemens.com

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1. Introduction

This package acquires B1 maps using a Turbo FLASH sequence preceeded by a magnetization preparation pulse. It is based on the product Turbo FLASH (TFL) sequence a_tfl.

In multiple runs of the sequence images can be acquired with and without pre-saturation. The application of a pre-saturation pulse reduces the longitudinal magnetization available for the succeeding imaging sequence according to the local flip angle of the preparation pulse (3): The ratio of the signal intensities of two images with and without pre-saturation gives the cosine of the preparation pulse. Images acquired without pre-saturation are referred to as reference images in this application guide.

The B1 mapping method is particularly developed for the use on a TX array system. However, it might also be used on a single transmit channel system. It acquires and calculates

1. Flip angle distribution maps of different transmit coils/ coil elements. Therefore, the saturation pulse can be applied on different transmit coil elements individually in different runs of a single measurement. For the excitation pulses of the imaging part – i.e. of the TFL sequence all transmit channels can be used. This imaging part is repeated with the same coil setup but without pre-saturation to acquire the reference image. Typically the reference image is acquired only once along with *n* saturation images, each acquired using a single transmit coil for saturation. The reference image is identical for mapping the flip angle distributions of all transmit fields. The flip angle distribution maps do not contain information about the phase relation amongst the different transmit fields.
2. Relative B1 maps: A series of TFL images are acquired using a single transmit coil at a time. These relative B1 maps also contain the phase distribution of the transmit fields relative to each other.

Both acquisitions 1 and 2 can be realized in a single scan or in separate measurements.

2. Sequence

The product TFL sequence a_tfl is a single shot FLASH implementation with minimum TE and TR. The basic sequence timing is shown in Fig. 1. The sequence splits into 2 parts: A pre-saturation part and a TFL imaging part.

The RF transmission for both parts can flexibly be configured via external configuration files. I.e. an RF shim setting can be defined to be used for the excitation pulses. An array of RF shim settings can be defined to be applied to the pre-saturation pulses in different repetitions. E.g. for each repetition the RF is transmitted on a different individual channel for the pre-saturation pulse, while all channels are used with a specific RF shim setting for the excitation pulses during the imaging module.

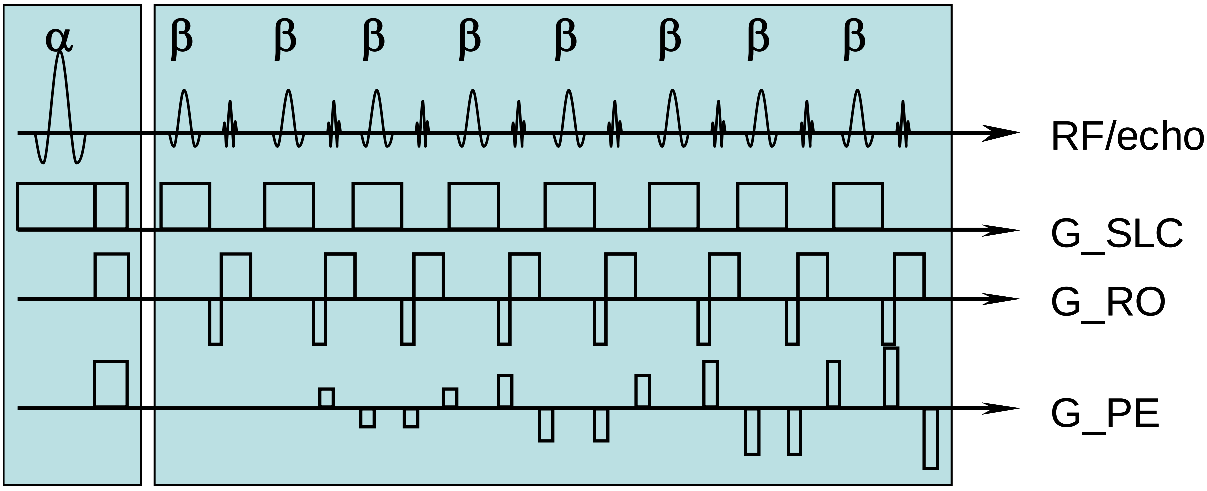

Fig. 1: Basic sequence scheme for centric reordered TFL with pre-saturation

2.1. TFL Imaging

After pre-saturation with flip angle α the longitudinal magnetization evolves over time TI according to T1 relaxation:

$$M_z(TI) = M_0((\cos(\alpha)-1)\exp(-\frac{TI}{T1})+1).$$

Typically the relaxation between pre-saturation and excitation is neglected. This results in a longitudinal magnetization of cos(α) which is available for a succeeding excitation. To rectify this assumption slight modifications have been made to the TFL imaging sequence.

Centric reordering

Neglecting T1 relaxation does certainly not hold for the entire TFL excitation train. Therefore, a centric reordering is used, encoding the centre of k-space first after preparation. Towards the outer k-space parts T1 relaxation leads more and more to false estimation of the flip angle. The B1 map post processing will typically apply a filter along the phase encoding direction, assuming a slowly varying B1 field distribution.

Mulit shot (EPI-factor)

To reduce the degradation of the point spread function (see above) a “multi shot” segmented TFL variant is offered. K-space is acquired in *n* shots in an interleaved manner like in a TSE sequence. I.e. each TFL echo train covers the full k-space but only records each n-th line. The EPI-factor on the “Sequence-Part 2- Card” gives the number *n* of TR- repetitions to acquire the full k-space.

Note: with an even number of shots each shot covers only half the k-space: all odd numbered shots cover the lower half of the k-space, all even numbered shots cover the upper part of the k-space. The phase encoding steps within a single shot are therefore linearly reordered from k-space centre outwards.

Interleaved multi slice

Multi shot acquisitions allow acquisition of the different shots on different slices in an interleaved way. Therefore, the option for interleaved multi slice acquisition was implemented.

VERSE

VERSE RF-pulses have been implemented for excitation and slice selective (sinc) preparation pulses. To use this, choose RF pulse type = Low SAR on the protocol card: Sequence/part 2. Typically the VERSE option is to be used when the maximum peak power limits the maximum allowed flip angle given a certain slice thickness of the slice selective preparation pulse.

2.2. Pre-Saturation

The pre-saturation RF pulse and surrounding spoiler gradients pulses are implemented as a sequence building block (SBB) in the class “SBBMagPrep”. Different types of RF-pulses can be chosen and parameters regarding the slice definition of the pre-saturation pulse can be set. All parameters controlling the preparation SBB are found on the “sequence – special – card” on the left hand side. For some more details see the section Protocol parameters.

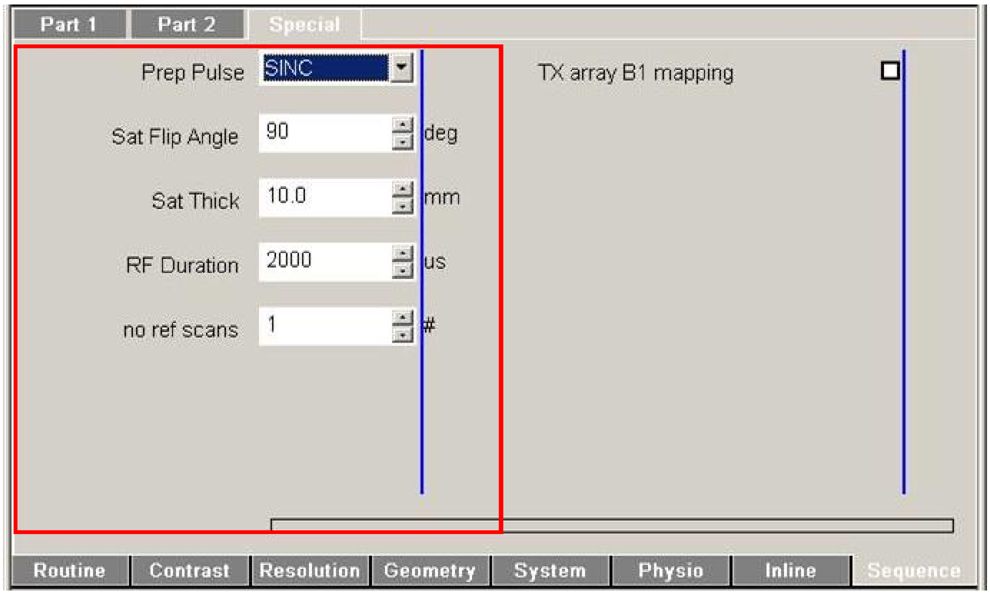

Fig. 1: user parameters on the special card defining the pre-saturation SBB

Different RF pulse types can be chosen to be used for pre-saturation. If “pre pulse” is chosen to be *OFF,* no pre-saturation is executed. The sequence acquires conventional TFL images.

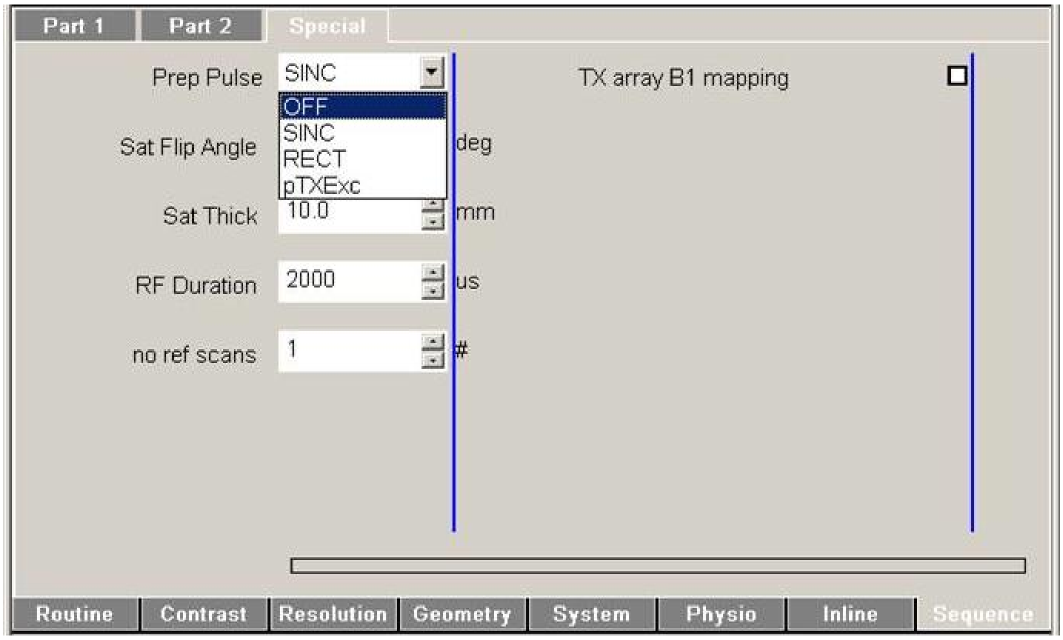

Fig. 2: selection for the pre-saturation RF pulse

Slice selective pre-saturation: SINC

The pre pulse type *SINC* is implemented as slice selective RF pulse. In order not to falsify the calculated flip angle by signal from the slope of the slice profile, the flip angle of the pre-saturatin pulse needs to be constant over the slice which is selected by the excitation pulses of the imaging sequence. This is realized by choosing a saturation slice, which is thicker than the imaging slice. The thickness of the saturation slice can be set via the parameter "*Sat Thick*" independently of the (imaging) slice thickness. A slice broadening of a factor of 2 is recommended.

In the presence of off-resonance frequencies e.g. due to chemical shift between water and fat, the excited slice is spatially shifted for different frequencies. The spatial shift is determined by the amplitude of the slice selection gradient. In order to saturate (spatially) the same slice as being excited for imaging for all frequencies, the slice selection gradient amplitudes for the pre-saturation pulse and the excitation pulses of the TFL sequence are identical. This provides consistency for the calculated flip angles of different chemical shift species.

However, with the gradient amplitude being fixed, the above mentioned slice broadening of the pre-saturation must be achieved via an increased bandwidth of the RF-pulse. Therefore the thickness of the saturation slice is typically limited by the peak transmit power of the pre-saturation pulse. Please check in the "System/ Transmitter/Receiver" card the transmit voltage of the preparation pulse. It might be limited by the maximum allowed voltage.

If the peak power is too limited you might choose VERSEd SINC pulses. Therefore go to exam card: "Sequence/Part 2" and choose RF pulse type = Low SAR.

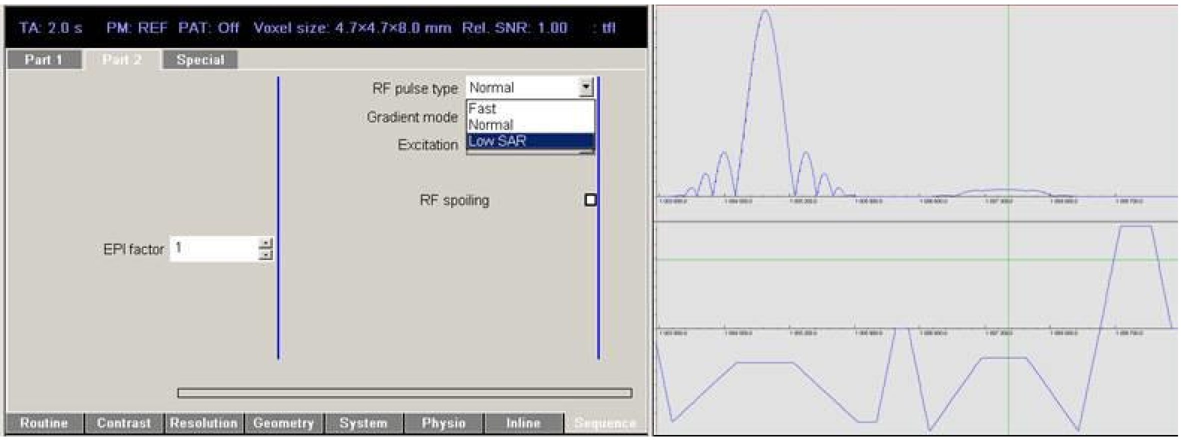

Fig. 3: selecting VERSE for slice selective preparation and excitation pulses (left) and resulting RF- and slice gradient wave form for the preparation and the first excitation pulse (right)

Non- slice selective pre-saturation: RECT

For non-selective pre-saturation a rectangular RF pulse is implemented. No parameters regarding slice definition are required. Rectangular pulses are typically less limited in the achieved flip angle within a limited duration and have shown less sensitivity to TOF-artefacts. However, be aware that the measured flip angle is not only defined by B1 but also by off-resonance. The bandwidths of non-selective RF pulses need to be large enough to saturate fat and water (or any off-resonance frequency in the slice of interest) equally.

Pre-saturation using arbitrary RF and gradient pulses: pTXExc

Externally designed RF- and gradient pulses can be loaded as saturation pulse to directly measure the magnetization generated by this pulse. The pulse format is described in the UHF wiki (http://www.mr-idea.com). The pulse files need to be stored in c:\MedCom\MriCustomer\seq\RFPulses\pTXArbitrary.ini (or pTXComposite.ini)

RF Duration

The RF duration defines the length of the pre-saturation RF pulse. It determines mainly the inversion time between preparation and excitation, which is neglected in the reconstruction.

Please note, that the slice selection gradient amplitude for the preparation pulse is locked to the amplitude of the excitation pulses. Given a desired slice thickness of the preparation slice this also locks the RF bandwidth. In other words, changing the RF pulse duration hardly changes neither the peak power nor the total power of the pulse. The duration of the RF pulse rather determines the slice profile of the saturation pulse.

Number of reference scans: no ref scans

The number of reference scans can be defined. Only the last reference scan is used for the B1 map calculation. Reference scans acquire Turbo Flash images using a certain transmit coil combination (RF shim) for excitation. They apply a pre-saturation SBB with zero flip angle. I.e. all gradients of the SBB are executed but the RF amplitude is set to 0. The reference scan required for B1 mapping is the same for all channels and needs to be acquired only once. However, to prepare a "steady state" using a TR that doesn't allow full relaxation between scans an additional scan might be useful.

2.3. TX array B1 mapping

Selecting "TX array B1 mapping" on the Sequence/special exam card (Fig. 4) opens the possibility to

1. acquire a number of TFL images on individual channels used for **relative B1** mapping and for calculation of the transmit **phase** maps relative to each other.

2. acquire a number of pre-saturated images using different shim settings for the preparation pulse (including using individual TX coil elements for presaturation). These scans are used to calculate the flip angle (or correspondingly the B1 amplitude) of the pre-saturatin RF pulses. Assuming a linear dependence between flip angle and B1, the **amplitude** of the B1 maps are calculated from the flip angle maps.

RF settings in "single channel mode"

As any other sequence, the B1 mapping sequence can be run on a TX array in a single channel mode. In other words, the sequence runs on all channels (MPCUs) identically applying the amplitude and phases to the TX RF channels defined in the TX array user interface. These RF shim settings apply to both the preparation pulse as well as to the excitation pulses during the TFL read out. This mode is enabled, when the selection box "TX array B1 mapping" on the Sequence/ special – card is de-selected. In this mode, neither phase maps nor relative B1 maps can be acquired (*# phase + rel B1 maps = 0*)

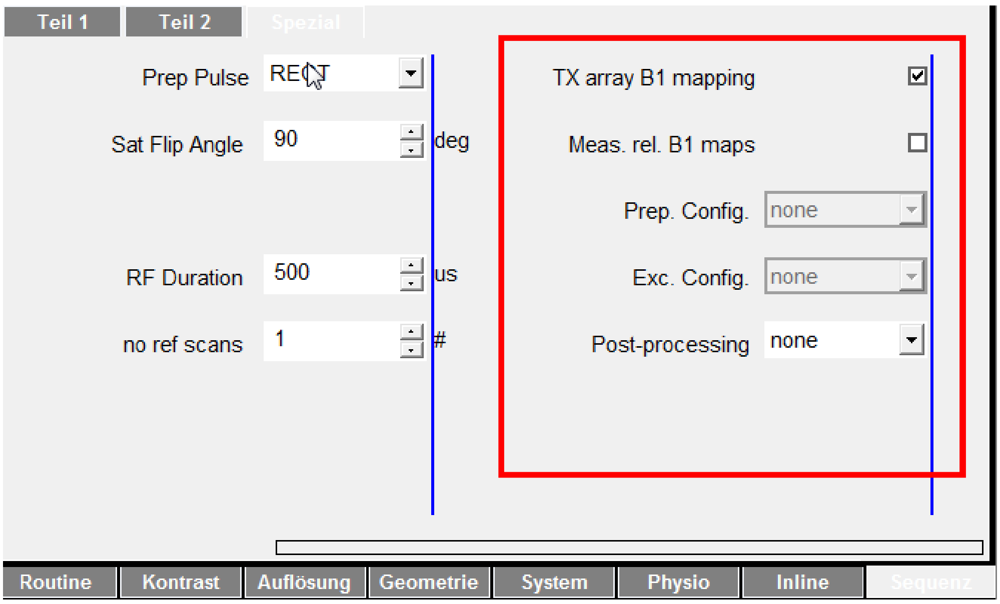

Fig. 4: user parameters on the special card defining the TX array B1 mapping

Settings in multi channel mode

When selecting “TX array B1 mapping” on the Sequence/ special – card, several additional options are available:

a) *Meas rel. B1/ phase maps*: By default, the relative B1 maps (TFL images w/o pre-saturation) are acquired on individual channels without any phase offsets. I.e. in the first scan only the first channel (master channel) is transmitting RF, in the second scan only the second channel (slave channel 1) is transmitting RF etc.

b) *Prep. Config:* By default, the excitation pulses applied for the reference scan and during the TFL read out are played out on all TX channels using the RF shim setting in the TX array user interface. The pre-saturation pulses are sequentially applied to different individual channels in different scans. I.e. in the first scan (after the reference scan) the pre-saturation RF pulse is applied only to the first channel (master channel), in the second scan the pre-saturation RF pulse is applied only the second channel (slave channel 1) etc.

   If a prep Config file is selected (any valid .ini file in seq/RFPulses can be used), all RF shim sets defined in the .ini file are used as pre-saturation pulse. For example for “matrix” postprocessing, the file should define as many RF shim sets as there are transmit channels. The sequence will then measure B1 amplitude maps of all these shim sets.

c) Exc. Config: A .ini file can be specified that contains a single RF shim set that is used for the excitation pulses of the turbo-flash readout. If no file is selected, the current system shim (see TX Array UI) is used.

d) *B1 map post-processing*: By default, no post-processing is performed (for details, see section 2.4)

Tx array B1 mapping loop structure

The loop structure controlled by the parameters on the Sequence/ special – card is depicted in Fig. 5.

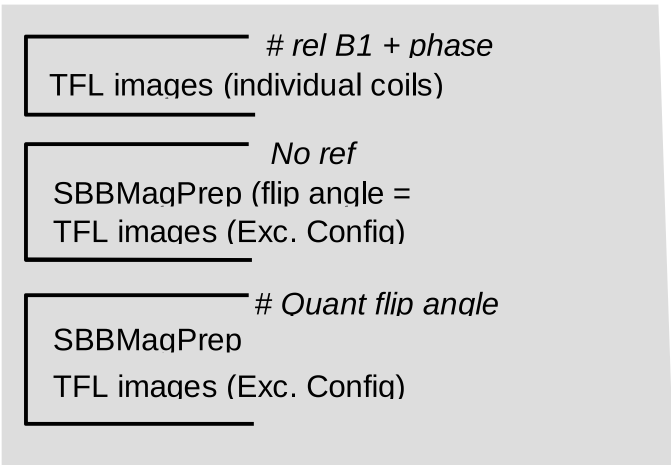

Figure 5: Inner structure of the TX array loop (free loop).

Selecting # Quant fip angle maps = 2 and # phase + rel B1 maps = 2 on the protocol card shown in Fig. 4 will run a sequence on channel 1 (master channel) as plotted by the POET simulation tool in Fig. 6.

Additional parameters were: slices = 1; EPI-factor=1. For demonstration purposes the repetition time was chosen very short TR = 300ms. The pre-saturation parts can be identified by the (negative) peak gradient amplitudes of the spoilers prior to a TFL train and the peak RF amplitudes. For the reference scan the RF amplitude is zero, but the gradient spoiler is applied. Note that only one out of the 2 channels is shown. In those scans in which RF is switched off on this channel, RF is transmitted on the second channel.

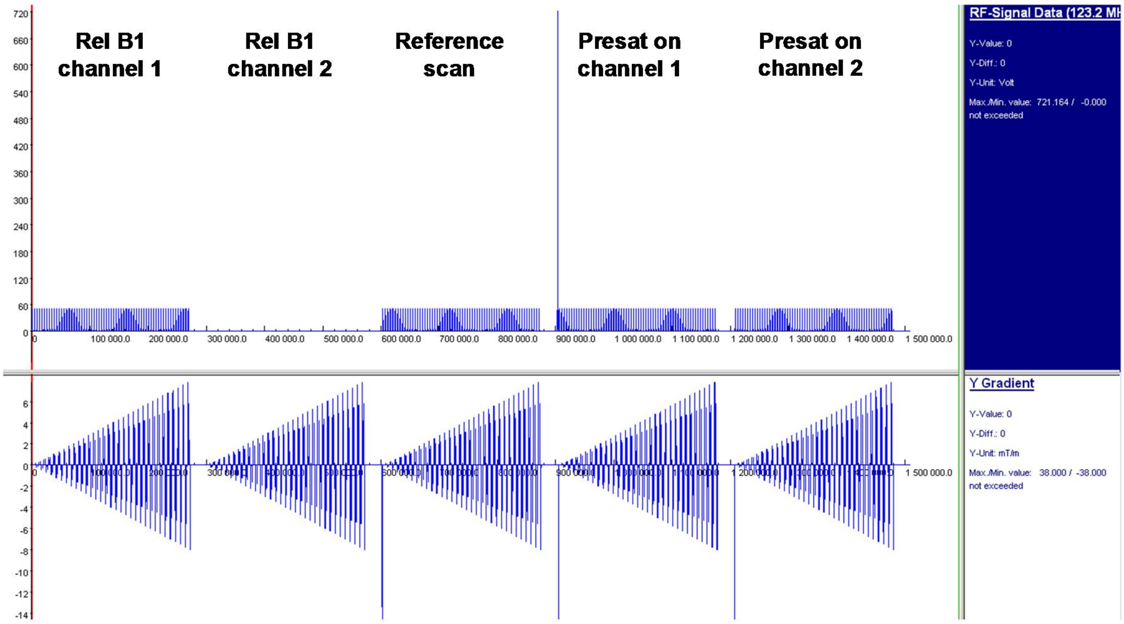

Fig. 6: POET simulation result (RF and PE) for channel 1 of a protocol acquiring 2 relative B1 maps and 2 quantitative B1 maps.

2.4. B1 mapping calculation

The ICE program “IceProgramPrepB1Map “detects which of the following maps can be reconstructed from the acquired data.

Relative B1-amplitude maps

Relative B1 maps are calculated from low tip angle gradient echo images acquired while transmitting on individual channels (“# phase + rel B1 maps”). The **magnitude** of the relative B1 maps are calculated using the following equations:

$$\left|\mathrm{relB1}_j(x)\right| = 4095 \cdot \frac{\left|S_j(x)\right|}{\sqrt{\sum_n \left|S_n(x)\right|^2}} = 4095 \cdot \frac{\left|\sin(\alpha_j(x))\right|}{\sqrt{\sum_n \left|\sin(\alpha_n(x))\right|^2}}$$

with

$$\left|S_j\right| = \sin(\alpha_j(x)) \cdot \rho(x) \cdot \sqrt{\sum_i \left|R_i(x)\right|^2}$$

S is the signal intensity measured when transmitting on individual channels. Signals from different receive channels are combined calculating the square root of the sum of square over all receive channels. The tissue related spatial signal weighting is given by $\rho(x)$. If the measured signal intensity is proportional to the sine of the achieved flip angle (no steady state effects), the relative B1 maps give the flip angle distribution for each transmit coil weighted by the sum of transmit sensitivities over all transmit coils. The magnitudes are scaled to fit values between 0 and 4095. In order to avoid the signal range to be determined by noise due to a vanishing denominator, a thresh hold can be defined by the parameter noise suppression on the special card. The thresh hold is defined as part per mill relative to the maximum of the signal intensity. If the signal intensity of the denominator drops below the thresh hold, the calculated ratio is reduced by a factor of 1000.

Relative B1-phase maps

The **phases** of the B1 filed maps are also calculated from the low tip angle gradient echo images acquired while transmitting on individual channels ("# phase + rel B1 maps"). For a given voxel the transmit phases for the different channels can only be determined relative to each other. Here they are calculated relative to a virtual reference image.

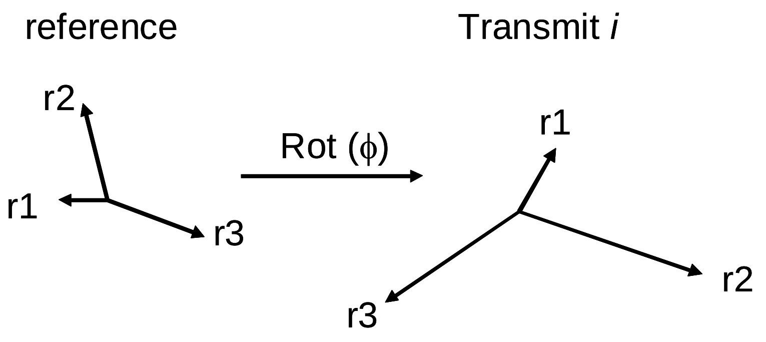

Fig. 7: Example of receive signals for a single voxel for two different transmit modes.

For any transmit channel *j* the signals measured in different receive channels r1…rn are rotated by the transmit phase $\phi_j(x)$. This rotation angle is calculated voxel by voxel via

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$$\phi_j(x) = 0.5 * angle\left(\frac{\sum_i ref_i * \overline{TX_{ij}}}{\sum_i \overline{ref_i} * TX_{ij}}\right).$$

Where ref_i is the signal intensity of the receive channel *i* of the virtual reference image and TX_{ij} is the measured signal of receive channel *i* when transmitting with channel *j* only. The virtual reference image is calculated as simple sum over all transmit images:

$$ref_i = \sum_j TX_{ij}$$

The phases displayed in the phase images are between $-\pi$ and π corresponding to values between 2048-1800 and 2048+1800.

Quantitative B1 amplitude maps

To calculate the flip angle of the pre-saturation pulse it is assumed that the magnitude of the pre-saturated images P is reduced by the cosine of the flip angle relative to the reference image REF for any receive channel i. For each transmit channel j a least square fit over the receive channels is performed to calculate the $\cos(\alpha)$ for each voxel.

Subsequently the inverse of cosine is calculated for each transmit channel. The displayed flip angle values are scaled to a range between 0 and 1800 corresponding to flip angles in degrees between 0 and 180°.

Note: The nominal flip angle which is given in the dicom images refers to the saturation flip angle. For the single channel mode ("*TX array B1 mapping*" being deselected) this value may differ from the desired flip angle set in the protocol (sequence/ special card) in case the desired flip angle requires a peak voltage, which cannot be realized. In this case the actual nominal flip angle is given which can be achieved given the limited peak voltage.

In order to adjust the reference voltage to a certain ROI, the reference voltage with which the B1 map has been acquired is multiplied by a

scale factor = nominal flip angle/ mean flip angle over ROI.

For TX array B1 mapping the nominal flip angle given in the dicom images is always identical to the desired saturation flip angle given in the protocol. The user needs to ensure, that the peak power for the saturation pulse doesn't exceed the limits for the desired saturation flip angle.

B1 map postprocessing

Depending on the protocol parameter "Postprocessing" on the special card, additional postprocessing steps on the calculated B1+ maps are performed. These are:

- "hybrid":
    - If absolute B1 maps of **all individual channels** are measured with this scan and relative B1 maps of all individual channels are available, this method merges both sets of maps to extend the dynamic range of the resulting B1 maps. Therefore, for flip-angles lower than the *"lower merge*

bound" (special card property) are taken from relative B1 maps and flip-angles higher than the *"higher marge bound"* are taken from the absolute B1 maps. In between, a weighted average of both maps is used to estimate the final flip-angle.

- If absolute B1 maps of **one or more different RF shim settings** (not individual channels) are measured and relative B1 maps of all individual channels are available, the relative B1 maps are quantified with the absolute maps of the RF shim sets:

$$\alpha_j(x) = \left|\mathrm{relB1}_j(x)\right| * \frac{\alpha_{shim}(x)}{\left|\sum \mathrm{relB1}_j(x)\right|}$$

where alpha_shim(x) is the flip-angle of one measured shim set. If more than one shim set is measured, the mean of alpha_j(x) for these shim sets is calculated.

- "matrix": To reconstruct the absolute B1 maps of all *n* individual channels, this post-processing method needs *n* absolute B1 maps of linear independent shim sets and the corresponding phase images. This allows to measure B1 maps with a high dynamic range. Based on the shim sets defined in the "prep. Config" .ini file, a matrix A is defined. The B1 values of the individual channels is calculated by:

$$\underline{B1}(x) = A^{-1}\,\underline{B1}_{measured}(x)$$

Therefore, it is necessary that the measured shim sets are linear independent.

Note: Relative B1 maps/ phase maps need to be available for post-processing. These maps can be measured with the current scan (by enabling "meas. Rel. B1 maps") or by a previous scan with either the tfl_b1map sequence or gre_ptx sequence. The previous scan must have the same number of slices with the same orientation and matrix size as the current scan.

3. Protocols

3.1. General imaging parameters

- TR: choose TR long enough to achieve full relaxation of longitudinal magnetization before the saturation scans: TR>>T1. If TR is too short, the B1 mapping will overestimate the flip angle of the succeeding saturation pulse. If TR is limited it might be possible to reduce TR and choosing "*no ref scans*" >=2 (number of reference scans) on the special card (Fig. 4)
- Flip angle (exam card: contrast): The flip angle (or transmit voltage) of the excitation pulses is to be chosen as large as required to gain reasonable SNR in the reference image and as small as possible in order to minimize smearing artefacts along the PE direction. (Note the point spread function of a centrically reordered FLASH sequence in the transient phase)

- Reordering/ TFL echo train: For measuring absolute B1 maps using pre-saturation pulses, the k-space reordering must be centric. In general, the echo spacing is to be minimized to reduce the impact of T1 relaxation over the TFL echo train.

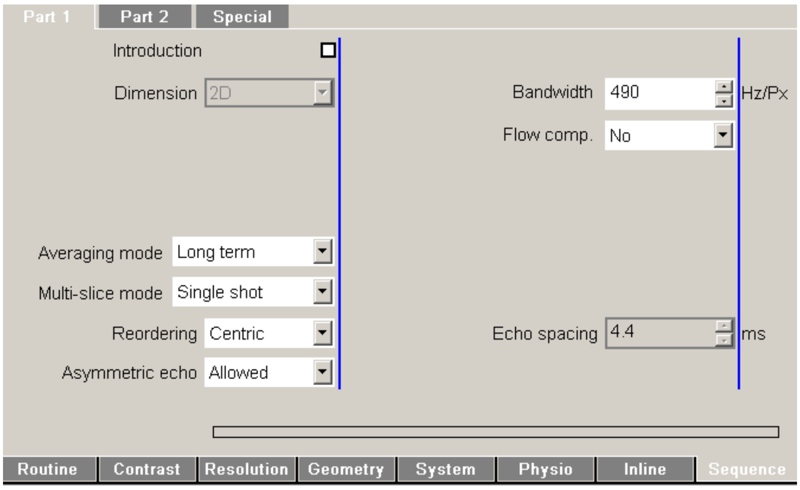

Fig. 8: Exam Task card Sequence/ Part 1

- Segmented acquisition: Choose the number of segments (EPI factor) according to measurement time requirements and high frequency components in the B1 maps to be acquired. Low EPI factors act like a low pass filter resulting in a smoothened B1 field distribution.

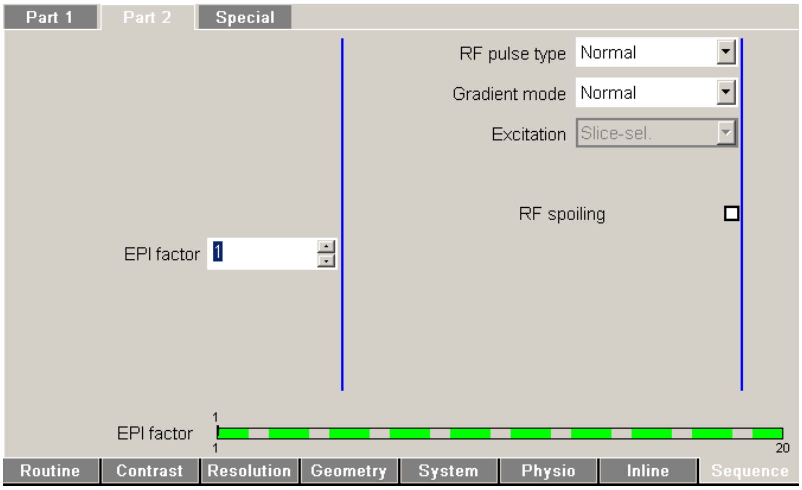

Fig. 9: Exam Task card Sequence/ Part 2

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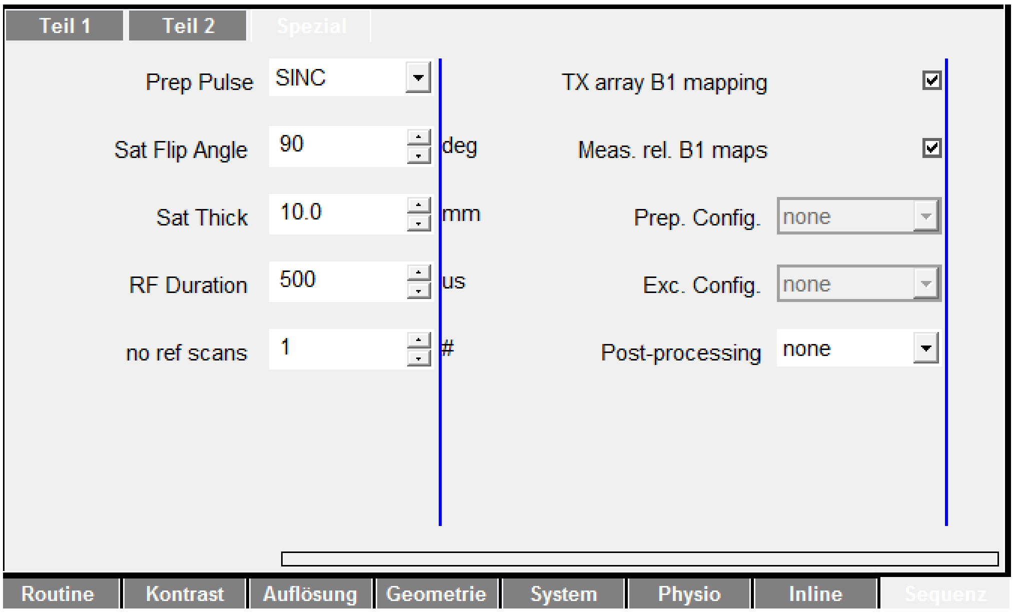

Fig. 10: Exam Task Card Sequence/ Special for acquisition of relative B1 maps

3.2. Relative B1 maps

To acquire relative B1 maps additionally to the absolute B1 maps, select “Meas. Rel. B1 maps” on the sequence special card. Note, that the flip angle/ transmit voltage of the excitation pulse might be increased when transmitting on single channels only as compared to using all transmit channels for the acquisition of the reference image. To acquire relative B1 maps only, use gre_ptx sequence.

3.3. Magnitude B1 maps

To acquire only B1 magnitude maps (=flip angle maps), turn on the preparation pulse.

- If “TX array B1 mapping” is deselected, the single channel mode is active (see: RF settings in “single channel mode”). The selected number of reference scans is executed followed by a single pre-saturated scan.
- If “TX array B1 mapping” is selected, optional configuration files can be chosen from the drop-down menu. (see chapter 2.3)
- Additionally a B1 map postprocessing step performed in ICE can be selected:
  - “hybrid”:
    - If absolute B1 maps of all individual images are measured with this scan and relative B1 maps of all individual channels are available (see below), this method merges both set of maps to extend the dynamic range of the resulting B1 maps. Therefore, for flip-angles lower than the lower merge bound are taken from relative B1 maps and flip-angles higher than the higher marge bound are taken from the absolute B1 maps. In between, both maps are used to estimate the final flip-angle.
    - If one or more absolute B1 maps of different RF shim settings are measured and relative B1 maps of all individual channels are

available (see belo), the relative B1 maps are quantified with the absolute maps of the RF shim sets.

- "matrix": To reconstruct the absolute B1 maps of all *n* individual channels, this post-processing method needs *n* absolute B1 maps of linear independent shim sets and the corresponding phase images. This allows to measure B1 maps with a high dynamic range.
- Relative B1 maps/ phase maps need to be available for post-processing. These maps can be measured with the current scan (by enabling "meas. Rel. B1 maps") or by a previous scan with either the tfl_b1map sequence or gre_ptx sequence. The previous scan must have the same number of slices with the same orientation and matrix size as the current scan.

4. Installation

Installation of this package should be performed by an experienced user. For installation you need to access the file-system of the scanner ("Advanced User" functionality), which requires a password. Please contact the local application support for this information.

4.1. Installation of executables on scanner

The installation on the scanner can be executed with the following steps:

- For the first installation: start Install_WIP543B_VB17.exe from anywhere (either open Explorer and double-click the installation program or start in a command shell)

In case there might be a previous installation of the ICE program on the scanner perform the following steps prior to installation:

- Open IDEACmdTool in a command shell
- unload PAS
- restart image calculation

The following files will automatically be installed to the system:

```
C:\MedCom\MriCustomer\IceConfigurators\IceProgramPrepB1Map.evp
C:\MedCom\bin\IceProgramB1Map.dll
C:\MedCom\bin\IceProgramB1Map.evp
C:\MedCom\MCIR\Med\lib\libIceProgramB1Map.so
C:\MedCom\MriCustomer\seq\tfl_WIP543B_B1map.dll
C:\MedCom\MriCustomer\seq\ tfl_WIP543B_B1map.i86
```

Create new measurement protocols using the Exam-Explorer for the new sequence tfl_WIP543_B1map. The new protocols can be inserted into an existing exam by the "insert sequence" functionality from the "User Sequences" tree.

4.2. Installation of source code in IDEA environment

To install the source code in your IDEA environment, please follow instructions:

- Copy the n4 and n4_deli_vb17a folders to your idea environment.
- compile the sequence a_tfl_b1map and copy the compiled files to the scanner like described above (automatic installation)
- compile the ICE program and copy the files to the scanner like described above (automatic installation). Remember to also copy the ICE configurator

5. Literature (a small selection)

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