

Parallel Transmission (pTX) Technology*

MR Imaging with an 8-Channel RF Transmit Array

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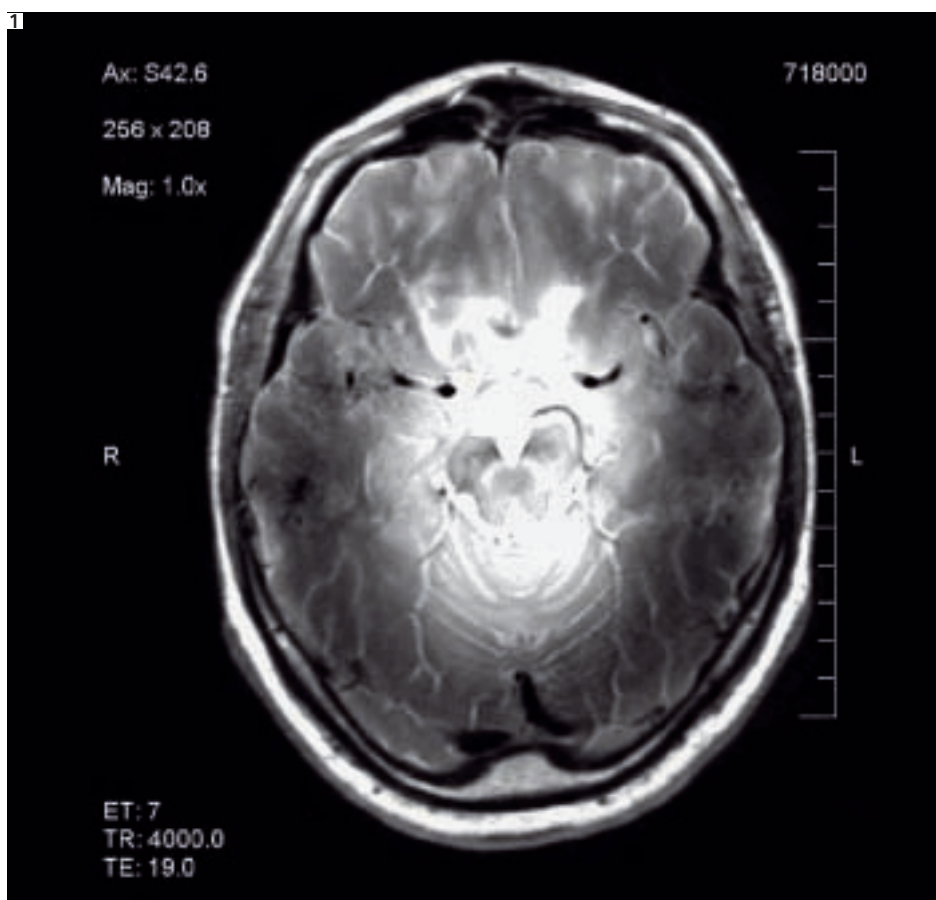
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Introduction

In recent years there has been a trend towards higher field strength in MR imaging. Nowadays 3 Tesla is already routinely used for clinical imaging, and there is a tendency to move towards even higher field strengths for human imaging, like 7T. But besides the many potential advantages of ultra-high field MRI, there are also some methodological challenges like the destructive interference of transmit RF fields within a typical volume coil [1, 2]. These effects arise when the RF wavelength reaches the dimension of the human head or body and can lead to center brightening in the head at 7T (Fig.1) and shading in abdominal imaging at 3T. The spatial variations of the B_1 field lead to reduced tissue contrast and inhomogeneous image intensity. Several methods have been explored to compensate for these spatial variations of the transmit field. These methods include the application of shaped 2D and 3D RF pulses [3] or "RF shimming", where the channels of the transmitting coil are driven with tunable global RF-phase and amplitude in order to optimize the homogeneity of the resulting B_1 field [4, 5, 6].

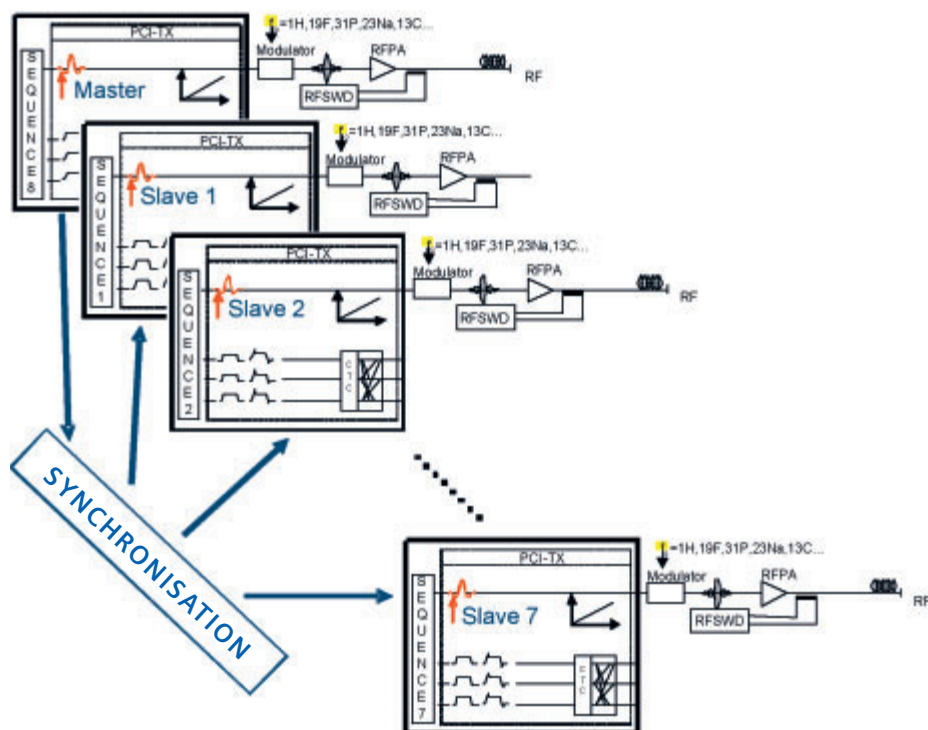
So far 2D and 3D RF pulses were not practical in clinical MR imaging, since the duration of the pulses is too long for normal sequences. Parallel transmission (pTX) techniques have demonstrated the feasibility of accelerating time consuming 2D and 3D excitation pulses, to accommodate clinical sequences [3, 4, 7]. Another challenge linked to the design of tailored 2D and 3D RF pulses and RF shimming is the need for a transmit coil with preferably highly decoupled elements. On cur-



1 Center brightening in the head at 7T.

rent coil designs this requirement is often reduced to a high degree of decoupling between next neighboring elements. This article describes the design and setup of a parallel Transmission (pTX) prototype Siemens MAGNETOM Trio, A Tim System

equipped with an 8-channel transmit array. This prototype MR system was used in combination with two different TX coils to acquire phantom and in vivo images with 1 to 8 fold accelerated 2D and 3D RF pulses.



❑ Block diagram of the Transmit Array system.

❑ SAR simulations in the head.

❑ Transmit only 8-channel head coil.

Experimental Setup

System setup

A prototype 8-channel transmit array in a master-slave configuration was used, with one measurement control unit acting as the “master” controlling the other 7 “slaves” [8]. The transmit array was attached to a 3T MAGNETOM Trio, A Tim System, hence the primary console of the scanner was determined as the master (Fig. 2). Cloning the standard Siemens measurement control unit (MPCU) for all 7 slaves enables to run 8 independent sequences with individual RF shapes and characteristics, individual B_0 eddy current compensation and 3 additional gradient channels per unit, which can be used for gradient array [9] or dynamic shimming applications. Each of the 8 independent RF pulses is amplified by a separate 8 kW Dressler RF amplifier. For safety reasons, each channel includes its own independent RF power monitor (SAR supervision) which will switch off the RF in each channel if the SAR limit in any of the channels is exceeded. Moreover, the SAR settings can be configured for each channel indi-

vidually limiting the peak power and the average power within the 6 minutes and 10 seconds time interval according to the IEC 60601-2-33 standard.

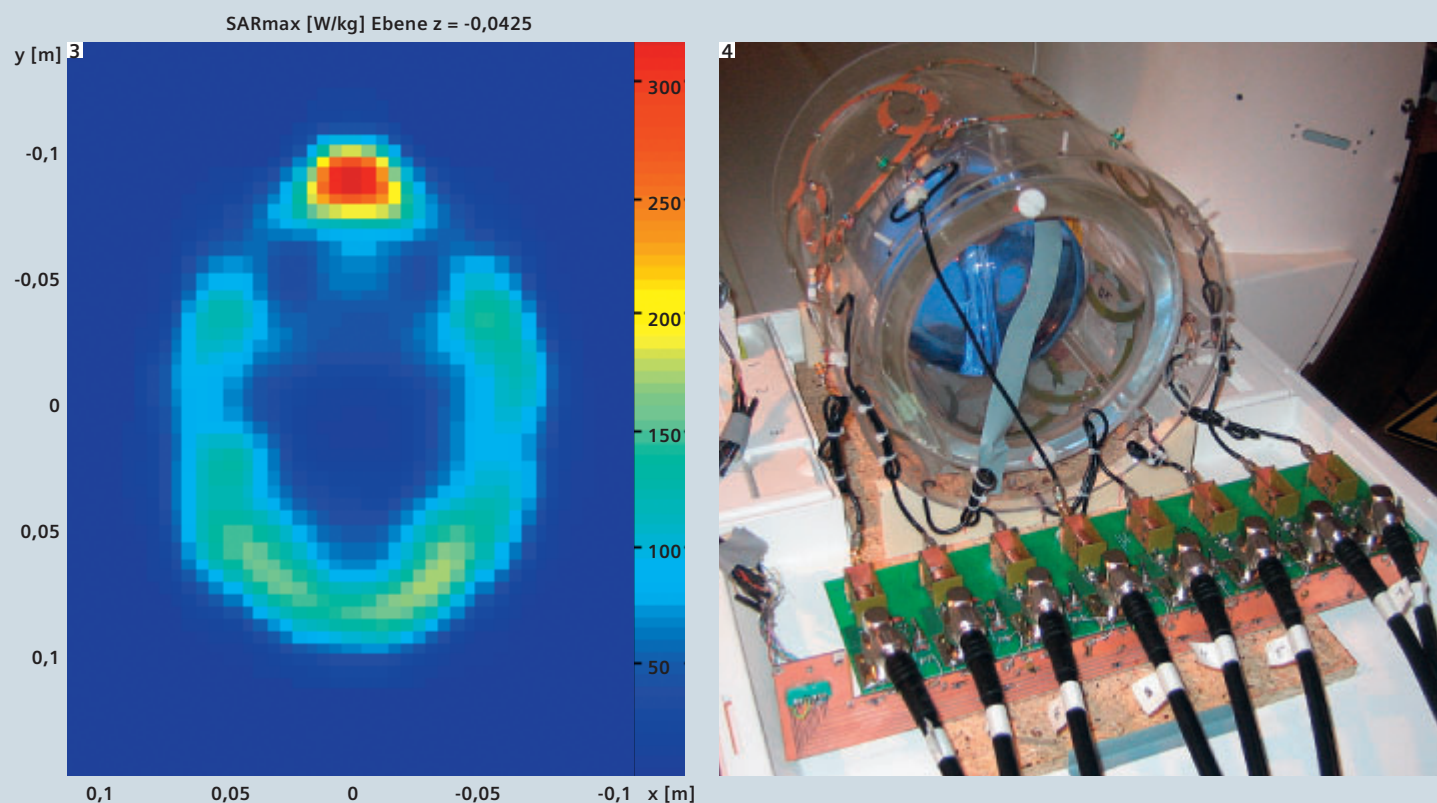
SAR calculation and safety concept

To ensure the safe operation and fulfillment of the IEC limits for SAR of the system in human imaging, the power limits were calculated before starting with the in vivo experiments. For this purpose a commercial program was used, which applies the Finite Integration Technique (FIT). The simulations were performed for the 8-channel head coil and the 8-channel body coil. The worst case SAR was calculated by summation of the E-field magnitude of all coil elements for all voxels in the human model. These worst case E-fields and the knowledge of the tissue properties were used to calculate the 10 g averaged local SAR and the whole-body SAR (Fig. 3). The calculated whole-body SAR was scaled down until the local SAR

limits were fulfilled. These new whole-body SAR limits were divided by the number of transmit channels and were applied to the SAR supervision of each channel. With this concept the RF safety concerning whole-body and local SAR limits is guaranteed, even if one or more of the amplifiers will fail.

Transmit coils

Two different 8-channel coils were used for parallel transmission: The first coil is a pTX only head coil (Fig. 4), which was used for the RF excitation in combination with the body coil receiving the RF signals [10]. This TX only coil was designed as a degenerated birdcage coil (DBC) [11], which basically can be used in two mode configurations, using either the eight “loop mode” basis set or the orthogonal birdcage modes as driven by an 8 x 8 Butler matrix [12]. The Butler matrix has 8 coaxial inputs and 8 coaxial outputs, which can therefore produce



8 independent modes. The big advantage of using the modes of a birdcage coil excited by a Butler matrix is that they form naturally decoupled orthogonal modes which do not require additional decoupling strategies. This decoupling is essential for a parallel transmission methodology, since – similar to a parallel receive array – the capability of a transmit array to accelerate the spatially tailored excitation pulses depends on the spatially differing B_1 profiles of the individual array elements.

The second coil used for the experiments is an 8-channel TX/RX body coil, which also allowed the insertion of a Butler matrix into the TX and the RX path to generate orthogonal modes [13].

With both coils in a first step the magnitude and phase profiles of the transmitted B_1 field have been measured. To avoid an interference with the receive coil profile this measurement was performed for both 8-channel coils using the uniform standard CP mode of the scanner body

coil for RF reception. The amplitude and phase of these B_1 fields were then used for the calculation of the RF pulse shapes as described in the next section.

RF pulse design

Different RF waveforms in the low flip angle domain were calculated based on the formalism used by Grissom et al. [14]. For excitation we used two types of gradient trajectories [3]:

The first trajectory consisted of a 2D excitation with a spiral trajectory in (k_x, k_y) and no encoding in z-direction. This 2D trajectory can be used to excite a high resolution target profile in the 2D plane. With this pulse design accelerations of integer factors of 2 through 8 can be utilized by successively increasing separation between the turns in the k-space trajectory. At a gradient amplitude of 35 mT/m and a slew rate of 150 T/m/s the duration of these 2D pulses could be reduced from 9.47 ms in the unaccelerated

case ($R=1$) to 2.42 ms for $R=4$, 1.64 ms for $R=6$ and only 1.26 ms for $R=8$ respectively. Therefore the $R=8$ accelerated pulse was 7.5 times shorter than the unaccelerated pulse, which will make their application in clinical pulse sequences possible.

The second trajectory consisted of a 3D k-space excitation using a set of line segments or “spokes” in the k_z direction placed at regular intervals in the (k_x, k_y) plane [3, 15, 16, 17]. Using a sinc-like RF waveform during the transversal of each spoke achieves a sharp slice selection in z but with low resolution control of the in-plane magnetization profile. Two versions of these trajectories were designed and tested: one with 4 spokes with a pulse length of 3.42 ms and one with 1 spoke with a pulse length of 1.2 ms. With such a trajectory it is possible to achieve a uniform excitation across the phantom despite the nonuniform nature of the 8 individual excitation profiles.

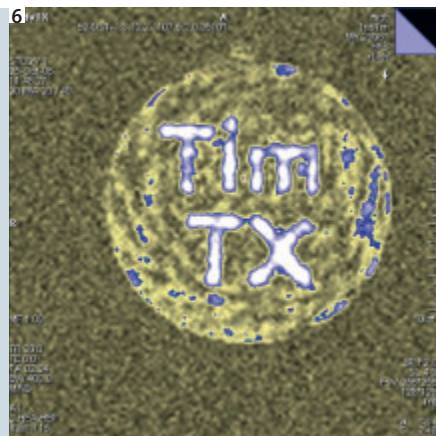
Image examples

Phantom measurements

The 2D trajectory in combination with the 8-channel pTX head coil was used to excite a high-resolution spatial pattern of letters in the (x, y) plane. The resolution for this experiment was set to 5 mm with a FoV of 180 mm. Fig. 5 shows the image using an acceleration factor of $R=4$. The

high resolution "Tim TX" logo (Fig. 6) was also acquired using the 2D trajectory with an acceleration of $R=4$. For this image parallel transmit and parallel receive have been used simultaneously by employing the 8-channel TX/RX body coil for excitation and the standard Siemens 12-channel

Head Matrix coil for reception of the data. Fig. 7 shows as an example the image of a phantom using the 3D homogeneous excitation with 4 spokes and an acceleration factor of $R=4$. For this measurement the RF pulse duration was 3.42 ms.



5 MIT logo excitation using a 2D trajectory and the TX head coil, $R = 4$.

6 "Tim TX" logo, 2D excitation with body coil, acquisition with 12-channel Head Matrix coil, $R = 4$.

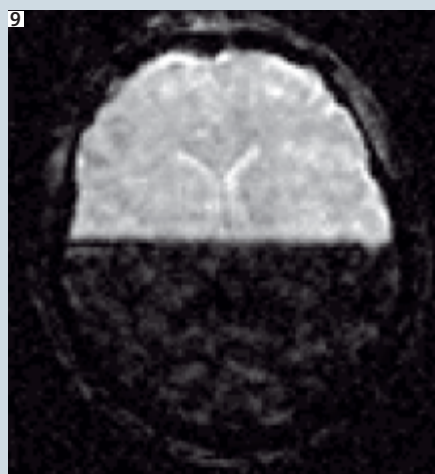
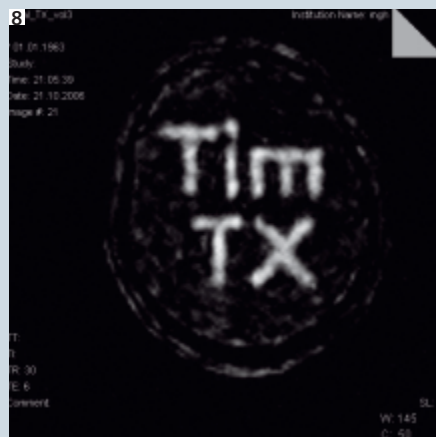
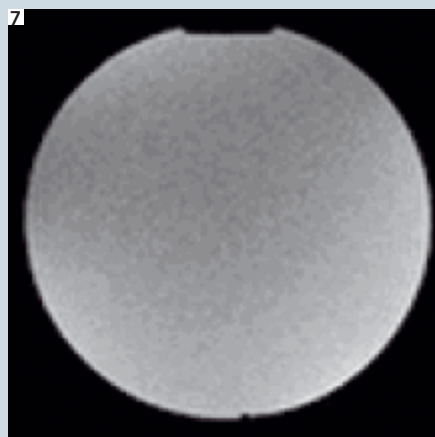
7 3D homogenous excitation using the 4 spokes trajectory.

8 "Tim TX" logo in the human head acquired with the TX head coil using an acceleration of 4.

9 "Half brain" excitation with the TX head coil, $R = 4$.

10 3D excitation of a homogenous slice in the brain using the TX/RX body coil for excitation.

11 3D excitation of a homogeneous slice in the human torso using the TX/RX body coil for excitation.



In vivo measurements

Using the TX only head coil for excitation and the 2D trajectory with an acceleration factor $R=4$ the “Tim TX” logo could also be excited in the human brain (Fig. 8). Moreover with this coil/pulse configuration we were also able to excite only one half of the subject’s brain (Fig. 9) using

an acceleration factor of $R=4$. Excitation of homogeneous brightness profiles in the head (Fig. 10) and the torso (Fig. 11) were obtained with the TX 8-channel body coil using the 3D pulses with a 4 spokes design as described above.

Conclusion

We have developed a new setup of a parallel Transmission (pTX) prototype Siemens MAGNETOM Trio, A Tim System equipped with an 8-channel transmit array. This new scanner was successfully tested in combination with two different 8-channel coils and two different RF pulse designs. With this combination of modi-

fied software and hardware we were able to acquire phantom and in vivo images with homogeneous signal distribution and high resolution spatial patterns. First results with the pTX array are very promising and raise the possibility of performing highly homogeneous head and whole-body imaging not only at 3T but furthermore at ultra high field strength like 7T, where destructive interference of transmit RF fields can lead to clinically compromised image quality. Moreover the design of 2D trajectories in combination with acceleration factors of up to 8 also raise the possibility to use these 2D pulses in clinical sequences, where the duration of the RF pulse is crucial.

* WIP – Works in Progress. The information is preliminary. The sequence is under development and not commercially available in the U.S., and its future availability cannot be ensured.

References

- Hoult DI, Phil D. Sensitivity and power deposition in a high-field imaging experiment. *J Magn Reson Imaging* 2000; 12(1): 46–67.
- Collins CM, Liu W, Schreiber W, Yang QX, Smith MB. Central brightening due to constructive interference with, without, and despite dielectric resonance. *J Magn Reson Imaging* 2005; 21(2): 192–196.
- Setsompop K, Wald LL, Alagappan V, Gagoski B, Hebrank F, Fontius F, Schmitt F, Adalsteinsson E. Parallel RF Transmission with Eight Channels at 3 Tesla. *Magn Reson Med* 2006; 56(5): 1163–1171.
- Katscher U, Bornert P, Leussler C, van den Brink JS. Transmit SENSE. *Magn Reson Med* 2003; 49(1): 144–150.
- Vaughan, J.T., DelaBarre, L., Snyder, C., Adriany, G., Collins, C., Van de Moortele, P-F., Moeller, S., Ritter J., Strupp, J., Andersen, P., Tian, J., Smith, M., Ugurbil, K., RF Image Optimization at 7T & 9.4T, 2005, ISMRM. Miami Beach, Florida, USA. p. 953.
- Adriany, G., Van de Moortele, P-F., Wiesinger, F., Moeller, S., Strupp, J., Andersen, P., Snyder, C., Zhang, X., Chen, W., Pruessmann, K.P., Boesiger, P., Vaughan, J.T., Ugurbil, K., Transmit and receive transmission line arrays for 7 Tesla parallel imaging. *Magn Reson Med*, 2005. 53(2): p. 434–445
- Zhu Y. Parallel excitation with an array of transmit coils. *Magn Reson Med* 2004; 51(4): 775–784.
- Fontius U., et al., A Flexible 8-Channel RF Transmit Array System for Parallel Excitation, 2006, ISMRM, Seattle, Washington, USA, p. 127
- Parker DL, Hadley JR. Multiple-Region Gradient Arrays for Extended Field of View, Increased Performance, and Reduced Nerve Stimulation in Magnetic Resonance Imaging, *Magn Reson Med*, 2006; 56 (6): 1251–1260.
- Alagappan V, Nistler J, Adalsteinsson E, Setsompop K, Fontius U, Vester M, Wiggins GC, Hebrank F, Renz W, Schmitt F, Wald LL. A degenerate Mode Band-Pass Birdcage for Accelerated Parallel excitation. Submitted for *Magn Reson Med*.
- Lin FH, Kwong KK, Huang U, Belliveau JW, Wald LL. Degenerate mode birdcage volume coil for sensitivity-encoded imaging. *Magn Reson Med* 2003; 50(5): 1107–1111.
- Moody HJ. The systematic design of the Butler matrix. *IEEE Transaction on Antenna and Propagation* 1964: 786–788.
- Nistler J. et al, Using a mode concept to reduce hardware efforts for multi channel transmit array, 2006, ISMRM, Seattle, Washington, USA, p. 2024
- Grissom W, Yip C-Y, Noll DC. A new method for the design of RF pulses in Transmit SENSE, Proceedings of the 2nd International Workshop on Parallel Imaging, Zurich, Switzerland 2004. p. 95.
- Saekho S, Boada FE, Noll DC, Stenger VA. Small tip angle three-dimensional tailored radiofrequency slab-select pulse for reduced B1 inhomogeneity at 3 T. *Magn Reson Med* 2005; 53(2): 479–484.
- Ulloa J, P. I, Hajnal JV. Exploring 3D RF shimming for slice selective imaging. 2005; ISMRM. Miami Beach, Florida, USA. p. 21.
- Saekho S, Yip C-Y, Noll DC, Boada FE, Stenger VA. A Fast-kz 3D Tailored RF Pulse for Reduced B1 Inhomogeneity. 2005; ISMRM. Miami Beach, Florida, USA. p. 22.

Acknowledgments

We would like to thank Melanie Schmitt for her valuable assistance in the preparation of this article.

