PARALLEL SPATIALLY SELECTIVE EXCITATION USING NONLINEAR NON-BIJECTIVE PATLOC ENCODING FIELDS: EXPERIMENTAL REALIZATION AND FIRST RESULTS

J. T. Schneider[1,2], M. Haas[2], S. Ohrel[1], H. Lehr[1], W. Ruhm[1], H. Post[1], J. Hennig[2], and P. Ullmann[1]

[1]Bruker BioSpin MRI GmbH, Ettlingen, Germany, [2]Dept. of Radiology, Medical Physics, University Medical Center Freiburg, Freiburg, Germany

Introduction: The concept of PatLoc (Parallel Imaging Technique Using Local Gradients) [1] proposes the application of non-linear, non-bijective Spatially Encoding Magnetic Fields (SEMs) that can substitute or be added to conventional gradient fields with linear SEMs while the introduced encoding ambiguity is compensated for by parallel acquisition with sensitivity encoding. During the last years, several promising characteristics of PatLoc encoding have been reported on the acquisition side and there is strong evidence that these advantages can be exploited beneficially for Parallel Spatially Selective Excitation (PEX [2] / Transmit SENSE [3]) experiments, too: Locally increased spatial resolution [4] can improve the accuracy of excited target patterns [5]; encoding capabilities of PatLoc SEMs may outperform those of linear SEMS in specific regions [2] allowing higher excitation fidelity; finally faster switching times of symmetrically designed PatLoc gradient coils [6] may afford shorter pulse durations, which is one of the main limiting factors of Spatially Selective Excitation (SSE). In analogy to parallel acquisition, parallel transmission is mandatory in order to resolve encoding ambiguities during excitation.

Based on previous work on parallel transmission and PatLoc hardware [6] as well as on design algorithms for parallel SSE pulses for PatLoc SEMs [5,7], this work demonstrates the first experimental realization of PEX with non-linear, non-bijective SEMs.

Methods: The experiments were carried out on a 9.4 T BioSpec small-animal MR-scanner (Bruker BioSpin MRI, Germany) in a homogenous, T_1-doped water phantom. For 2D PatLoc encoding, the conventional linear gradients for read and phase encoding were substituted by quadrupolar SEMs of a PatLoc coil placed as insert into the standard gradient system [6]. For the slice-gradient, the standard linear SEM was used. Since the encoding fields have to be known for SSE and image reconstruction, the PatLoc fields were measured in the object with a multi gradient-echo sequence using the linear SEMs while feeding a calibration current into the PatLoc coil. Based on the geometry and amplitude of the measured field maps, optimized maps (**Fig. 1**) without noise were generated by simulating the gradient coil fields numerically. These SEMs were used for encoding during excitation as well as during acquisition. Consequently, besides parallel excitation also parallel reception and PatLoc image reconstruction as described in [2] was mandatory. This setup greatly simplifies the experiments since the PatLoc SEMs can substitute the conventional ones during the whole sequence without the need to operate PatLoc and corresponding conventional coils in parallel.

For parallel transmission an 8-element TxRx coil array was driven by 8 independent Tx-channels. The same coil elements were used for parallel reception with 8 Rx-channels. B_1 transmit and receive sensitivities of the coil elements were measured inside the object for the purpose of pulse calculation and image reconstruction.

2D SSE pulse shapes $I_l(t)$ for excitation of a profile of transverse magnetization $M_T(\mathbf{r})$ were calculated by iteratively solving the following equation in the small tip-angle regime as proposed in [5]: $M_T(\mathbf{r}) = i\gamma M_0(\mathbf{r}) \int_0^T \sum_l S_l(\mathbf{r}) I_l(t) e^{i\varphi(\mathbf{r},t)}\,\mathrm{d}t$

Note, that the nonlinear gradient fields are incorporated into this equation by the explicit phase $\varphi(\mathbf{r},t)$ which is usually expressed by means of a k-space trajectory ($\varphi(\mathbf{r},t)=\mathbf{k}\cdot\mathbf{r}$) which however is not possible for non-linear SEMs. The spatial ambiguity of the phase evolution has to be resolved by the spatially dependent transmit sensitivities $S_l(\mathbf{r})$. The gradient waveform was designed as a spiral with 16 revolutions and it was scaled to achieve equal field strength at the object boundaries as with conventional linear SEMs that define a field of excitation of $(6.4\text{ cm})^2$ and a 32x32 excitation matrix. Deviations of the waveform concerning amplitudes and timing delays were measured by a local fieldprobe [6] attached to the water phantom. This calibration data was incorporated into the scaling of $\varphi(\mathbf{r},t)$ in order to adapt the RF pulses for the actually applied SEMs.

Since pulses were selective in 2 dimensions only, selectivity in the third dimension was achieved by slice selective refocusing followed by a PatLoc encoded RARE readout.

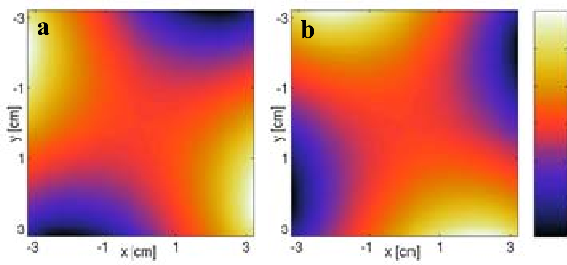

*Fig. 1: Quadrupolar PatLoc SEMs [kHz/Ampere] for read (**a**) and phase (**b**) encoding replacing the conventional linear SEMs.*

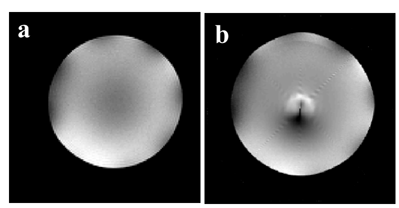

*Fig. 2: Water phantom imaged with linear SEMs (**a**) and PatLoc SEMs (**b**).*

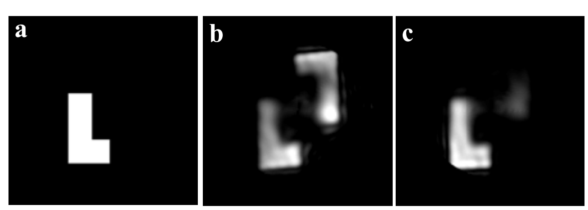

*Fig. 3: SSE with PatLoc fields: (**a**) Target pattern. (**b**) single channel pulse results in duplicated pattern (**c**) correct excitation with multi-channel PEX-pulse.*

Results: Fig. 2a shows the used phantom, encoded with linear SEMs. To verify correct PatLoc encoding for acquisition and image reconstruction, the scan was repeated with PatLoc SEMs. The resulting image (**Fig. 2b**) represents the correct geometry and exhibits the typical PatLoc characteristics of large voxels with high signal intensity in the centre and smaller voxel sizes in the periphery. SSE was performed afterwards in order to excite an "L"-shaped target pattern (**Fig. 3a**). Calculating a pulse for one single channel and applying this pulse by all transmit channels in a B_1-shimmed mode results in **Fig 3b**. The ambiguity of the encoding fields is not resolved by the single-channel pulse and results in a duplicated target pattern. In contrast, an appropriately calculated multi-channel pulse provides more degrees of freedom and compensates for the ambiguity resulting in the desired target pattern (**Fig. 3c**).

Conclusion & Outlook: This work demonstrates the experimental feasibility of spatially selective excitation based on PatLoc SEMs. Furthermore, it confirms previous theoretical simulation studies regarding pulse design for PatLoc SEMs [4,5]. Due to the non-bijective character of SEMs, parallel transmission for sensitivity encoding is mandatory to resolve encoding ambiguities. Residual artifacts in the images are likely to be caused by imperfections during measurement and application of the PatLoc SEMs. Both effects may be compensated for by a measurement of the local phase evolution in non-linear SEMs to which the pulses can be adapted as described in [9]. Based on the successful realization in this work, the proposed benefits of PatLoc encoding for PEX, like resolution enhancement, improved encoding capabilities and faster switching times, will be assessed in the future. Additionally, simultaneous operation of linear gradients and PatLoc fields is going to be realized. It will simplify setup and calibration procedures and will help to distinguish between PatLoc characteristics during excitation and acquisition. Beyond the scope of the work, the setup employed here can be seen as a representative model for encoding fields with arbitrary (but known) geometry without restriction to linearity or bijectivity. Even such complex fields allow spatial encoding for excitation as well as for acquisition while deficiencies in gradient encoding can effectively be compensated for by parallel transmission and parallel reception and RF sensitivity encoding.

Acknowledgements: This work is part of the INUMAC project supported by the German Federal Ministry of Education and Research. Grant #13N9207.

The authors thank Gerrit Schultz and Dr. Daniel Gallichan for valuable support concerning the PatLoc image reconstruction.

References:

[1] Hennig J. et al.; Magn Res Mater Phy 2008, 21:5

[2] Zhu Y.; MRM 2004, 51:775

[3] Katscher U. et al., MRM 2003, 49:144

[4] Schultz G.; MRM 2010, 64:1390

[5] Haas M. et al.; ISMRM 3rd WS parallel MRI 2009, 35

[6] Ohrel S. et al.; ISMRM 2010, 3936

[7] Haas M. et al.; ISMRM 2010, 4929

[8] Schneider J.T. et al.; ISMRM 2010, 4926

[9] Schneider J.T. et al.; MRM i.p. 2010/11, 64/65