EXPLOITING PHASE ENCODING CAPABILITIES OF PARALLEL EXCITATION FOR IMPROVED SPATIAL SELECTIVITY IN INNER-VOLUME IMAGING

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Introduction: During the last years, Spatially Selective Excitation (SSE) has become practicable in combination with parallel RF transmission. SSE applications like inner-volume imaging (IVI) [1] or targeted spectroscopy [2] utilize the possibility to restrict the generation of transverse magnetization M_T to specified target volumes by spatial amplitude modulation according to a given target pattern. However, the potential of SSE to additionally control the spatial phase distribution of M_T has been barely exploited so far, although spatial phase modulation offers new promising applications [3]. This work introduces Inner Volume Imaging by Phase Encoding (IVIP) and demonstrates that phase modulation during excitation can be used instead of amplitude modulation to realize spatial selectivity for IVI. It is shown that with this approach spatial selectivity can be enhanced by mitigating certain limitations of SSE pulses which otherwise significantly deteriorate the amplitude modulation accuracy.

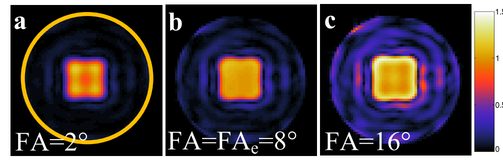

*Fig. 1: 3D SSE of a cubic target volume in a spherical phantom (circle): pulse imperfections can be neglected for small target flip-angles (**a**) but they become strongly pronounced at larger flip-angles (**b**,**c**).*

In order to select an inner-volume by amplitude modulation, RF pulses are typically calculated to excite M_T with a finite flip-angle (FA) inside a target volume, while outside this volume FA should be zero. However because of physical limitations (e.g. Gibbs ringing due to limited resolution) and experimental imperfections (off-resonances, gradient imperfections, etc.), artifacts excited by small, but finite flip-angles (typically less than 10% of the target FA) may be generated outside the target volume. When exciting with small target flip-angles the signal amplitude related to such artifacts is typically smaller by more than one order of magnitude than the amplitude from the desired signal (**Fig. 1a**) as long signal amplitude depends linearly on FA. However, for short repetition times (TR) or large flip-angles, saturation effects can no longer be neglected and the dependency of signal amplitude on FA in the steady state is highly non-linear as described by the equation and the graph in **Fig. 2** for the example of gradient echo signals. This extremely non-uniform weighting of desired and undesired signal results in highly pronounced artifacts as shown in **Fig. 1b,c**. This limits the application of SSE, e.g. for 3D scans with reasonable flip-angles and short TRs. The IVIP approach overcomes this limitation by exciting the whole object with homogenous FA amplitude close to the Ernst angle (FA_e) and realizing the volume selection by spatial phase encoding of the generated M_T.

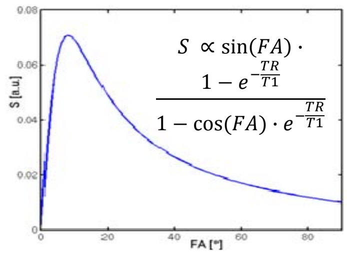

Fig. 2: Dependency of gradient echo signal on FA for TR=15ms, T_1=1s.

Methods: Experiments were carried out on a 9.4 T BioSpec small-animal MRI scanner (Bruker BioSpin MRI, Ettlingen, Germany). An 8-element TxRx array was driven by 8 independent Tx channels for Parallel Excitation. For the first proof of principle, a 3D cubic volume was selected in a spherical water phantom (T_1 = 1 s) and as a second experiment, zoomed imaging in a tangerine was performed. A 3D FLASH sequence was applied in which the excitation pulse was substituted by a 3D parallel SSE pulse (duration 5.3 ms, 3D k-space trajectory: stack of spirals, 3-fold acceleration); TR was set to 15 ms.
The SSE pulses were calculated for the purpose of spatial selection by amplitude modulation (target amplitude 1/0 inside/outside the specified volumes) as well as for selection by phase modulation in the IVIP approach. For the latter one, signal separation from inside and outside the specified volumes was achieved by a simple Fourier encoding scheme: In two scans, two different SSE pulses were applied, both generating a distribution of M_T with homogenous amplitude but differing in the phase profile. The first pulse generated a homogenous phase 0° of the distribution of M_T while the second pulse generated a phase pattern with phase 0°/180° inside/outside the specified volumes.

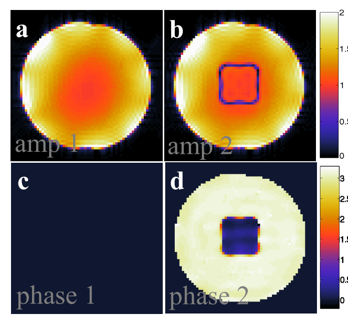

*Fig. 3: Two excitation profiles with homogenous amplitudes (**a**,**c**) but different phase patterns (**b**,**d**) for IVIP.*

Results: As already shown in **Fig. 1**, spatial selection by amplitude modulation results in pronounced artifacts due to the non-linear dependence of signal intensity on FA. The two images acquired for IVIP are depicted in **Fig. 3** as amplitude and phase images (relative two the first image). Excitation with a homogenous flip-angle near the plateau around FA_e = 8° in the signal curve of **Fig. 2** consequently reduces the sensitivity to flip-angle deviations of the SSE pulse while signal efficiency is optimized. Note that the measured amplitude distribution is weighted by the receive profile of the coil array leading to increased image intensity near the coil elements. Complex summation of the two acquired images, results in the magnitude image shown in **Fig. 4a**. The realization of the 0°/180° phase profiles with high fidelity (**Fig. 3b,d**) allowed selection of the desired region with high accuracy demonstrating the feasibility of spatial selection by the IVIP approach. Furthermore, ringing artifacts that were clearly visible for the amplitude modulation approach, shown in **Fig. 1c**, were significantly reduced due to equal weighting of undesired and desired M_T. Even larger flip-angles of 16°, which were absolutely unfeasible with amplitude modulation (**Fig. 1d**), result in good image quality with IVIP (**Fig. 4b**).

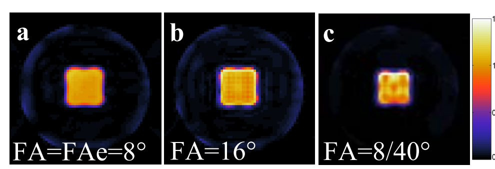

*Fig. 4: Volume Selection by IVIP (**a**) after summation of images from Fig.3; even with higher flip angles (**b**) artifacts are significantly reduced (compared to Fig. 1c); in combination with amplitude modulation undesired signal is perfectly suppressed (**c**)*

Residual artifacts at the phantom boundaries can probably be attributed to off-resonances which lead to phase deviations and therefore to incomplete signal cancelation after summation of the two datasets. In this case, selectivity can be further increased by combining phase and amplitude modulation: Excitation of the target volume with FA_e, while the rest of the object is excited with larger flip-angles results in partly saturation of the unwanted parts with lower sensitivity to flip-angle variations and with decreased sensitivity to phase deviations due to lower signal amplitudes. **Fig. 4c** shows a preliminary result of this approach with FA = 8° inside the target volume and FA = 40° outside. Nearly perfect signal suppression outside the target volume was achieved, but also a less homogeneous signal distribution inside the volume. In this case, appropriate calculation of large flip-angle SSE pulses [4] instead of using the small flip-angle approximation for pulse calculation – as done here – should improve image quality and is going to be assessed.
Finally, zoomed imaging with IVIP was performed in a tangerine (**Fig. 5a**). The 3D-FOV was reduced to the target volume. Although this results in backfolding artifacts (**Fig. 5b,c**), the (phase encoded) aliased signal contributions cancel out after summation (**Fig. 5d**).

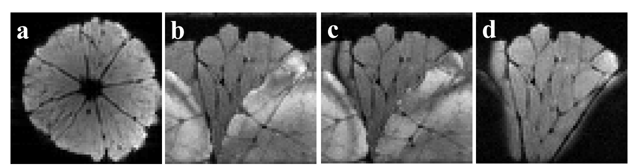

*Fig. 5: Zoomed imaging in a tangerine: Pilot scan (**a**), reduced FOV images with different phase modulation (**b**,**c**), summation of b+c for final image (**d**).*

Discussion: SSE by phase modulation can achieve high spatial selectivity by equal weighting of desired and undesired M_T. The effects of limitations of SSE pulses which are evident in case of amplitude modulation can be mitigated and even efficiently suppressed by IVIP. Especially 3D IVI with short repetition times can highly profit from this technique. Due to the required acquisition of two images with different phase modulation, the minimum scan time is doubled. However, SNR efficiency does not change since the summation of the two images acts as averaging which is typical in small-animal imaging anyway. A second limitation of this approach is the excitation of the whole object preventing multi slice or multi inner-volume imaging with interleaved excitation of different volumes due to saturation effects.

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