Slice Selective Parallel Excitation in the Presence of Off-Resonance

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Introduction: Three dimensional (3D) tailored RF excitation requires writing into a 3D excitation k-space. Parallel transmit[1,2] (PT) methods can be used to make this process more efficient. When the desired 3D excitation includes a requirement for a precisely defined slice, the through slice direction (k_z) in excitation k-space becomes extended and it is useful to employ slice selective sub-pulses to ensure good control over slice profile[3]. Slice selectivity is essential for most practical applications but introduces a number of increased difficulties compared to the non-selective parallel transmit approaches that have mostly been demonstrated to date[4]. A key factor is increased excitation duration compared to 2D methods and therefore greater vulnerability to off-resonance effects leading to errors between the desired and the achieved excitations. The duration of the sub-pulses can be minimised at the cost of degraded slice profile and increased pulse bandwidth. To maintain reasonable slice thickness, strong slice-selective gradients are required and these introduce further off-resonance effects in the form of eddy currents produced by switching the polarity of the z-gradient, G_z, as k_z is alternately traversed. The trade-off between excitation resolution and duration also has an effect in-plane, where the number of sub-pulses dictates the extent of coverage in $\{k_x, k_y\}$ and therefore the excitation resolution in-plane. Increased resolution achieved with longer excitations can be out-weighed by increased off-resonance effects and the associated excitation distortion[5]. This can be problematic for PT in which accurate combination of the excitations produced by each transmit element is required, particularly when these excitations are spatially aliased i.e. acceleration factor, R, > 1. However, the increased k-space coverage that can be achieved via PT may also be used to mitigate these effects in slice-selective excitation, either to reduce the excitation duration for a given resolution; to increase the resolution for a given duration; or to improve the achievable off-resonance compensation. The latter two effects are demonstrated here.

$$ex(x,y) = \sum_{c}^{coils} \sum_{k}^{pulses} s_c(x,y).e^{i\phi_{evolution}(x,y,k)} e^{i\phi_{eddy}(x,y,k)} FT\left[B_{1c}(k)\right] \quad (1)$$

$$\| ex_{des}(x,y) - ex(x,y) \| \quad (2)$$

Methods: A 3D slice-selective excitation following a Cartesian EPI trajectory was used. The fast encoding direction was along k_z to achieve non-aliased slice-selection in z. The in-plane excitation profile in {x,y} was achieved by modulating the amplitude and phase of the slice-selective sub-pulses based on their location in $\{k_x,k_y\}$. A two element transmit/receive coil was built and operated for serial transmit experiments on a 3.0T Philips Intera scanner (Best, Netherlands). The coil can be used either to transmit the same excitation on each element concurrently or to transmit independent excitations on each element consecutively. In the latter case the acquired images were combined off line by complex addition to estimate the net excitation that would be achieved if transmitting on each element concurrently in the small tip angle[6] (STA) regime. Working in this regime, the excitation achieved using the set of slice selective sub-pulses $B_{1,c}(k)$ applied through coil c with transmit sensitivity $s_c(x,y)$ is given by equation 1 where $\phi_{evolution}$ and ϕ_{eddy} describe phase evolution and eddy current off-resonance components respectively. This equation predicts how the excitation will be warped by off-resonance and so can be used in an optimisation to minimise the least squares difference between the achieved excitation, $ex(x,y)$, and the desired excitation, $ex_{des}(x,y)$, using equation 2. Off-resonance information was calibrated by acquiring three gradient echo images each with a single non-zero sub-pulse at incremented locations along the slice-selective EPI excitation trajectory with no in-plane encoding. The phase evolution component of the off-resonance was calculated as half the phase difference between the two images acquired with the same G_z polarity for the non-zero sub-pulse. The eddy current component was then calculated as the difference between two images acquired with opposite G_z polarity for the non-zero sub-pulse, minus the phase evolution component previously calculated. Magnitude transmit sensitivities and the relative phase of the transmit elements were calibrated via the concurrent acquisition of SE and STE images after consecutive transmission on each transmit element as outlined in [7]. A phantom filled with copper sulphate doped saline was used.

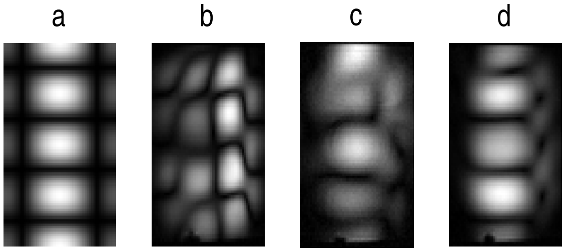

Figure 1: The simulated desired parallel excitation is shown in (a). Off-resonance effects lead to a distorted excitation (b). These effects can be calibrated and minimised through optimisation (c). Greater k-space coverage is achieved with R=2 in the vertical direction while keeping the total number of pulses fixed leading to improved resolution of the excitation and greater off-resonance compensation, (d).

Results: Figure 1a shows the desired excitation simulated in the STA regime assuming the ideal situation of no off-resonance. To achieve the resolution of the desired excitation 5 pulses were used to traverse k_z at locations distributed along k_x (vertical) and 3 pulses were used along k_y (horizontal) leading to a total excitation duration of 15.4ms. Significant distortion occurs when this excitation is implemented on the two-channel T/R coil due to the off-resonance effects associated with the extended duration of the tailored slice-selective excitation. The result is in fact a modulation with different periodicity in the horizontal direction (fig. 1b). In fig. 1c only 9 pulses (3 in each direction giving an excitation duration of 9.1ms) were used but the quality of the excitation is still improved through optimisation incorporating the off resonance and transmit sensitivity calibration data. The desired pattern has been almost fully restored. Parallel excitation offers further improvement to both the excitation resolution and off-resonance compensation as shown in fig. 1d. Each of the acquired images (b-d) is also modulated by the highly non-uniform receive sensitivity of the array. The acquisition can be repeated with a time-consuming 3D readout to directly visualise the full excitation pattern. A plot along the slice-select direction shows that the acquisition is genuinely slice-selective (fig. 2).

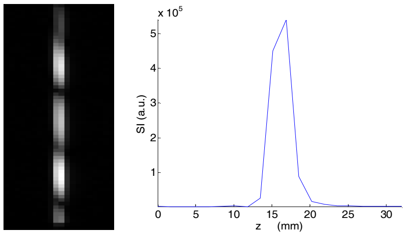

Figure 2: The central x-z plane (left) from combined multi-coil 3D readout data with R=2 along x and the corresponding slice profile (right) showing the genuinely slice-selective nature of the accelerated excitation.

Discussion: As parallel transmit makes the transition from demonstration experiments to a practical and useful tool for imaging and spectroscopy it is inevitable that full slice selective excitations with well defined slice profiles will be required. These require longer duration RF excitations to achieve the necessary coverage of excitation k-space. We have shown that by careful calibration of off resonance effects including from eddy currents, it is feasible to achieve designed accelerated slice selective excitations with effective control of artefacts and low levels of distortion.

References: [1] Katscher U. *et al.* MRM 2003;49:144-150. [2] Zhu YD. MRM 2004;51:775-784. [3] Saekho, S. *et al.* MRM 2006;55;4;719-724. [4] Ullman P. *et al.*MRM 2005;54:994-1001. [5] Setsompop *et al.* MRM 2006; 56:1163-1171. [6]Pauly J *et al.* JMR 1989;81:43-56. [7] Callaghan, M.F. *et al.* ISMRM 2006, #2627.

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