Introduction

Based on a superposition of spatially linear and nonlinear magnetic field components, ExLoc [1] allows selection of slices with flexible curvature, orientation and position. As the encoding fields generated are oriented orthogonal to each other, spatial encoding along the curved dimension is achieved, thus maintaining a local rectangular shape of the individual voxels (Fig. 1). No complex and time consuming multidimensional RF-pulses are necessary.

In this work we explore ExLoc’s potential for multi-slice imaging. Selection and encoding of stacks of slices by maintaining the curved geometry for each slice results in improved relevant volume coverage for fewer excited slices and thus increased efficiency for particular applications (Fig. 2). We present the results of experiments performed on a phantom, as well as a demonstration in vivo.

Methods

Within ExLoc imaging, conventional multi-slice selection with constant RF-pulse bandwidth BW and constant frequency-offset increment would result in slices with centre thickness (CT = max. thickness of a curved ExLoc slice) and inter-slice spacing varying from slice to slice as a result of the non-linear nature of the encoding field applied during slice selection. Figure 3a qualitatively sketches the variation in CT for a second order field. One possible solution for selection of multiple slices with constant CT and equidistant spacing might be a respective shift of the nonlinear encoding field for every selection, resulting in shifted copies of the original slice. However, as slice thickness also varies along the curved slice-dimension, adjacent slices would no longer fit together without overlap, thus preventing an efficient coverage. As an alternative, individual adaptation of the RF-pulse bandwidth and frequency increment for every single slice would allow a defined center thickness and slice position in combination with complementary slice shapes. Figure 3b demonstrates the principle. The individual RF-pulse bandwidths BW and frequency offsets for a given center thickness CT and inter-slice spacing can either be calculated from an analytical field description or from a reference field map.

For demonstration purposes, the multi-slice ExLoc concept was implemented on a 3T MAGNETOM Trio Tim system (Siemens, Erlangen, Germany) with a PatLoc gradient insert which generates fields of the form $x^2$ and $2xy$ in addition to the standard linear gradients [2]. The available field components of first and second order allow adaptation of slice curvature, orientation and position along one slice dimension. Data acquisition was performed with an adapted spin echo sequence. Individual bandwidths and frequency offsets were automatically calculated by the sequence for every single slice based on an analytical description of the field components. To visualize the shape of the selected slices, cross-sections were imaged with linear encoding perpendicular to the excited slices. Prior to in-vivo imaging, the sequence was evaluated for peripheral nerve stimulation and acoustic noise to meet IRB guidelines [3].

Results and Discussion

Fig. 4 presents cross sections of stacks of slices within a homogenous phantom for conventional multi-slice selection (a) and with bandwidth and frequency offset adaptation for every RF pulse (b). With the latter, slices exhibit constant CT and inter-slice distance. A stack of 7 curved slices (TR/TE: 600/25 ms; matrix: 256 × 256; FOV: 29.8 × 23.7 × 21.0 cm; CT: 8.8 mm) is presented in Fig. 5. The stack is oriented along the occipital lobe (a), resulting in a stepwise penetration into the brain (b - h). Compared to conventional planar multi-slice imaging, spatially separated brain regions with similar distance from the skull can now be imaged in the same slice. This may allow, for example, a more direct comparison of the hemispheres in neuroimaging. In multi-slice mode the individual slices are encoded with different combinations of the nonlinear fields. This causes a variation in resolution between the slices, combined with different FOV sizes along the curved dimension.

As demonstrated in phantom and in vivo, ExLoc enables multi-slice imaging with constant center thickness and inter-slice spacing. This allows efficient coverage also for extended volumes, which can not be described with a single curved slice. In future work, we will also apply the multi-slice ExLoc concept to echo planar imaging for functional imaging.

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References