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The clinical relevance of distortion correction in presurgical fMRI at 7 T

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ABSTRACT

Presurgical planning with fMRI benefits from increased reliability and the possibility to reduce measurement time introduced by using ultra-high field. Echo-planar imaging suffers, however, from geometric distortions which scale with field strength and potentially give rise to clinically significant displacement of functional activation.

We evaluate the effectiveness of a dynamic distortion correction (DDC) method based on unmodified single-echo EPI in the context of simulated presurgical planning fMRI at 7 T and compare it with static distortion correction (SDC). The extent of distortion in EPI and activation shifts are investigated in a group of eleven patients with a range of neuropathologies who performed a motor task. The consequences of neglecting to correct images for susceptibility-induced distortions are assessed in a clinical context.

It was possible to generate time series of EPI-based field maps which were free of artifacts in the eloquent brain areas relevant to presurgical fMRI, despite the presence of signal dropouts caused by pathologies and post-operative sites. Distortions of up to 5.1 mm were observed in the primary motor cortex in raw EPI. These were accurately corrected with DDC and slightly less accurately with SDC. The dynamic nature of distortions in UHF clinical fMRI was demonstrated via investigation of temporal variation in voxel shift maps, confirming the potential inadequacy of SDC based on a single reference field map, particularly in the vicinity of pathologies or in the presence of motion. In two patients, the distortion correction was potentially clinically significant in that it might have affected the localization or interpretation of activation and could thereby have influenced the treatment plan.

Distortion correction is shown to be effective and clinically relevant in presurgical planning at 7 T.

1. Introduction

Functional brain networks can be rapidly and non-invasively localized using functional MRI (fMRI), making it an attractive modality in presurgical mapping in patients with brain tumors and epilepsy. The aim is to allow neurosurgeons to identify relevant anatomical landmarks (e.g. the central sulcus for the motor function), which demarcate brain regions that should be preserved in the excision of pathological tissue or epileptogenic foci in order to avoid post-surgical deficits. Functional localization is of special interest in diseased brains, in which normal cortical anatomy may be distorted by the pathology due to mass effects, hindering the easy identification of these landmarks (Lehericy et al., 2000). The most common tasks recruit motor, somatosensory, language, and memory function, and good correlation has been demonstrated between fMRI results and 'gold standard' methods (Adcock et al., 2003; Binder et al., 1996; Kashida et al., 2016; Stevens et al., 2016).

Presurgical planning with fMRI benefits from increased reliability and the possibility to reduce measurement time introduced by using ultra-high field (UHF), due to the higher signal-to-noise ratio (SNR) and increased blood-oxygen-level dependent (BOLD) contrast (Beisteiner et al., 2011; Triantafyllou et al., 2005; van der Zwaag et al., 2009). Echo-planar imaging (EPI) suffers, however, from geometric distortion mostly in the phase-encoding direction (Jezzard and Balaban, 1995) in the presence of susceptibility-related field inhomogeneities which lead to mislocalization of activation (Cusack et al., 2003). Distortion scales linearly with field strength, making it important that an accurate correction be used at UHF. This is of

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particular relevance in the context of presurgical planning, in which potential shifts in activation caused by geometric distortion may lead to misidentification of essential functional landmarks and impact the surgical approach (Dymerska et al., 2014; Robinson et al., 2010). Therefore, accurate determination of these landmarks is of utmost importance prior to surgery. During the surgical procedure itself, cortical tissue displacements greater than 10 mm have been reported due to brain surface deformation following craniotomy. However, to mitigate this problem, relevant anatomical landmarks or surfaces determined *a priori* may be labelled correctly after bone flap removal to enable tracking of deformation during the operation (Hill et al., 1998; Roberts et al., 1998).

Distortions in fMRI are typically corrected with a "static" approach, in which a map of local deviations from the static magnetic field, B_0, is acquired prior to or subsequent to fMRI runs (Jezzard and Balaban, 1995; Robinson and Jovicich, 2011). This approach fails, however, to capture changes in B_0 which occur during the fMRI acquisition due to motion (Jezzard and Clare, 1999), respiration (Zahneisen et al., 2014; Zeller et al., 2014), or heating of the gradient system (Foerster et al., 2005).

One dynamic approach to correcting susceptibility-related distortions is to model susceptibility-by-movement effects (Andersson et al., 2001), although this neglects non-motion sources such as respiration. Alternatively, a time-series of B_0 field maps can be extracted from the phase of the fMRI data if a multi-echo EPI sequence is used (Hutton et al., 2002; Poser and Norris, 2009; Visser et al., 2012; Weiskopf et al., 2005). This, however, constrains the achievable spatial resolution, particularly with short T_2^* at UHF. Field maps can also be derived from adjacent time points in single-echo EPI if the TE is 'jittered' between two values (Dymerska et al., 2016b). Alternatively, Hahn et al. (2009) and Ooi et al. (2013) proposed single-echo EPI-based dynamic approaches, in which field changes between a reference or mean volume and the rest of the EPI time series are calculated. Up to 3 T, these methods allow phase unwrapping to be avoided since phase difference values are typically within 2π. This is not the case at 7 T, however (Dymerska et al., 2016a). The Hahn et al. and Ooi et al. approaches also have the disadvantage that a second unwarping step is required to remove distortions present in the reference time point image, which requires a static field map. Marques and Bowtell (2005) and Lamberton et al. (2007) outlined how field maps can be derived from an unmodified, single-echo EPI time series if the non-B_0-related contributions to the total EPI phase (the receiver phase offsets (Robinson et al., 2011)) are known. This approach has been further developed to yield robust results for array coils at UHF and large motion (Dymerska et al., 2016a) but has not yet been applied in a clinical context. Brain tumors and post-operative sites are highly heterogeneous in composition, and can be expected to generate larger field offsets and higher gradients in the field than are observed in the general population, leading to large distortions and signal dropout. These can be anticipated to prove challenging to remove phase wraps from, due to signal voids (Robinson et al., 2016), and distortion-correct, due to the need for substantial interpolation and correct treatment of signal which is "piled up" or swapped across a boundary (Robinson and Jovicich, 2011).

Dynamic distortion correction (DDC) is applied in this study in a cohort of patients with diverse brain pathologies who performed a motor task at 7 T and compared with a static conventional approach based on gradient echo field mapping. The extent of distortions in EPI at UHF, the effectiveness of distortion correction in the presence of pathologies, and the potential clinical implications of carrying out presurgical planning on the basis of 7 T fMRI results without correcting the mislocalization of activation are assessed.

2. Materials and methods

This study was designed to assess the effectiveness of a dynamic correction of susceptibility-related distortions in simulated presurgical fMRI in a clinical population performing a motor task and compare it with a conventional static distortion correction (SDC) approach. The potential impact of the correction on a presurgical treatment plan was evaluated. The geometry of EPI images before and after distortion correction were compared with a distortion-free gradient echo (GE) reference scan within the primary target region – the motoric cortex. Mislocalization of activation due to distortion was identified by comparing functional maps generated with uncorrected and distortion-corrected data overlaid on a GE reference image.

2.1. Participants

Candidate patients were contacted by physicians from the Departments of Internal Medicine (Division of Oncology) and Neurosurgery of the Vienna General Hospital and from the Neurology Department of the Wilhelminenspital, Vienna, and the Neurosurgery Department of the Rudolfstiftung, Vienna. Written informed consent was provided by all participants, and the study was approved by the Ethics Committee of the Medical University of Vienna.

All 12 patients (mean age 46 ± 12 years old, 7 females) were in a good general state of health at the time of measurement and were able to perform the task. One female patient aged 62 with an oligoastrocytoma in the right parieto-frontal region was excluded from this study due to excessive motion. Patient demographics and clinical details are given in Table 1.

2.2. Task

Patients were asked to perform up to 10 runs (depending on tolerance) of a hand paradigm in a block design, except for one patient (P1), who performed an elbow task and P6, who only completed 9 runs

Table 1
Patient demographics and clinical information. Patient IDs were attributed in chronological data acquisition order and are used in subsequent images and descriptions in the text.

Patient ID	Age	Gender	Affected hand	Pathology
P1	58	F	R	Developmental venous anomaly, left insular cortex
P2	34	M	L	2 oligodendrogliomas grade II, 1 right frontal, 1 right central
P3	55	F	R	Secondary glioblastoma, left temporal
P4	37	F	R	Glioblastoma, left temporo-frontal
P5	52	F	L	Anaplastic astrocytoma grade III, right temporo-occipital
P6	30	M	L	Anaplastic astrocytoma, right frontal
P7	55	M	L	Oligoastrocytoma, right occipital, with multiple bilateral metastases
P8	58	F	R	Anaplastic oligodendroglioma grade III, left frontal
P9	33	F	R	Arteriovenous malformation, left hemisphere
P10	46	M	R	Suspected low grade glioma, precentral left
P11	34	M	L	Oligoastrocytoma, right frontal