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Susceptibility artefact correction using dynamic graph cuts: Application to neurosurgery

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ABSTRACT

Echo Planar Imaging (EPI) is routinely used in diffusion and functional MR imaging due to its rapid acquisition time. However, the long readout period makes it prone to *susceptibility artefacts* which results in geometric and intensity distortions of the acquired image. The use of these distorted images for neuronavigation hampers the effectiveness of image-guided surgery systems as critical white matter tracts and functionally eloquent brain areas cannot be accurately localised. In this paper, we present a novel method for correction of distortions arising from susceptibility artefacts in EPI images. The proposed method combines fieldmap and image registration based correction techniques in a unified framework. A phase unwrapping algorithm is presented that can efficiently compute the B_0 magnetic field inhomogeneity map as well as the uncertainty associated with the estimated solution through the use of dynamic graph cuts. This information is fed to a subsequent image registration step to further refine the results in areas with high uncertainty. This work has been integrated into the surgical workflow at the National Hospital for Neurology and Neurosurgery and its effectiveness in correcting for geometric distortions due to susceptibility artefacts is demonstrated on EPI images acquired with an interventional MRI scanner during neurosurgery.
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1. Introduction

Echo Planar Imaging (EPI) provides high temporal resolution and is routinely used in functional magnetic resonance imaging (fMRI) and diffusion weighted imaging (DWI) sequences. In recent years, interventional MRI (iMRI) is fast emerging as a popular imaging choice for image-guided neurosurgery. The high spatial resolution, excellent soft tissue contrast and the lack of ionising radiation makes iMRI an attractive imaging option for guiding interventions. Furthermore, along with conventional structural imaging, current commercial iMRI scanners can also perform diffusion-weighted and functional imaging which allows for intra-operative visualisation of eloquent brain areas and critical white matter tracts along with the surgical target areas. Modern iMRI scanners use EPI sequences to acquire DWI images during neurosurgery, which can be then used for localisation of critical white matter tracts that lie close to the surgical field. EPI performs fast imaging by sampling the selected slice with one excitation pulse and fast gradient blipping. However, this results in very low bandwidth in the phase encoding direction, which makes EPI images highly susceptible to small perturbations of the magnetic field, giving rise to various artefacts because of the magnetic field inhomogeneities. The primary source of *susceptibility artefacts* is the difference in magnetic susceptibility between various tissues being imaged. In the context of neuroimaging, this leads to severe geometric and intensity distortions in areas like the brain stem, frontal and temporal lobes. The distortions are especially severe as the surgically resected cavity contains air and induces high susceptibility differences by introducing an air-tissue interface and leading to large distortions around the area of resection.

The National Hospital for Neurology and Neurosurgery (NHNN) in London is one of the leading centres for surgical management of focal epilepsy in the UK. Epilepsy is a common and debilitating neurological disorder and around one-third of patients with focal epilepsy are refractory to treatment with anti-epileptic drugs.

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The majority have temporal lobe epilepsy for which anterior temporal lobe resection is a well-established and effective treatment (Wiebe et al., 2001). An important source of morbidity during anterior temporal lobe resection arises due to damage to a white matter tract called the optic radiation during the surgical intervention. This can lead to severe visual field deficits that can result in a significant loss of vision, even if the patient is seizure free after surgery. Since the optic radiation cannot be identified visually during surgery without appropriate imaging, its accurate localisation and real-time display could be crucial in improving the surgical outcome for patients undergoing anterior temporal lobe resection. Recent studies have shown that the use of diffusion weighted EPI images along with structural images in non-rigid registration algorithms can accurately localise brain structures of interest during neurosurgical procedures (Daga et al., 2012; Winston et al., 2011). There is also an interest in performing tractography on interventional DWI images to segment white matter structures of interest (Chen et al., 2009; Sun et al., 2011; Andrea et al., 2012; Cardoso et al., 2012). Hence, it is important to accurately compensate for susceptibility artefacts to be able to efficiently use EPI images for neuronavigation.

Correction of susceptibility induced distortions in EPI images falls under two broad categories: fieldmap estimation and non-linear image registration. The fieldmap estimation approach is the estimation of B_0 magnetic field inhomogeneity at every voxel from phase images acquired at different echo times as demonstrated in (Jezzard and Balaban, 1995; Funai et al., 2008; Jenkinson, 2003). It was shown in Wu et al. (2008) that correction of susceptibility artefacts by fieldmaps can be inaccurate in regions of high field inhomogeneity. This is especially critical when correcting EPI images that are acquired using interventional MRI during a neurosurgical procedure. The area of resection often lies in close proximity to critical white matter tracts and as the neurosurgical procedure progresses, information on the exact current location of the tract is beneficial for surgical planning. However it is exactly at the resection margin with the brain/air interface that the B_0 magnetic field is most inhomogeneous and produces maximum geometric and intensity distortions. A popular alternative to fieldmaps is to use intensity based non-rigid image registration techniques to register the distorted EPI image to a high resolution undistorted T1-weighted MRI (Kybic et al., 2000; Merhof et al., 2007; Tao et al., 2009; Huang et al., 2008). However, the EPI images acquired interventionally have low signal-to-noise ratio and suffer from various artefacts which makes intensity based image registration challenging. A recent work by Irfanoglu et al. (2011), an extension of Jenkinson et al. (2004), proposed the generation of fieldmap estimates from structural images, which was then used to sample a non-uniform B-spline grid for an elastic registration based correction step. This procedure, however, is difficult to apply in the interventional setting due to the complex physical environment around the resection area and the need for tissue segmentation maps. Registration based approaches which require acquisition of an additional EPI image have also been proposed (Studholme et al., 2000; Ruthotto et al., 2012).

Additionally, any proposed solution must work within the stringent time constraints of a neurosurgical procedure. The current patient transfer time from the intra-operative scanner, after an imaging session, to the surgical bed at NHNN is between 7 and 9 min. *All* image analysis tasks must be performed within this time window to ensure no extra time is added to the surgery.

This work meets the aforementioned challenges by combining the fieldmap and image registration based correction approach in a unified scheme. The main idea behind the proposed work is a novel phase unwrapping algorithm that can also compute the uncertainty associated with the estimated fieldmap. The deformation field generated from the fieldmap correction step and the associated uncertainty measure are used to initialise and guide a subsequent image registration step. The overall workflow can be visualised as Fig. 1. The proposed work is also suitable to be used within the neurosurgical environment due to use of fast optimisation provided by graph cuts.

The main contributions of this work are:

- A phase unwrapping algorithm using dynamic graph cuts that also determines the uncertainty associated with the estimated solution.
- A registration algorithm that can be utilise the uncertainty information estimated from the phase unwrapping step to refine the results in areas where the fieldmap estimates are likely to be incorrect.
- Demonstrate the use of the proposed method during neurosurgery at NHNN, London on 13 patients within the time constraints of the intervention.

The paper is organised as follows: we describe our iMRI setup and NHNN in Section 2. Section 3 describes the noise model in the MRI phase images and highlights the assumptions of our phase model. Section 4 describes the graph cuts based phase unwrapping method. Section 5 describes how uncertainty information can be computed from the phase unwrapping step and can be used with an image registration method to further improve results. Validation on synthetic and clinical datasets are described in Sections 6.1 and 6.2 respectively.

2. Interventional MRI setup

The iMRI setup at NHNN, London consists of a 1.5 T Siemens (Erlangen, Germany) Espree MRI machine. There is a dedicated operating room 8 channel MR head coil which incorporates a surgical headrest. The operating table is fitted with an MR compatible head-holder and is placed outside the 5 Gauss line during surgery which enables the surgeons to perform the procedure using standard non-MR-compatible surgical instruments. The table can interface with the MR scanner to allow the patient to be moved in and out of the scanner for intra-operative imaging. The facility is equipped with a BrainLAB VectorVision® Sky neuronavigation system which provides real-time tracking of surgical markers and tools, *global* image registration and visualisation facilities. The operating room is also equipped with an Opmi Pentero confocal surgical microscope (Carl Zeiss), supporting the injection of colour overlays from the navigation system. The location of the microscope's focal point is tracked using the navigation system and an array of four infra-red reflectors mounted on the microscope's optical head. A snapshot of the iMR surgical room is shown in Fig. 2.

The current interventional workflow at NHNN acquires iMR images at two timepoints: after performing the craniotomy and after the temporal pole resection. Structural and diffusion weighted images are acquired and are corrected for gradient non-linearities and susceptibility artefacts (using the proposed method). The images are then used as target images in a non-rigid image registration scheme presented in Daga et al. (2012), which uses both the structural and diffusion weighted images in a bivariate similarity measure. The deformation field obtained from the image registration step is used to propagate the pre-operatively parcellated white matter tracts to the intra-operative geometry for neuronavigation. Susceptibility artefacts create severe distortions around the area of resection in the diffusion weighted images and it is important to correct for them for accurate image registration. In addition, the neurosurgery environment is complex and there are stringent time constraints. As already mentioned, the patient transfer time after an imaging session to the surgical bed

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