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# Augment low-field intra-operative MRI with preoperative MRI using a hybrid non-rigid registration method

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ABSTRACT

*Background:* Preoperatively acquired diffusion tensor image (DTI) and blood oxygen level dependent (BOLD) have been proved to be effective in providing more anatomical and functional information; however, the brain deformation induced by brain shift and tumor resection severely impairs the correspondence between the image space and the patient space in image-guided neurosurgery.
*Method:* To address the brain deformation, we developed a hybrid non-rigid registration method to register high-field preoperative MRI with low-field intra-operative MRI in order to recover the deformation induced by brain shift and tumor resection. The registered DTI and BOLD are fused with low-field intra-operative MRI for image-guided neurosurgery.
*Results:* The proposed hybrid registration method was evaluated by comparing the landmarks predicted by the hybrid registration method with the landmarks identified in the low-field intra-operative MRI for 10 patients. The prediction error of the hybrid method is $1.92 \pm 0.54$ mm, and the compensation accuracy is $74.3 \pm 5.0\%$. Compared to the landmarks far from the resection region, those near the resection region demonstrated a higher compensation accuracy (*P*-value = .003) although these landmarks had larger initial displacements.
*Conclusions:* The proposed hybrid registration method is able to bring preoperatively acquired BOLD and DTI into the operating room and compensate for the deformation to augment low-field intra-operative MRI with rich anatomical and functional information.


*Abbreviations:* BOLD, blood oxygen level dependent; FA, fractional anisotropy; FEM, finite element method; FFD, free-from deformation; GUI, graphic user interface; IAD, image aided diagnosis; iMRI, intra-operative magnetic resonance imaging; RPM, robust point matching; XFEM, extended finite element method.

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## 1. Introduction

Neuronavigation has significantly improved the accuracy and safety of surgery. However, intra-operative brain shift and tumor resection can cause significant brain deformation, which renders the preoperatively acquired images inaccurate in reflecting the scenario in the operating room [1,2]. Currently, high-field intra-operative magnetic resonance imaging (iMRI) systems can offer high quality anatomic and/or functional images for neuronavigation before and during operations. Despite its remarkable advantages, high-field iMRI system is still unpopular in clinical practice due to its prohibitive cost and stringent requirement for the associated facilitates [3,4]. On the contrary, a low-field iMRI system has a moderate cost and can be easily deployed in the operating room although it only offers limited anatomical images. Via a low-field iMRI system, the pre-operatively acquired functional images might be intra-operatively used in the operating room. The above considerations motivate us to find a way to correct the deformation in the functional images acquired from the high-field MRI system to integrate the functional images with the low-field iMRI.

Non-rigid registration (NRR) is expected to be a promising technique in accounting for brain deformation. Non-rigid registration can be divided into three categories: intensity-based methods, point-based methods, and their combination. The intensity-based methods measure the similarity of the intensity between the reference image and the floating image using suitable metrics such as Cross-Correlation [5], Mutual Information [6], Optic Flow [7], and Histogram Dispersion [8]. Intensity-based methods can utilize the full image content, but are susceptible to local intensity change. The difficulties in aligning preoperative MRI with low-field iMRI are the poor quality of the low-field iMRI and the missing data induced by the tumor resection. Point-based registration method is well known for its robustness against noise and outliers. Point-based registration method is not capable of fully recovering the entire deformation without enough feature points, but is effective in locally refining the registration, which motivates us to develop a hybrid non-rigid registration method to deal with tumor resection. A hybrid registration method can incorporate both the intensity information of the pixels or voxels and the geometrical information of the feature points. Cachier et al. [27] introduced an iconic feature based (IFB) algorithm and positioned it between the intensity and geometry based registration method. This hybrid method used both intensity and geometrical distance by alternating correspondence estimation based on intensity and the transform by fitting the pairs. They generalized the existing registration methods and produced a new energy for IFB registration. The comparison with other registration approaches demonstrated the advantage of this hybrid method. Rohr et al. [28] developed a hybrid method to align gel electrophoresis images for protein analysis. They localized landmarks using a model fitting technique and then incorporated these landmarks into an elastic registration method. They conducted experiments on the electrophoresis images of different levels of complexity. The results showed significant improvement brought by the landmarks. Lu et al. [29] presented a hybrid non-rigid registration method to correct distortion in Diffusion Weighted Imaging (DWI). This method incorporated automatically detected landmarks into the diffeomorphic Demons algorithm with Mutual Information as the metric and Gaussian radial basis functions as the transform. Compared to a pure intensity based method, the proposed hybrid method demonstrated better distortion correction of DWI.

Compensating for the deformation caused by tumor resection is a very challenging problem. Lots of studies employed the finite element method (FEM) to deal with tumor resection. Miga et al. [9] investigated tissue retraction and resection using sparse available data in the operating room and a finite element model. They used a two-step method: (1) remove tissue volume by manual deletion of model elements that coincide with the targeted zone and then (2) apply boundary conditions to the new surfaces created during the excision process. Vigneron et al. [10] used the extended finite element method (XFEM) to model surgical cuts, retractions and resections. XFEM eliminates the computationally expensive remeshing for the standard finite element method. The experiment on the simulation of 2D retraction demonstrated the effectiveness of this method. Based on the bijective Demons algorithm, Risholm et al. [11] presented a registration framework to handle tumor resection. They used a level set method to automatically detect resected regions. Also, Risholm et al. [12] presented an elastic FEM-based registration method, but this method was limited to the registration of 2D pre- and intra-operative images, where a superficial tumor has been resected. In our previous work [13], we also developed a FEM-based registration method to deal with tumor resection. This method treated the resection region as one unknown variable and resolved it using a Nested Expectation and Maximization strategy. Ding et al. [14] presented a semi-automatic method based on post-brain tumor resection and laser range data. Vessels were identified in both preoperative MRI and laser range image, and then the Robust Point Matching (RPM) method [15] was used to force the corresponding vessels to exactly match each other under the constraint of the bending energy of the whole image. Zhuang et al. [23] introduced a similar 3D laser range scanner into the operating room to capture the deformed cortical surface. They used the surface deformation as a boundary condition to drive a finite element linear elastic model to estimate the entire brain deformation. In our previous work [16], we developed a hybrid non-rigid registration method and have successfully applied it to the registration of the cine image with the Delay-Enhanced Cardiac MRI. In our previous work, surgeons were responsible for providing the point-to-point correspondence of the feature points. Since it is not easy to identify corresponding feature points in the vicinity of the tumor in the preoperative MRI and iMRI, in this work, we extend our previous work to allow surgeons to select tumor boundary and resection boundary without requirement for point-to-point correspondence. The extended 3D hybrid method not only inherits the benefits coming from both image intensity and feature points, but also removes the requirement for point correspondence. Compared to the FEM-based methods, the proposed method does not need brain segmentation and mesh generation, two necessary steps to build a finite element model, and therefore is more suitable for clinical practice. After registration, the recovered deformation serves