Improved visualization of brain anatomy and function, for surgery, through real-time non-rigid registration

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Objective

Recent advances in functional MRI (fMRI) and diffusion tensor imaging (DTI) enable the delineation of eloquent cortical areas and the underlying white matter tracts that connect them. Information from each of these modalities can dramatically impact the decision to operate, but the use of pre-surgical data for on-line, intraoperative decision making is hampered by the on-going changes in patient anatomy during surgery. Intraoperative magnetic resonance imaging has been developed to enable ready visualization of intraprocedural changes in the configuration of the patient, and to enable improved surgical navigation, monitoring and targeting [1]. We propose to increase the intraoperative utility of data acquired preoperatively by compensating, in real-time, for brain deformation, or shift, during surgery.
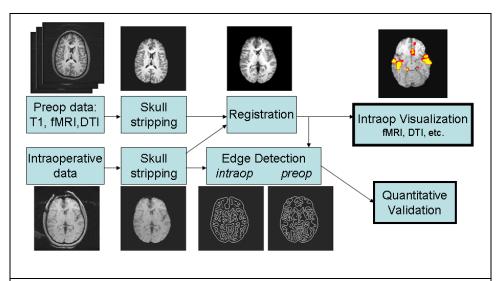
Methods

In this study, the ongoing changes in patient anatomy inducted by surgery were compensated through biomechanics-based non-rigid registration. Figure 1 illustrates the processing pipeline used. We first removed extra-cerebral tissue, a procedure called skull stripping, by computing the intracranial cavity segmentation for both the preoperative and the intraoperative volumes and then masking the original data. To achieve an initial coarse alignment, we used rigid body registration based on mutual information to align the preoperative data to the intraoperative data. The intraoperative brain deformation for non-rigid registration was computed using the specialized nonlinear finite element algorithms we previously verified for realistic simulation of the physics of brain (and other soft tissue) deformation behavior [2]. The algorithms were implemented on a Graphics Processing Unit (GPU), which facilitates an order of magnitude increase in computational speed in comparison to computations on a personal computer processor. The finite element algorithms for simulation of the brain deformation behavior were integrated with the previously validated procedures for analysis of fMRI and DTI for image-guided neurosurgery, which enabled application of the brain deformation predicted using these algorithms to warp (i.e. non-rigidly register) the preoperatively obtained fMRI and DTI images to the brain anatomy during surgery. For evaluation of the registration accuracy using automatically generated features (one case of craniotomy induced brain shift was studied), an edge detection filter as proposed by Canny [3] was applied to compute the salient edges of the intraoperative and the registered preoperative images. Then the 95% Hausdorff distance between the edges in these images was computed in a region of interest surrounding the resection, as published in [4].

Results

Our finite element algorithm for realistic simulation of the physics of brain deformation predicted the intraoperative brain deformation with a computation time of 3 seconds. The maximum 95% Hausdorff distance between the automatically detected salient edges in the registered and intraoperative images was 2.58 mm. This implies a very good overall registration, of subvoxel accuracy, given the intraoperative voxel size of 0.9x0.9x2.5 mm. Preoperative functional imaging and diffusion tensor imaging was warped using the deformation field generated by the finite element algorithms. An example of warped preoperative fMRI aligned with intraoperative MRI is shown in figure 1.

Conclusion

Non-rigid alignment of preoperative MRI significantly increases its utility for intraoperative decision making. Our proposed biomechanics-based algorithm is able to compensate for brain shift during surgery in real time, and with very good overall registration accuracy. Combined with the availability of intraoperative MRI, preoperative data can be warped and adapted to the current configuration of the patient's brain when required by the surgeon. Such visualization may dramatically improve surgical decision making, potentially leading to a more complete resection of diseased tissue with fewer adverse neurological consequences.

Figure 1. Illustration of visualization of preoperative fMRI aligned with intraoperative MRI. Preoperative MRI is segmented and aligned to intraoperative MRI using a biomechanical registration algorithm. fMRI from a Stroop test is shown fused to the intraoperative MRI using the computed registration transform. Assessment of alignment quality is done by comparison of automatically generated edges.

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