Streamlines non-linear registration using MR-Ultrasound for intra-operative brain shift correction

François Rheault[1], Louis Collins[2, 3], Maxime Descoteaux[1]

1. Computer Sciences department, Sherbrooke University, Canada
2. Biomedical Engineering department, McGill University, Canada
3. Neurology and Neurosurgery department, McGill University, Canada

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Purpose: White matter (WM) tractography is increasingly being used for neurosurgical intervention. By observing disruption or displacement of well-known WM bundles by tumor growth [1], changes in surgical approach and resection can be made to minimize risks. A neurosurgeon's awareness to patient's structural connectivity allows for intra-operative adjustments. Unfortunately, once the craniotomy is performed, brain structures might move because of pressure variations (brain shift). Various approaches exist to maintain the images' integrity throughout the surgery. The use of ultrasound (US) as a baseline for registration is a cost effective and real-time alternative with adequate results for the needs of neurosurgeons in the operating room (OR) [2]. At the moment, this method is only applied to anatomical images (T1), while the precomputed tractography of the patient is not moved or deformed. Consequently, tractography is often limited to planning stages instead of real-time OR use.

Methods: By applying displacement vectors from the intra-operative US registration to deform the patient's tractogram, neurosurgeons are able to visualize the anatomical images as well as the structural connectivity throughout the whole procedure. Tractography consists of a deterministic whole brain tracking using fODFs of order 8, seeding and masking was done using a fractional anisotropy (FA) threshold [3]. To facilitate computation streamlines were generated in voxel space. Nine eloquent pathways (bundles) were segmented for visualization purpose as well as increasing the amount of information available to neurosurgeons. The non-linear registration obtained from the US consists in a grid with the same dimensions as the anatomical image and filled with displacement vectors. Instead of using data from intra-operative US registration, a synthetic deformation field [4] was used to simulate the brain shift. Then, the deformation field was applied to the T1 and the tractogram, resulting in streamlines with an appropriate position when visualized with the T1. Considering that points' 3D coordinates are not integer and that the deformation field is piecewise smooth, a linear interpolation was used along each dimension of the displacement vector.

Results: When the original WM bundles are visualized with the warped T1, streamlines with an incorrect path can be found around the tumor. In some places, the disparity is striking, such as at the ventricles frontiers where some invalid streamlines go through cerebrospinal fluid as seen in figure 1. Our method could enable neurosurgeons to visualize deformed bundles without discrepancy between the T1 and the streamlines. By trying various synthetic deformation fields, we observed that some deformation fields have a dominant direction and result in a greater displacement of streamlines going in a perpendicular direction. For example, the cingulum bundle's main direction is in the Y axis, a deformation mainly in the Y axis does not particularly change the path of the bundle while a deformation in the X or Z axis results in path changes easier to perceive (fig 2). Storing streamlines in voxel space enabled an efficient computation, fast enough to use in the OR, using an addition of each 3D point with the appropriate displacement vector.

Conclusion: WM tractography is essentially used as a planning tool, mainly because neurosurgeons' mental mapping of the preoperative tractography to the patient shifted brain is burdensome. As a solution, we developed a method to extend intra-operative US brain shift correction to segmented bundles. This approach aims to provide neurosurgeons with reliable information about WM structural connectivity while in the OR. The next step is to use the method with genuine US deformation fields obtained during a surgery.

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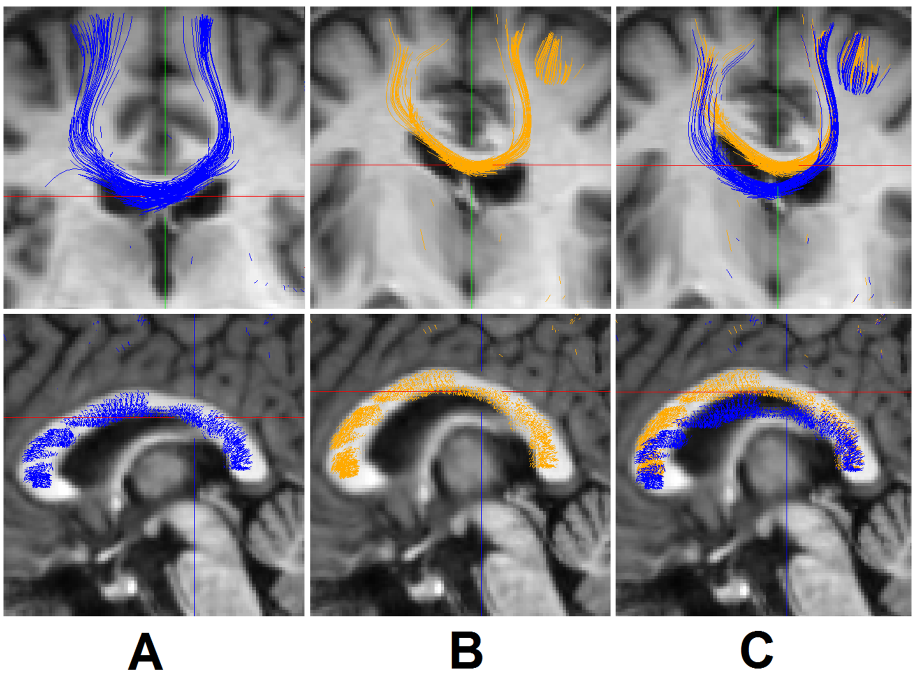

Figure 1: Intersecting streamlines from the corpus callosum with 3D planes.
A) original datasets, B) deformed datasets and C) original (blue) and deformed (orange) corpus callosum over the warped T1.

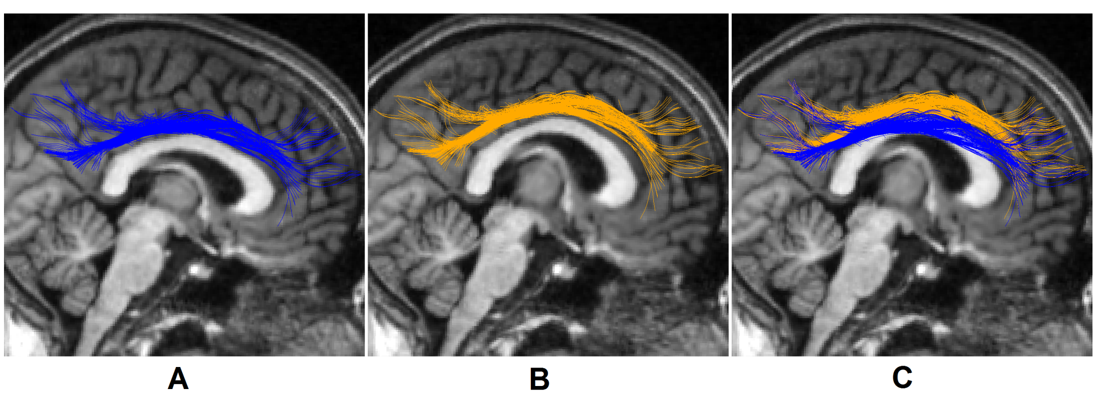

Figure 2: 3D view of the the segmented cingulum.
A) original datasets, B) deformed datasets and C) original (blue) and deformed (orange) cingulum over the warped T1.