A Markov-Random-Field-Based Biomechanical Tumor Growth Model for Atlas-Based Segmentation of Brain Tumor Images

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Abstract—**We show the application of a new technique for soft tissue deformations to brain atlas images. The proposed method consists of computing local voxel displacements based on a Markov Random Field approach, taking into account biomechanical tissue properties. The technique is designed for atlas-based segmentation of brain tumor images within a clinically-oriented workflow. It offers the possibility to modify a healthy brain atlas by introducing a tumor seed and grow the tumor to its approximate patient tumor shape, simulating mass effect on the surrounding tissues. Subsequently the patient image can be implicitly segmented by registering the modified tumor-bearing brain atlas to the pathologic patient image.**

I. INTRODUCTION

FOR image analysis and biomechanical modeling the accurate segmentation of important brain structures is of significant interest. An established way to classify tissue types in healthy humans is to do atlas-based segmentation of different tissue types like grey matter (GM), white matter (WM) and cerebrospinal fluid (CSF) [1]. However, in case of brain tumor images this approach fails due to the missing tumor prior in the atlas image. Solutions to this problem have been suggested by several groups [2-4]. The common idea is to introduce a tumor seed into the atlas and grow it to its approximate patient-specific shape using different methods. Cuadra et al. [2] use a simple model of lesion growth without any biomechanical justification, while Mohamed et al. [3] use a more complex finite element model (FEM) considering mechanical tissue properties. Zacharaki et al. [4] employ a linear elasticity model on regular grids. A concise overview of the state of the art was presented by Angelini et al. in [5].

FEM-based methods offer the desired possibility to incorporate mechanical properties into the tumor-induced deformations. However, they suffer from the need to create a volumetric mesh and usually require a significant amount of computation time. Furthermore, the mesh-free method suggested in [4] runs on a subsampled version of the image in order to circumvent the high computational cost.

II. MATERIALS AND METHODS

We suggest a clinically-oriented and mesh-free method to model soft-tissue deformations, which is applicable to atlas-based segmentation of brain tumor images. The deformation technique is based on finite differences in a local neighborhood of each voxel using Markov Random Fields (MRF). The idea was initially proposed by Seiler et al. in [6] and applied to 2-dimensional atlas-based segmentation of brain tumor images in [7]. Here we show the extension of the tumor growth model to 3D as well as preliminary results on patient data.

A. Hierarchical Displacement Model

The general idea to model soft tissue deformations is to minimize an energy function of the type

$$U_{total} = U_{prior} + U_{observation} \tag{1}$$

U_{prior} represents the biomechanical information of the brain tissues and $U_{observation}$ introduces boundary conditions. Minimization of these energies is done in cliques of a neighborhood system surrounding a center voxel. The local tissue characteristics are based on their Young's modulus. The minimization of the chosen energy function yields the tumor-induced growth and deformation according to the given tissue characteristics and boundary conditions.

The displacement model is applied to the atlas image in a hierarchical way, which offers the possibility to use fast and stable local optimizers. As a local optimizer, iterative conditional modes (ICM) is used to find the best solution at each level of hierarchy.

B. Application to Tumor Growth Modeling

We assume a radial, outward pushing force of the tumor. The growth is performed in an iterative way in order to circumvent warping problems. When the desired patient tumor shape is attained, tumor growth is stopped. We want to emphasize that this deformation method is not intended to be a viable tumor growth model, but should be rather considered as a fast and simple, yet biomechanically justified technique to introduce tumor-induced deformations into an atlas image. This modified atlas image later serves as input for non-rigid registration to the pathologic patient image in order to recover the remaining deformations and thus, implicitly segment the different tissue types.

III. RESULTS

As a reference to demonstrate the modeling results, we chose the freely available SRI24 atlas [8]. This average atlas is well-suited for the intended registration purpose thanks to its sharpness.

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In figure 1 a 3D volume rendered image of the modified atlas label map with tumor is shown. The initial and the final step of the tumor growth and tissue displacement process are depicted. At the top, a rendering of the atlas with the initial tumor seed is shown. For better visualization it is cut open at the tumor seed location. The picture in the middle shows the same atlas rendering at the final iteration of the displacement process. It can be observed how the surrounding tissues are deformed. Despite the radially outward pushing tumor, the deformation is not exactly circular due to the different tissue characteristics as can be seen from the axial zoom image in the middle row of figure 1. The bottom part of figure 1 presents the magnitude of the displacement vector field (DVF) applied to each voxel in the 3D image. The displacement is largest inside the tumor area, but also the surrounding tissue are affected. The impact of the tissue displacement is decreasing, the further the voxels are away from the current tumor region.

The 4 different labels for WM, GM, CSF and tumor can be used to segment the patient image after application of a non-rigid registration technique.

IV. Discussion and Conclusion

A simple and clinically-oriented method to deform brain tissues in an atlas image was presented. This method can be used as an initialization step to modify a healthy brain atlas in order to be able to perform atlas-based segmentation of brain tumor images. The atlas labels can be warped to the patient image with the deformation field, which is obtained using non-rigid registration techniques for matching the modified atlas to the pathologic patient image.

MRF approaches are well-suited for parallelization which offers the possibility to significantly speed up the deformation process in the future by exploiting GPU-based computations.

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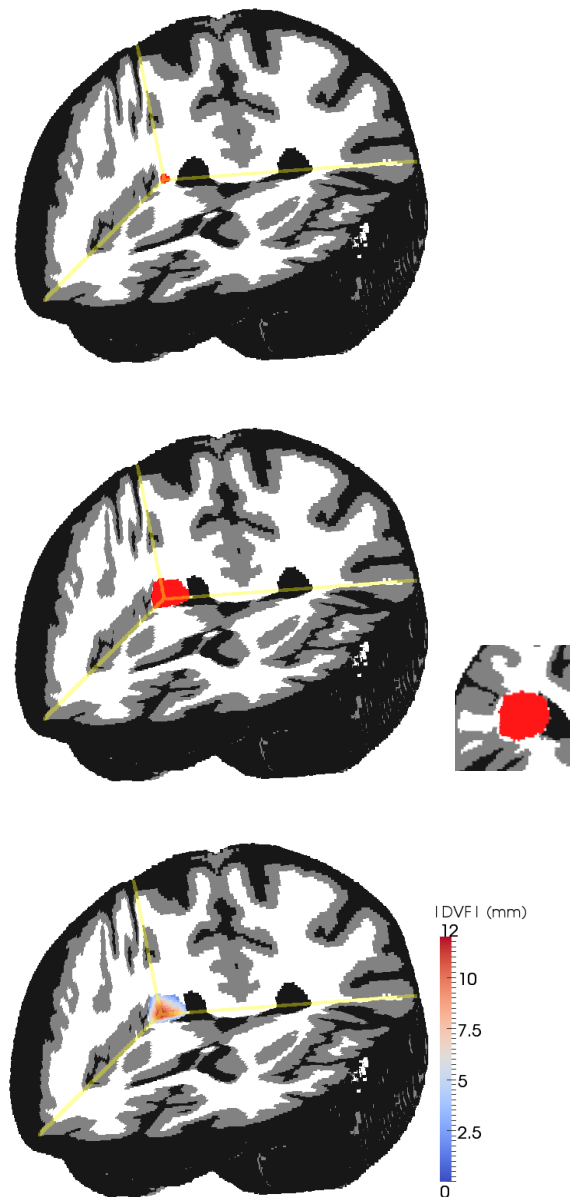
Fig. 1. 3D volume rendering of the modified SRI24 atlas. CSF is black, grey matter grey, white matter white and the tumor is drawn in red. From top to bottom: Atlas with tumor seed, modified atlas after 6th growth iteration and zoom on the tumor region in axial view, magnitude of the DVF at each voxel position.