Non-linear Intraoperative Correction of Brain Shift with 1.5 T Data

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Abstract. Intraoperative brain deformation (brain shift) induces a decrease in accuracy of neuronavigation systems during surgery. In order to compensate for occurring deformation of brain tissue, registration of time-shifted MR image sequences has to be conducted. In this paper we present a practical application of a novel approach for non-linear registration of medical images. The algorithm has been already tested with 0.2 T data. In this work we have performed a comprehensive comparative registration study with pairs of pre- and intraoperative 1.5 T scans of brain tumor patients. Additionally, a new system for data visualization was developed, which was specifically designed for the purpose of intraoperative inspection.

1 Introduction

The extent of brain shift has been intensively investigated by different research groups presenting various methods within the last years. In order to analyze and compenstate for this phenomenon, one can perform a registration of pre- and intraoperative brain images. Non-rigid registration of medical data was investigated first in [1]. Among the various registration approaches that have been developed over the last years, pure voxel-based algorithms form the most significant group. As an advantage they carry out registration without any fiducial markers and explicit segmentation of corresponding features. These approaches are based on the intensity information only [2,3]. Another mathematical concept has also been developed to model the behavior of the brain in a non-linear way during surgery [4,5]. However, none of these algorithms has been routinely applied in clinical practice. This is mostly related to the high computation time needed for the registration, which makes their application critical during surgery.

Another possibility to analyze brain shift by registration is based on applying specialized, commercial neuronavigation systems for the purpose of registration. They allow evaluation of changing brain position during surgery. All these commercial systems, however, perform the registration with the use of anatomical (e.g. points) or extrinsic landmarks (e.g. stereotactic frame or fiducial markers) [6]. With these systems, only a rigid transformation between the pre- and intraoperative images can be determined, thus, the occurring soft tissue deformation cannot be satisfactorily compensated for.

In this paper we introduce a novel voxel-based registration approach that combines geometric transformations processed by graphics hardware to reduce computation time, thus supporting intraoperative use. We presented the details of the approach already in [7,8]. The method was so far tested exclusively with 0.2 T data. As a part of the presented work, the algorithm has been incorporated into a new system assisting the intraoperative analysis of registered pre- and intraoperative 1.5 T brain images. It contributes to improvemed surgical procedures, since the surgeon can now access the information about the direction and the magnitude of the occurring brain shift directly. Overall, the presented method provides a better analysis of the image data during the ongoing course of an operation.

The paper consists of 5 sections. An overview of the registration method and a precise description of the underlying algorithm are given in Section 2. In Section 3 the newly developed visualization system is presented. Results of the experiments performed in a operating room conducted with 1.5 T pre- and intraoperative brain data are presented in Section 4. Finally, the work is summarized in Section 5.

2 Registration Approach

As an initial estimate of the non-linear registration solution, rigidly registered datasets are taken [9]. After the rigid registration, we deform one of the datasets using Free-Form Deformation (FFD) such that the deformed image is aligned with the reference image. The idea is to warp the space surrounding an object that will be then warped implicitly. In order to deform the space, a 3D Bezier tensor product is taken. This kind of FFD contains inherent elasticity, which makes it a good choice for describing the movements of soft tissue.

To accelerate the FFD, the most expensive computations are done in the texture processing unit of the graphics card. A single FFD consists of three steps. Firstly, an object in the object space is embedded in the initial lattice of control points in the texture space. Control points are then moved to a new location in the texture space, thereby changing the shape of the control lattice. Subsequently, in classical FFD the new positions for every object point are calculated, according to the new locations of the control points. Instead, to accelerate the FFD, here graphics hardware is extensively used and texture coordinates are computed only for a uniform discrete sparse grid of points. We then use the coordinates for approximation of the 3D Bezier function with piecewise linear 3D patches. Based on these computed coordinates, the deformation is then propagated on the whole volume using trilinear interpolation. To accelerate this operation 3D texture mapping is performed according to the coordinates and the corresponding image information obtained after trilinear interpolation in graphics subsystem.

The complete registration procedure consists of performing FFD steps until the similarity measure (mutual information) computed between the deformed volume and the reference dataset reaches its optimum.

3 Visualization System

For the purpose of intraoperative analysis and diagnosis a software system was developed. The program consists of a module that is responsible for the non-linear registration and another module supporting intraoperative visualization and the comparison of the registration results. The system has a comprehensive DICOM interface based on the open sources of the Oldenburg library, which is important for clinical application. This supports easy data flow between the MR scanner and the developed software.

The visualization unit includes features that allow an intuitive insight into the registered brain images. Built-in magic lenses enable simultaneous display of the registered pre- and intraoperative data. Based on the alpha-blending parameter the information from both datasets can be shown superimposed in one window (see Figure 1). This gives an enhanced visual feedback of the tissue deformation. The surgeon is thus informed directly about the extent and the direction of the occurring brain shift.

Additionally, the user has the possibility to interactively change display parameters (linear mapping of intensity values, contrast and windowing). These features make an intuitive inspection of the data possible, which contributes to a better understanding of the operation and to an optimized planning of the subsequent steps of the surgery. The quality of the system was confirmed by surgeons after evaluation experiments.

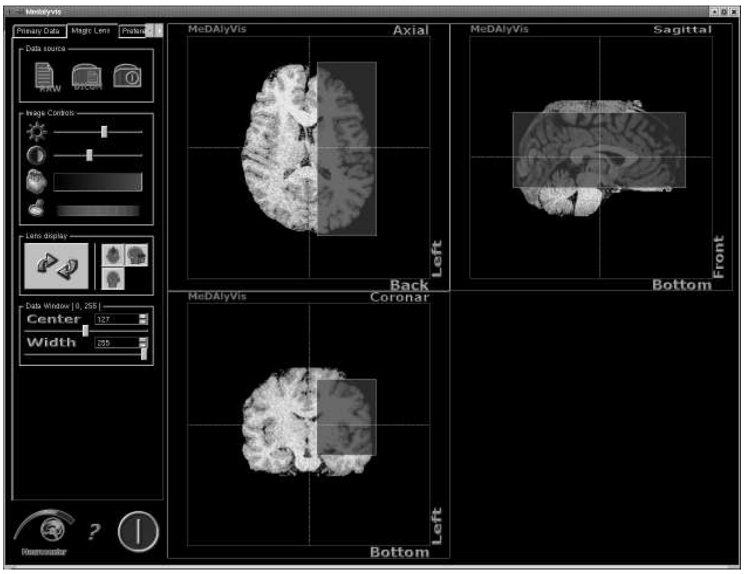

Fig. 1. A screenshot of the visualization module. Registered brain images are displayed in one image with magic lense technique

4 Results

We applied the algorithm successfully in 11 clinical cases of craniotomy at the Department of Neurosurgery of the University of Erlangen-Nuremberg. T1-weighted scans of the head were acquired with a Siemens Sonata 1.5 Tesla scanner before and during surgery on an open skull. The pre- and intraoperative volumes consisted of 512 x 512 x 160 voxels with the respective sizes of 0.44 mm x 0.44 mm x 0.89 mm. In all patients a significant brain shift occurred. Each of the dataset pairs was firstly registered rigidly and after that aligned non-linearly with the presented method.

Subsequently, neurosurgeons inspected the results of our new system visually. Experiments conducted with this system confirmed that intuitive analysis of the brain images is possible with the software. This analysis enabled a better understanding of brain shift during surgery and provided visual information about the magnitude and direction of the deformation. During visual inspection, above all, at the cortex and at the ventricles a good quality of the registration was observed by the surgeons, as presented in Figure 2.

Afterwards, quantitative measurements were performed to determine the quality of the implemented method more precisely. For that purpose, the magnitude of the brain shift at the brain surface and in the vicinity of the ventricles was considered. These measurements confirmed the visual assessment accomplished by the surgeons. The registration algorithm compensated for brain shift in 9 of 11 cases (see Section 5) within a precision range of 1.5 mm - 2.0 mm. These results come from a higher data resolution, good homogeneity and a low amount of noise in 1.5 T MR data. In 2 patients with a huge tumor resection, the method failed to match the pre- and intraoperative images satisfactorily.

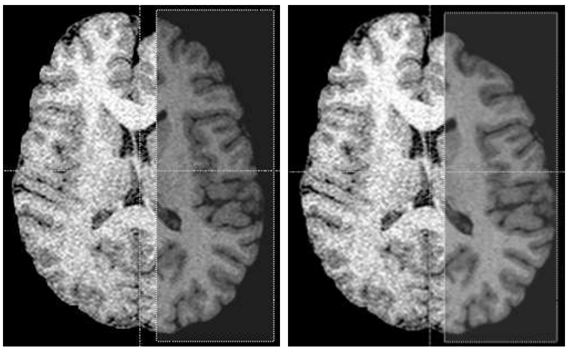

Fig. 2. Results of registration. *Left:* rigidly registered brain images. The preoperative image is displayed in the magic lense window over the intraoperative image. *Right:* brain images after non-linear correction. The magic lense shows the deformed preoperative image.

5 Conclusion

We presented a non-linear registration approach that is based on Free-Form Deformation. The method combines the flexibility of Bezier transformation with low computation times making use of graphics hardware in a novel manner. The algorithm performed satisfactorily in 9 of 11 cases. However, the evaluation showed also that Free-Form Deformation is not flexible enough for very pathological cases (see Section 4). For such situations other methods are required in order to perform the desired compensation for brain shift. In all other experiments the quality and efficiency of the approach was exhibited. Furthermore, intraoperative analysis of the registered data within the introduced visualization system contributed to an improvement of the surgical procedure.

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References

1. R. Bajcsy and S. Kovacic Multiresolution elastic matching, Computer Vision, Graphics and Image Processing, 1989, 46, pp. 1-21
2. P. Viola and W. Wells, Alignment by Maximization of Mutual Information, Proc. Vth Int. Conf. Comp. Vision, 1995, Cambridge, MA, pp. 16-23
3. A. Collignon, D. Vandermeulen, P. Suetens et al., Automated Multi-Modality Image Registration Based on Information Theory, Kluwen Acad. Publ's: Comput. Imag. and Vis., 1995, 3, pp. 263-274
4. D. Rueckert, L. I. Sonoda, C. Hayes et al., Nonrigid Registration Using Free-Form Deformations: Application to Breast MR Images, IEEE Trans. Med. Imaging, 1999, 18, pp. 712-721
5. C. Maurer, D. Hill, A. Martin et al., Investigation of Intraoperative Brain Deformation Using a 1,5T Interventional MR System: Preliminary Results, IEEE Trans Med Imaging, 1998, 17, pp. 817-825
6. R. H. Taylor et al., Computer-Integrated Surgery: Technology and Clinical Applications, Cambridge MA, MIT Press, 1996
7. G. Soza, P. Hastreiter, M. Bauer et al., Intraoperative Registration on Standard PC Graphics Hardware, Proc. BVM (Bildverarbeitung für die Medizin), 2002, pp. 334-337
8. G. Soza, M. Bauer, P. Hastreiter et al., Non-rigid Registration with Use of Hardware-Based 3D Bèezier Functions, Proc. MICCAI, 2002, pp. 549-556
9. Hastreiter P., Ertl T. Integrated Registration and Visualization of Medical Image Data Procs CGI 98, 78–85, 1998