High Performance Computing in Image Guided Therapy

Computer Assisted Three-Dimensional Planning and Real-Time Navigation for Neurosurgical Procedures

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Abstract. We routinely use three-dimensional (3D) reconstruction MRI techniques to understand the anatomic complexity of operative brain lesions and improve preoperative surgical planning. Additionally, we incorporate functional (f-MRI) and metabolic data (PET, SPECT) into the surgical planning, on a case to case basis, using a co-registration algorithm based on maximization of the inherent mutual information contained in the different data sets (MMI) [44]. Surgical planning is performed using MRI based 3D renderings of surgically critical structures such as eloquent cortex, gray matter nuclei, white matter tracts and blood vessels. Simulations using interactive manipulation of 3D data provide an efficient and comprehensive way to appreciate the anatomic relationships of the lesion with respect to the eloquent brain areas and vessels. They provide otherwise inaccessible information, essential for the safe and possibly complete surgical removal of brain lesions. In a second, still experimental step, we propose the use of the 3D reconstruction during surgery, in conjunction with our operative open configuration MR scanner (Signa SP) and real time navigation system, thus facilitating the real-time visualization and quantitative assessment of the intraoperative changes, with the final goal of further reducing the invasiveness, increasing the radicality and safety of the procedure and improving the patient's outcome.

1 Introduction

The ultimate goal of the neurosurgeon is to achieve a maximal and precise removal of a brain lesion without damaging normal and functionally eloquent brain tissue or important blood vessels, thus preserving the neurological function. This can be, in many instances, difficult to achieve, since the visual appearance of the lesion, especially that of benign brain tumors (low-grade gliomas) often doesn't differ much from that of normal brain. Another difficulty is represented by the inability to see under the surface of the brain as it is being dissected during the surgical procedure.

In the early days of Neurosurgery, the diagnosis and localization of a brain lesion relied exclusively upon the thorough clinical examination of the patient and interpretation of his symptoms and signs. With the advent of the X-ray examinations, additional indirect preoperative data could be taken into account for surgical planning (displacement of the vessels on the angiogram, displacement of the ventricles on the ventriculogram). The direct visualization of intracranial processes has only been possible since the development of the computed tomography (CT) and later of the magnetic resonance tomography. (MRI). Unlike the Digital Substraction Angiography (DSA), the MR- angiography allows the visualization of the intracranial vessels by non-invasive means, adding an important plus of preoperative information. Further developments, like the functional MRI (f-MRI) add to the localization of the sensory-motor and speech cortex. The positron emission tomography (PET) and the single photon emission computed tomography (SPECT) are able to supplement the global picture with metabolic data, allowing the differentiation of zones of active tumor growth from zones of radionecrosis in treated recurrent lesions, which by means of CT or MRI would be virtually impossible to achieve. [30, 36]

With the increasing number of imaging modalities, each highlighting one or more particular aspects of the brain morphology and function, the need for integrating the different facets into a global picture has arisen. This has been made possible by the introduction of high performance computers in the medical field and the development of image segmentation and registration algorithms.

Parallel to the development of the imaging techniques, several revolutionary developments have been made in the field of the operative neurosurgical technique. The operation microscope, adding optimal magnification and illumination to the operation field, has led to a drastic reduction in craniotomy size and made possible the access to deep seated brain lesions [33]. The development of the stereotactic frames added a precise targeting of intracranial lesions, however, they obstruct the surgical access for open tumor resections and cannot compensate for brain shift. The first inconvenience could be overcome by introducing the frameless stereotactical devices [10, 20, 21, 38, 39]. The major drawback of both frame- and frameless stereotactic devices is the use of preoperative data. With progress of the surgical procedure (tumor resection, opening of the subarachnoid or ventricular system with CSF loss, brain swelling, hemorrhage etc.), the morphology of the brain changes (“brain shift”), progressively rendering the preoperative images more and more inaccurate [32] (see Figure 5). The solution we developed was the construction of an open configuration operative magnet (SignaSP), which allows the surgery and imaging to be performed at the same place, making possible frequent image updates without the need of moving the patient and integrating a “near real-time” navigation system (Figure 4) [4, 11, 17].

2 Surgical Planning – breaking the „3D-Barrier“

Although visual interpretation of plain MR images is usually sufficient for the diagnosis, in order to plan and execute neurosurgical procedures, the physician has to mentally assemble the 2D images into a spatial representation of the relevant structures and their anatomical relationships. Additionally, the surgical planning requires viewing from different perspectives and estimates of the three-dimensional extent of the lesions. In some instances, the physician has to mentally align different scan modalities (e.g. MRI and SPECT) in order to choose the appropriate target point for a biopsy. Given the complexity of the intracranial anatomy, this mental task may be time consuming, difficult or, at times, impossible to accomplish.

Ideally, computer assisted surgical planning should achieve the following goals:

- data collection with optimal spatial and contrast resolution
- by means of manual, semiautomated and automated segmentation, proper identifcation of the lesion and the relevant anatomical structures
- co-registration of different scan modalities
- accurate 3D models, from the segmented data, witch can be manipulated at interactive speeds (zooming, rotation, translation, selective visualization and transparency change of the different structures)
- capacity of measuring distances between and volumes of the different structures

2.1 Image Acquisition

For surgical planning at our institution, the patient undergoes a standard image acquisition protocol using a 1.5 T MRI scanner (Signa, GE Medical Systems, Milwaukee, WI). The protocol consists of a 3D-SPGR (spoiled gradient echo, 124 slices, 1.5 mm slice thickness) as volumetric acquisition, T1 weighted images with and without contrast, T2-weighted images and, in some cases, proton density weighted images covering the whole brain. Additionally, a phase contrast MR-angiography is performed. The data are transferred from the MR scanner through a fast (100 Mbps) network connection to the processing workstations (Sun Microsystems, Mountain View, CA).

Low-grade gliomas (astrocytomas, oligodendrogliomas, mixed gliomas) appear hypointense on T1-weighted and hyperintense on T2-weighted images. They usually don’t show contrast uptake [14] (Figure 1). Intraoperatively, there are only slight differences between the visual appearance of the lesion and that of the surrounding normal brain tissue, making complete resection by means of conventional surgical techniques extremely difficult [4, 28]. On the other hand, these are benign lesions, affecting young patients, having the potential of becoming malignant [9, 27, 28, 29]. If completely removed, they could show long remission intervals or even be cured. Several studies indicate a significant time difference to recurrence and progression between low-grade gliomas after gross total removal and partial resection [2,3, 27, 28, 29, 37l].

High-grade gliomas (anaplastic astrocytomas, glioblastomas) show a more rapid, anarchic growth. As a correlate, they display diverse and inhomogenous imaging characteristics on MR and, because they disrupt the blood-brain-barrier, they show contrast enhancement [14].

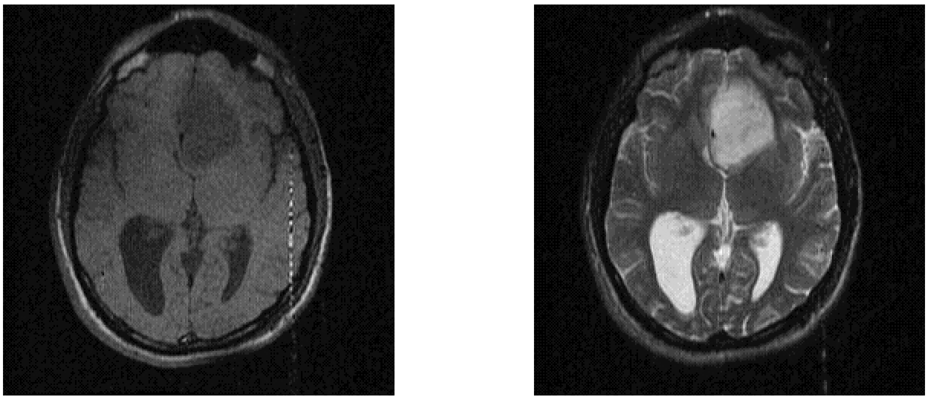

Figure 1: Extensive left frontal low-grade glioma. Left: T1-weighted image, showing a hypointense frontal tumor mass. Right: T2-weighted image at the same level. The lesion shows up as hyperintense.

2.2 Image Processing – Identifying the Key Information

In our laboratory, the data is segmented with a variety of manual, semiautomated or automated approaches. [11, 19, 40, 41, 42]

In order to reduce the noise level, the image data is filtered prior to segmentation. We have clinical applications involving segmentation of MR images which routinely uses anisotropic diffusion for enhancing the gray level image prior to segmentation [13]. By smoothing along structures and not across, the noise level can be reduced without severely blurring the image. For this purpose, we use a parallel implementation of the anisotropic diffusion algorithm.

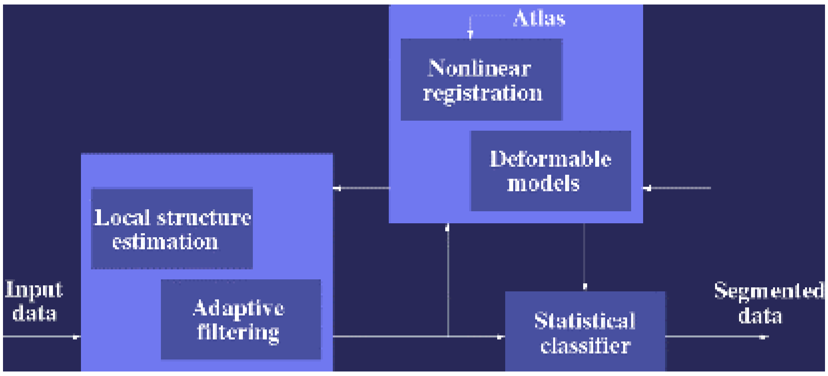

Figure 2: Segmentation paradigm

One of the software tools being used in our laboratory is the “3D-Slicer”. It has been developed at the Surgical Planning Lab in collaboration with the Artificial Intelligence Laboratory of The Massachusetts Institute of Technology [11].

The modular designed software was developed on top of the OpenGL graphics Library, using the Visualization Toolkit (Vtk) for processing and the Tcl/Tk scripting language for the user’s interface.

The 3D-Slicer offers a unique capability of integrating multimodal medical images (MRI, f-MRI, CT, SPECT, PET) into a single software environment. The multiple different data sets are aligned using a multimodal registration method based on the maximization of the inherent mutual information contained by the images originating from the same patient [44]. After the data are loaded, they are post-processed using various tools like thresholding, erosion, dilation, island removal, free hand drawing. From the labeled data, 3D models can be generated, based on the marching cubes algorithm.

A standard preoperative model consists of skin, brain, ventricles and vessels. Models of the pre- and postcentral gyrus, speech cortex and deep brain structures can be easily added, as the necessity dictates (Figure 3).

The 3D renderings represent an enrichment of the information provided by the 2D MR slices alone. They don’t change the diagnosis, but can contribute substantially to surgical planning by providing additional information regarding:

- the optimal craniotomy and coticotomy sites
- proximity of the lesion to the sensory and motor tracts and deep brain structures (basal ganglia)
- spatial relationship of the lesion to vascular structures
- position of cranial nerves
- possibility of simulation of different surgical approaches

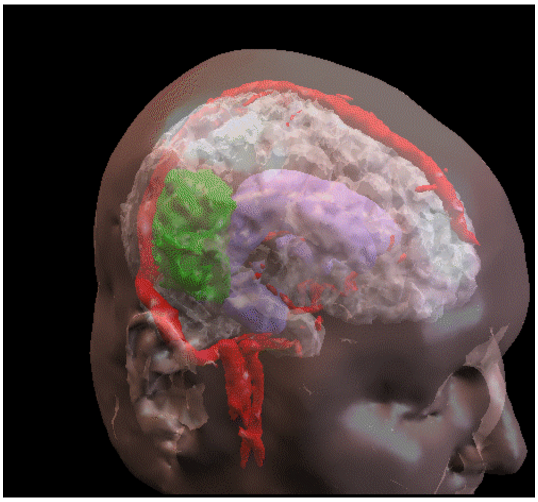

Figure 3: Standard preoperative 3D model (green - tumor; red - vessels; violet - ventricles)

3 Intraoperative Navigation

The capabilities of the 3D-Slicer are not limited to the surgical planning. Since 1999, the software has been integrated with the surgical open configuration 0.5 T MR-scanner at Brigham and Women’s Hospital (SignaSP, GE Medical Systems, Milwaukee, WI). Developed by General Electrics Medical Systems in cooperation with the BWH team, SignaSP combines several key components: vertically open bore which allows two surgeons to access the patient, sensors for interactive localization of the surgical instruments, intra-operative displays, computer workstations [4, 11, 17]. Unlike other intraoperative navigation systems, our system allows image updates as needed without having to move the patient in and out the bore, combining the surgery and imaging in the same place. Without the updates, the image data would quickly loose the accuracy with progressing surgery because the brain changes it’s shape due to tumor resection, swelling, hemorrhage and CSF lacking after opening the subarachnoid space or the ventricular system (“brain shift”) [32]. The tracking of the surgical instrument is performed by three high-resolution cameras mounted in the bore above the surgical field. Attached to the instrument is a star-shaped handle, having light-emitting diodes mounted on each arm. The cameras localize the LED’s on the handle and transmit the information to a computer workstation linked on one end to the scanner and on the other end to the SPL network, on which the 3D-Slicer software runs. The instrument’s position is updated with a fre-

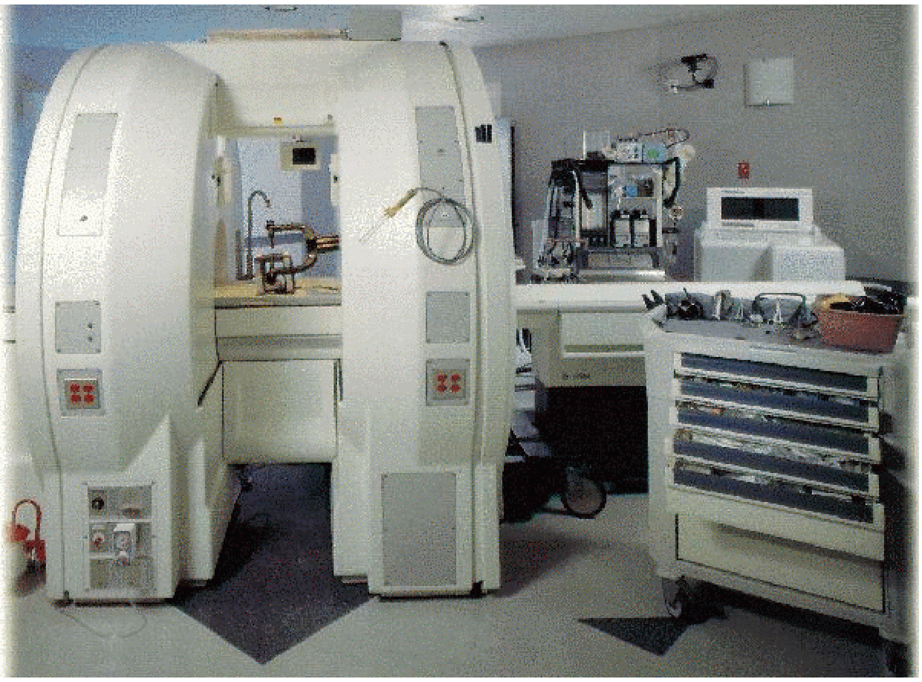

Figure 4: The operative open configuration 0.5 T MR scanner (SignaSP)

quency of 10 Hz. To avoid loss of information on interpolation of thick slices, 3D-SPGR (spoiled gradient recall) images are acquired and loaded into the 3D-Slicer. This allows reformatting of the image data in user-defined planes without significant loss of information. Using the star-shaped handle, the surgeon can browse through the updated volumetric images in a similar way a computer user would use a mouse, simulate different approaches and safely reach the target, with a minimal risk of compromising functional important brain structures or blood vessels (see Figure 6).

Based upon the updated volumetric images, a quantitative assessment of the surgical progress can be easily accomplished, by segmenting the apparent residual tumor and measuring it's volume, using the volume measuring capability of the 3D-Slicer software. (Figure 7)

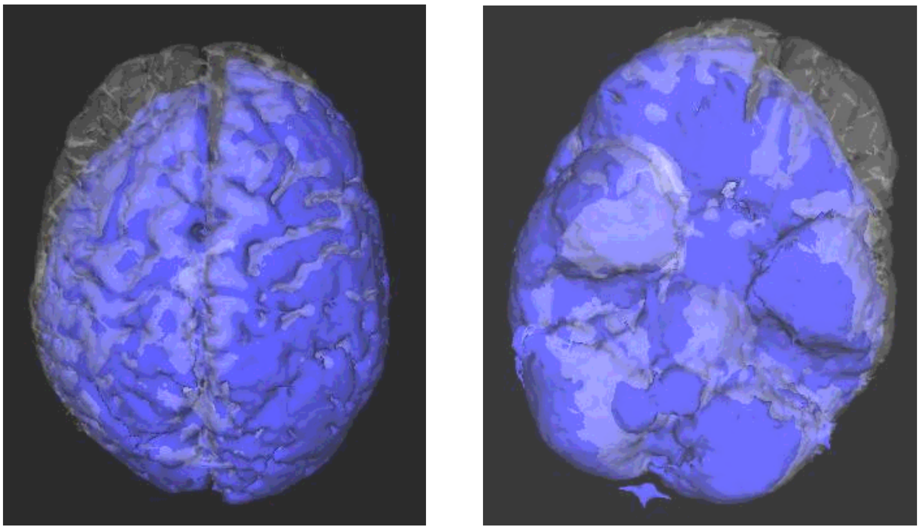

Figure 5: Illustration of brain shift. A 3D model of the brain was rendered starting from the initial 3D-SPGR, obtained before opening of the dura (transparent). A second 3D brain model of the same patient was rendered from an intraoperative SPGR, after opening of the dura and partial tumor resection (blue). The two models were rigidly registered using the MMI algorithm. Note the considerable amount of brain shift which occurred with the progression of surgery, even on the contralateral side.

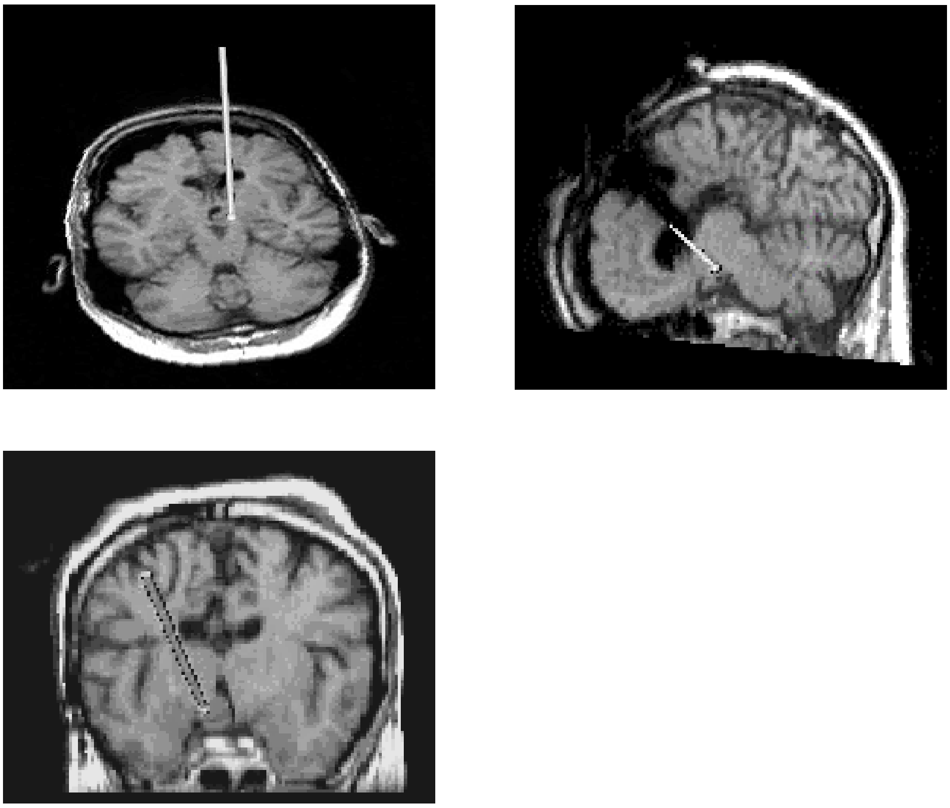

Figure 6: Example of real-time intraoperative navigation. The virtual instrument points at a small, anterior right hypothalamic lesion (hamartoma)

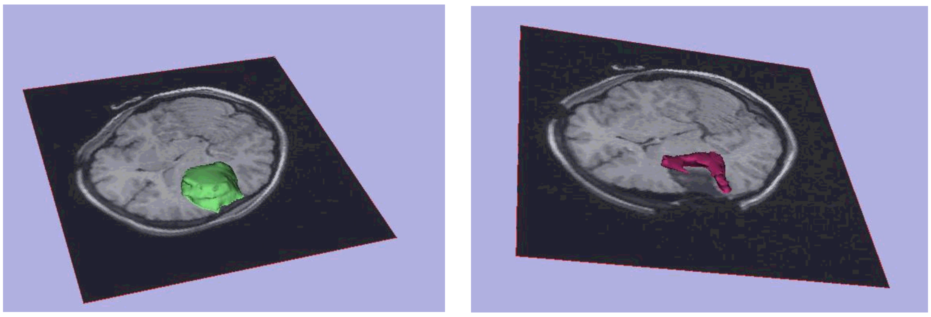

Figure 7: left – preoperative model of a left temporal low-grade glioma (volume=48.2 ml); right- model of the residual tumor (volume=10.4 ml)

4 3D-Navigation – A Glimpse in the Future

The final goal of the computer assisted surgical planning is to incorporate this techniques into the intraoperative navigation.

In order to be practicable, the intraoperative image data post-processing must comply with the time constraints imposed by the ongoing surgery and capture the shape changes due to brain shift.

We have developed a novel segmentation algorithm for the purpose of real-time intraoperative image segmentation [40, 41,42]. This method takes advantage of the existing preoperative MR acquisition and segmentation to generate a patient specific tem-

plate for the segmentation of the intraoperative data. Out of the preoperative data, a statistical model of the distribution of MR intensities of each relevant tissue class is built. The statistical model is encoded implicitly by interactively selecting groups of prototypical voxels, representative for each tissue class. The preoperative data is then segmented with the k-NN classification [23, 41]. The resulting model is used to moderate the classification of the intraoperative data. Details on this method have been extensively described in [42]. On our hardware (20 CPU Ultra HPC server, Sun Microsystems, Mountain View, CA), we can achieve a average rate of 2.9 slices per second. This rate is sufficiently high to exceed the rate at which MR slices can be acquired for surgical intervention.

Segmentation of intraoperative data helps to establish explicitly the regions of tissue that correspond in the preoperative and intraoperative data. It is then straightforward to apply our non-rigid registration algorithm for biomechanical simulation of the intraoperative “brain shift”. In a first step, an active surface algorithm is used to establish the correspondences between the surfaces of the pre- and intraoperative brain data. In a second step, the volumetric brain deformation implied by the surface changes is computed using a biomechanical model of the brain. The key concept is to apply forces to the volumetric model that will produce the same displacement field at the surfaces as was obtained with the active surface algorithm. Further details on this topic can be found in [8, 43]. The tests we have undertaken on a Sun Microsystems Ultra HPC 6000 machine with 20 250MHz CPUs indicate that we are able to assemble and solve a system of equations 2.5 times larger then necessary to obtain excellent results in a clinically compatible time frame. Our concept is not to require perfect accuracy from the elastic matching scheme, since it can form a part of a pipeline of cooperative image analysis modules in which feedback mechanisms are incorporated.

5 Conclusion

From the neurosurgeon’s perspective, high performance computing is a key enabling technology which, beyond the use as a research tool, provides the means for the integration of different imaging modalities, segmentation, registration, simulation and intraoperative navigation.. It facilitates an accurate surgical planning and makes possible the precise intraoperative location of the lesion and definition of its spatial relationship to the key anatomical structures to be preserved. This is a work in progress. The segmentation and registration algorithms have to be further refined. We strongly believe that the implementation of HPC will contribute in an important way in improving the outcome of the surgically manageable brain lesions.

Acknowledgement

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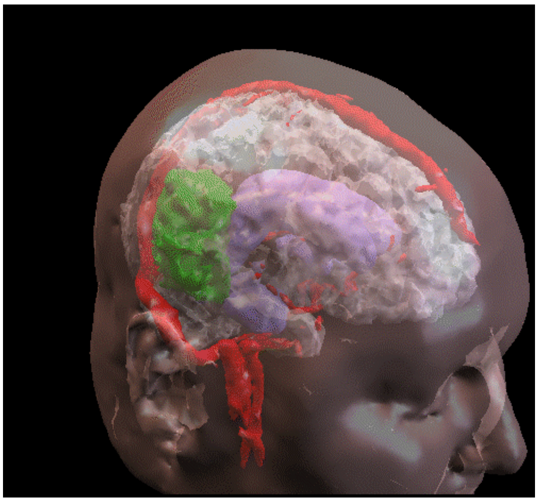

Fig. 3

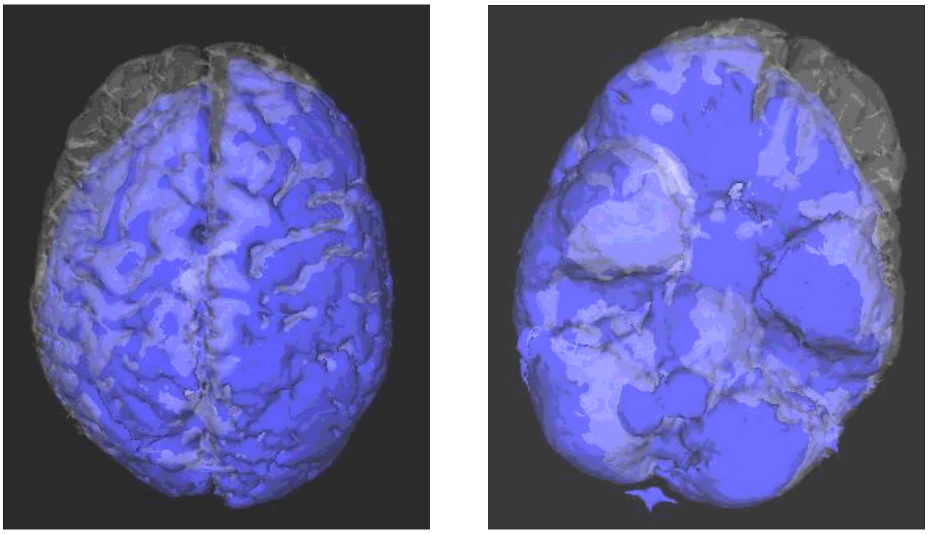

Fig. 5

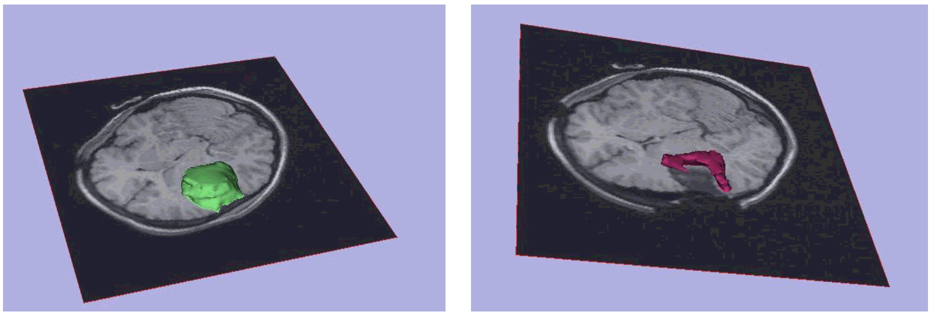

Fig. 7