Brain-shift aware risk map for Deep Brain Stimulation Planning

Alexandre Bilger, Caroline Essert, Christian Duriez, Stéphane Cotin

Brain-shift aware risk map for Deep Brain Stimulation Planning

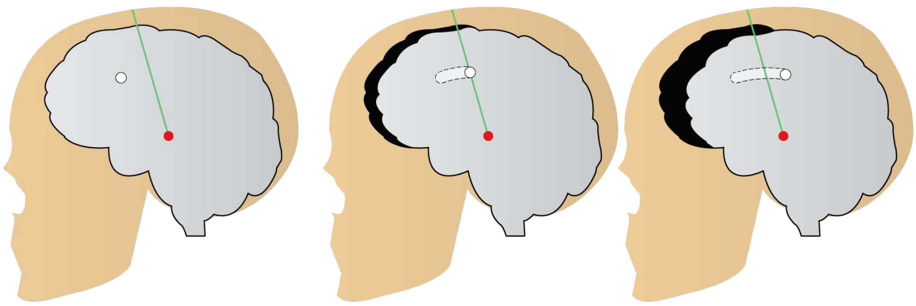
Bilger Alexandre[1], Essert Caroline[2], Duriez Christian[1], Cotin Stéphane[1]

[1] SHACRA Group, Inria Lille Nord-Europe, FRANCE
[2] LSIIT / Université de Strasbourg, FRANCE

Abstract. In Deep Brain Stimulation surgery, the efficiency of the procedure heavily relies on the accuracy of the placement of the stimulating electrode. Meanwhile, the effectiveness of the placement is difficult due to brain shifts occurring during and after the procedure. We propose an approach to overcome the limitations of current planning software that ignores brain shift. In particular, we consider the motion of vascular structures in order to reduce risks of dissecting a vessel during the procedure. Facing the difficulty to produce an exact brain shift prediction, we propose to build a brain shift aware risk map which embeds the vascular motion risk. This risk map is extrapolated using simulation from clinical studies that provide statistics on the displacement of anatomical landmarks during the procedure. Risk maps can be directly integrated into automatic path planning algorithms to better predict optimal electrode trajectories. The method relies on a physics-based simulation that takes into account brain deformation, electrode placement, cerebrospinal fluid, and vascular motion. The goal is to reproduce the spread of brain shift situations that are noted in clinical studies. Preliminary results show that it is possible to compute safe electrode trajectories even in case of brain shift and yet optimal regarding the placement within the targeted area.

1 Introduction

Over the past decade, Deep Brain Stimulation (DBS) has known a growing interest in neurology for the treatment of movement disorders such as Parkinson's disease or dystonia. This surgical procedure consists in implanting an electrode in deeply located structures of the brain, among which the SubThalamic Nucleus (STN). An accurate placement of the electrode is crucial to maximize outcomes and to prevent adverse effects. This placement is achieved in two main stages: first, pre-operative medical images of the patient are combined with the use of a stereotactic frame (and sometimes an atlas of the brain) to determine the target coordinates and optimal trajectory for the electrode(s). Second, the patient is taken to the operating room where a hole is drilled in the skull to insert electrodes into the brain according to the planned trajectory (two in the case of a bilateral implantation). However, the opening of the skull changes the intracranial pressure which causes a combination of deformation and motion of the brain known as *brain shift*.



(a) No brain shift (b) Intermediary brain shift (c) Maximal brain shift

Fig. 1: Sagittal projection of the brain for different possibilities of intensities of brain shift given an insertion point, from no brain shift (a) to a maximal brain shift (c). The trajectory is in green, from an insertion point on the scalp to the target in red. The area in black is the pneumocephalus. The white circle represents a vessel. In (a) the vessel lies in its initial position. In (b) and (c), we see its new position according to the brain shift, and the whole shape of its movement during the progression of the brain shift (light dotted shape).

The brain shift model remaining unknown, the deformation can not be anticipated. Fig. 1 represents different possible intensities of brain shift that might occur with the same insertion point. When this brain shift is significant, it can have an impact on the procedure and its outcome [10] [5]. The three main known issues are the following. The brain shift results in a difference of location of anatomical structures between the planning stage and the intra-operative set-up (blood vessels, ventricles, STN, Anterior and Posterior Commissures (AC/PC)). This difference means that 1) the effective location for the electrode can be quite remote from the planned location (5 mm or more in rare cases) [10], and 2) there is a risk that an anatomical structure (such as vessels) shifts to the area of the burr-hole. Therefore, it becomes impossible to implant the electrode without risking intracranial hemorrhage. In their survey, Benabib *et al.* [1] report that hemorrhages occurred in 8.4% of all the DBS patients, mostly at the entry point. Moreover, several weeks after the surgery a post-operative electrode migration can appear as the brain returns to its initial position when the subdural air introduced during surgery has resolved. As a result, 3) the electrode might no longer be in contact with the subthalamic area, and brain disorders might resume. Our main objective is to improve the trajectory planning part of the DBS procedure. In this paper, we propose to address problem #2 mentioned above, by presenting a preoperative approach that can reduce risks of dissecting a vessel due to brain shift.

In clinical routine, most neurosurgeons use commercial software such as Medtronic StealthStation or GE Advantage Windows. Such software provide a significant assistance in determining a good trajectory for the electrode. Usually the software proposes a default solution based on standard angles relatively to AC/PC landmarks or the stereotactic frame, without considering the surrounding anatomy, and lets the neurosurgeon interactively move the virtual electrode to a location which is assumed to be optimal in terms of targeting and avoidance of certain structures (mainly ventricles and blood vessels). As this task can be tedious and time consuming (from 10 to 50 minutes depending on the difficulty of the case), a few research groups have proposed to automate the search for an optimal trajectory [3] [11] [6] [2]. Brunenberg *et al.* [3] extract from a set of entry points some valid trajectories, but without ordering them. Their work, as well as those of Shamir *et al.* [11] consider only risk criteria, that are taken into account separately. Essert *et al.* [6] proposed a method based on a weighted combination of several types of criteria, applied to preoperative MRI. The method proposed by Bériault *et al.* [2] is very similar, but is applied on multi-modal MRI. This results in an accurate segmentation of anatomical structures of interest, however only a risk criteria is considered.

Yet, none of the previous planning solutions (manual or automatic) take into account brain deformation or the associated motion of its substructures: the computations are based on "*static*" pre-operative images. This is potentially risky as there is no guarantee that vital structures will not have moved before the insertion of the electrode, because of the opening of the skull, nor that the planned trajectory will actually be aiming at the subthalamic area, as it may also have shifted. The objective of our method is to consider brain shift in the preoperative trajectory planning. To this end, we propose the computation of an advanced "*brain shift aware*" risk map based not only on static pre-operative images, but on an estimation of the possible location of the vessels due to brain shift, taking into account different possible scenarios of deformations. This information can then be used in combination with any planning strategy, whether it is manual or automated.

To achieve this goal, we propose a framework which takes into account intracranial fluid loss, subdural air invasion, brain shift and vascular motion, and can rely on patient-specific data. This work includes the following features: physics-based models of the brain; mechanical interactions between the brain and the skull; influence of the surrounding cerebro-spinal fluid (CSF) and air invasion in the skull on the brain shift (including the asymmetry of the brain shift). We also consider the orientation of the patient on the operating table as it influences CSF loss and brain shift. Then we couple the results of the simulation with an automatic optimal trajectory planning system. Results from our simulations and computations (performed on generic dataset), show that 1) important brain shifts result in a significant vascular motion, 2) we can take this motion into account in the planning process with reduced computational load and no significant changes in the software and 3) we can compute automatically optimal trajectories based on this information, and the result is not too restrictive and still allows for solutions to be found.

This paper is organized as follows: Section 2 describes the simulation, and planning processes and how they are linked; Section 3 presents our preliminary results, and finally Section 4 concludes and addresses future steps for the method.

2 Materials & Methods

Our approach relies on a physics-based model of the brain tissue deformations, the contact response with the skull and the falx cerebri, and the interaction with the cerebro-spinal fluid (CSF). We perform numerical simulations to produce a brain shift aware risk map embedding the motion of the vascular structures as well as a measure of uncertainty about their exact location. The map is then used in a planning system to determine automatically optimal trajectories for the electrode. The approaches we used are presented in the following section.

2.1 Brain Shift Simulation

Previous works have studied the brain shift with intraoperative images. [8] use intraoperative MRI to register them but it requires a very costly equipment, whereas [9] estimate the brain shift with 3D-ultrasound. However, these intraoperative techniques assume the brain shift already occurred, therefore the possible trajectories are limited by the hole in the skull. Other works try to preoperatively predict the brain deformation in order to increase the electrode implantation accuracy, but these methods are based on parameters that are unknown at the planning step. We propose a method that helps surgeons to visualize a risk of brain shift using a patient specific simulation before the operation, during the planning. More specifically, our method indicates which zones should be avoided because of a high risk of the presence of vessels if a brain shift occurs, with different possible levels of intensity.

Numerical Simulation In brain deformation simulation research, many use a finite element method (FEM) associated with linear or non-linear material model, or eventually a fluid model. In our simulation we use a non-linear geometric FEM model with a linear constitutive law [7]: our model is adapted for large displacements and small deformations, which is appropriate in our case. The volume of each brain hemisphere is meshed as a set of tetrahedral elements. We also accurately compute the contacts between the brain, the inner part of the skull and the falx cerebri using static and dynamic friction law models [4] which reproduce, at a macroscopic level, the effect of the connective tissue in the subarachnoid space.

We also take CSF influence into account, which is acting on the brain and balancing the brain weight. The consequence of a CSF loss is a brain shift as the brain is more influenced by gravity than by fluid forces. The CSF action is modelled as external forces acting on the surface of the brain:

$$\mathbf{f}_{CSF} = \iint_S \rho g h(P) d\mathbf{S}$$

where ρ is the density of CSF, g is the norm of the gravity and h is the distance between a point P on the surface and the fluid level. This force is computed on each triangle S of the brain mesh that corresponds to the immersed surface.

Independently of the choice of the deformation model, we end up with the following differential system of non-linear equations

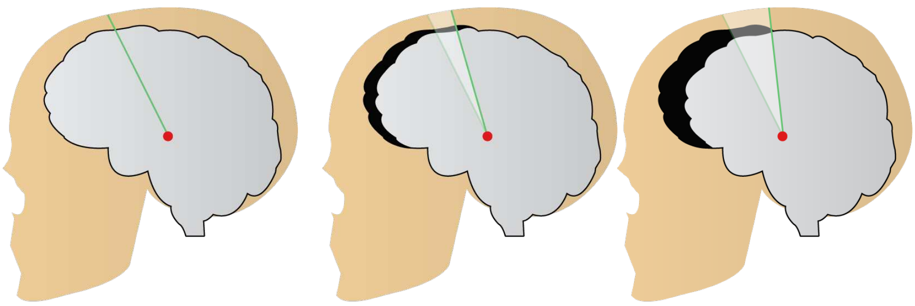
$$\mathbf{Ma} = \mathbf{f}(\mathbf{x}, \mathbf{v}) + \mathbf{p} + \mathbf{f}_{CSF} + \mathbf{H}^T \lambda$$

where $\mathbf{M}$ is the mass matrix, $\mathbf{f}$ gathers the internal forces. $\mathbf{a}$, $\mathbf{v}$ and $\mathbf{x}$ are respectively the acceleration, the velocity and the position of the nodes from the mesh. The forces $\mathbf{p}$ are exerted by the gravity and $\mathbf{f}_{CSF}$ by the CSF. Finally, $\mathbf{H}^T \lambda$ gathers constraints response resulting from unilateral contacts and bilateral constraints.

The vascular motion is associated to the brain motion, that is why we connect the vessels to the brain by keeping constant the barycentric coordinates of the vessels positions in the elements of the brain mesh.

To ensure stability and accuracy, we use an implicit integration scheme, and a GPU implementation guarantees a fast computation for a clinical use.

Construction of the Brain-Shift Aware Risk Map Two phenomena have to be taken into account: 1) the first one, illustrated on Fig.1, is the unknown exact intensity of the brain shift that will occur to the patient for a particular location of the burr hole. This is due to the complexity of the model of brain shift and the large number of parameters involved. For this reason, we chose to take into account all possible intensities of brain shift from no brain shift



(a) Anterior trajectory (b) Intermediary trajectory (c) Posterior trajectory

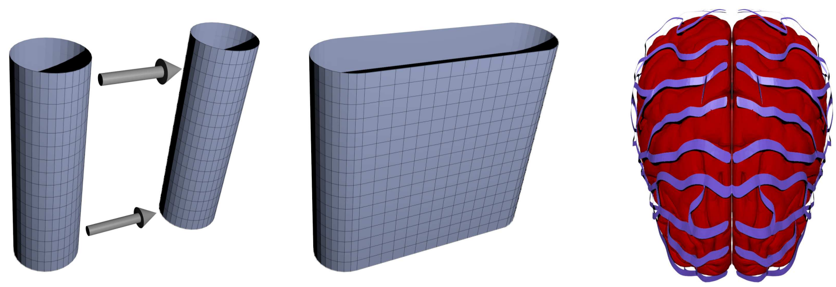
Fig. 2: Sagittal projection of the brain for 3 different trajectories. We assume that the brain shift depends on the location of the insertion point and on gravity. We depict here a patient in supine position. An anterior trajectory (a) causes a smaller brain shift than more posterior trajectories (b) and (c). Trajectories are in green and the target is in red. The area in black illustrates the maximum pneumocephalus that could occur in the worst case.

to a maximum brain shift for a particular insertion point; 2) the second one, illustrated on Fig.2, is the dependency between the maximum possible brain shift, the location chosen for the burr hole, and the orientation of the head compared to gravity. For this reason, we chose to browse the space of possible entry points and simulate the maximum brain shift for the different locations.

To address the first phenomenon, as there is no reliable patient specific brain shift model, we can not consider only the final position of the vessels in the worst case of brain shift. We don't know what will be the intensity of the brain shift, so we need to consider every possible position of the vessels for every possible intensity of brain shift. That is why we build, from the shapes and positions of the 3D meshes of the vascular system simulated for different intensities of brain shift, a larger 3D surface embedding all the possible positions of the vessels. Figs. 3a and 3b illustrate a representative example of how is built such a convoluted surface, whereas the simulated vascular network is depicted in Fig. 3c.

Addressing the second phenomenon implies to simulate the brain shift for several possible locations of the burr hole. The process presented in the previous paragraph is applied to a set of representative locations of the burr hole. This allows us to build an advanced risk map, where the risk associated to an insertion point is the distance between a trajectory and the vascular convoluted surface corresponding to this particular insertion point. By doing this, we forbid a trajectory to cross all intermediate positions of the vessels between its original and a maximal positions, to take into account every possibility of brain shift from the best to the worst.

With this method, a surgeon is able to avoid possibly moving vessels even without an accurate prediction about the exact brain shift or the CSF loss. In the following we show how we integrate this risk map in a planning software, in order to anticipate the movement of these structures.



(a) A vessel moving from one position to anoter

(b) 3D surface embedding the vascular motion

(c) Shift of the vascular network

Fig. 3

2.2 Automatic Computation of Electrode Trajectories

Once the brain shift aware risk map is produced, it can be easily used in any standard DBS planning software. The software we are using for this study has an additional feature: it includes a trajectory optimization process. This process is performed in two phases, thanks to a surgical constraints solver in the spirit of [6] or [2]. The first phase solves hard constraints, such as critical anatomical structures avoidance, and eliminates from an initial outer surface all insertion points impossible to consider in practice without injuring the patient. The second phase solves soft constraints, that correspond to preferences. They are described under the form of cost functions to minimize, aggregated into one linear combination of weighted constraints. The result of these soft constraints are displayed as color maps representing for each candidate insertion point the degree of satisfaction.

We defined a set of soft constraints, concerning the minimization of the risks for the patient and the optimization of the orientation in relation to the shape of the target. Among those soft constraints is one favoring a maximization of the distance between the candidate electrode and risky structures (which are in the case of DBS mostly vessels and ventricles). In this study we had to split this soft constraint in two separate constraints. The first one simply computes the distance between the electrode and the ventricles. The second one is adapted to use the advanced risk map described in section 2.1, so that the distance with the vessels takes into account the estimated brain shift.

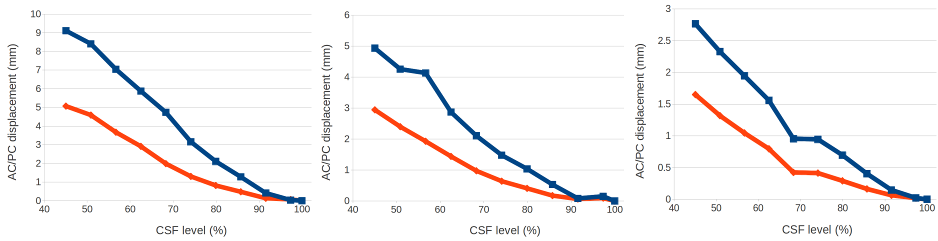
As a consequence, instead of maximizing the distance from the candidate electrode to the vessels extracted from the pre-operative MRI, *i.e.* in a static position, we maximize the distance from the candidate electrode to the set of positions where the vessels could lie if a brain shift occurs. Thanks to the advanced risk map, the estimated possible positions of the vessels depend on the location of the burr-hole involved by the position of the considered candidate electrode.

3 Results

This section presents the preliminary results of our method applied on a template of high-fidelity anatomical three-dimensional models of the brain. This contains brain tissues, skull, skin, ventricles, vessels and the target (STN). In the following, we will show how we use the simulation to produce a brain shift aware risk map, then we compute an optimal trajectory. In our tests, we consider the patient lying in the supine position. The CSF level is expressed in percentage from no CSF (0%) to full CSF volume (100%).

3.1 Independence of Mechanical Parameters

First, we show that our simulation reproduces the correlation between the volume of CSF lost and the anterior commissure (AC) shift, and the posterior commissure (PC) shift, found in [5] on a group of 66 patients. As there is a

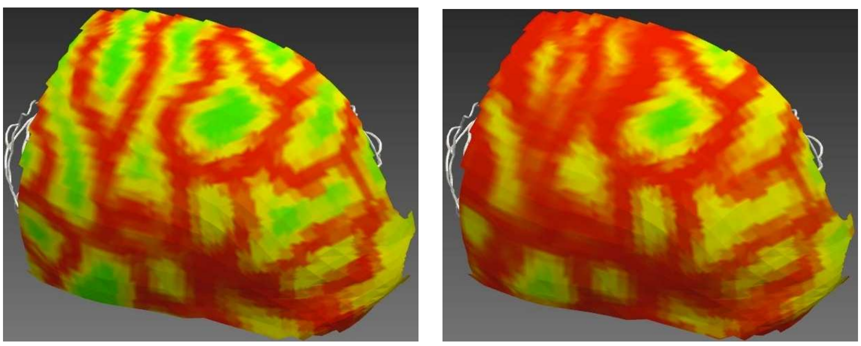


(a) E=6,000 Pa (b) E=12,000 Pa (c) E=24,000 Pa

Fig. 4: Shifts of AC/PC vs CSF level with three Young's modulus (E). Units of shifts are in mm. AC displacement in blue. PC displacement in orange.

large range of values for the Young's modulus of the brain in the literature (between 2,100 Pa and 40,000 Pa), this property has been measured with different mechanical parameters. The figure 4 relates the correlation in three simulations with different Young's modulus.

Obviously, the Young's modulus has an influence on the brain deformation. However, Fig. 4 shows that a specific brain deformation based on AC/PC displacement can be obtained whatever the Young's modulus. To reach the same deformation, the larger the Young's modulus is, the more the CSF has to leak out. That is why our approach is relatively independent of the mechanical parameters of the physical model. The model enables to get a valid geometrical deformation. As we could not anticipate the CSF loss, we can now parameterize our simulation with experimental measure like the AC/PC displacement.



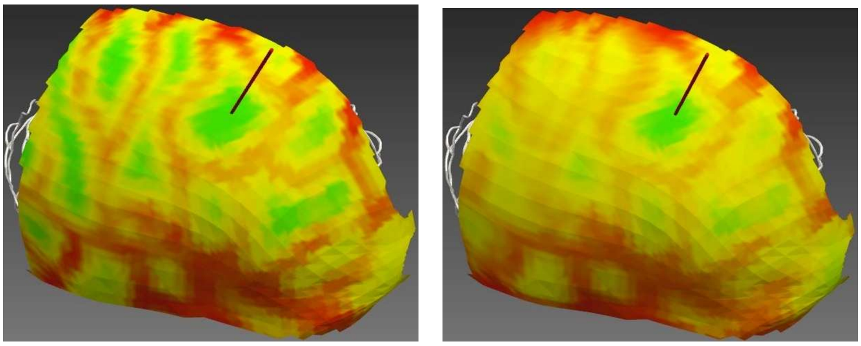
(a) Without brain shift (b) With brain shift

Fig. 5: Color maps representing the risk in relation to the proximity of the vessels, computed without/with taking into account a possible brain shift. In green the safest zones, in red the zones to avoid.

3.2 Integration in Planning Software

We compared the brain shift aware risk map with the regular distance map on the template. The result can be seen on Fig.5, which contains snapshots from the planning software. Two color maps corresponding to soft constraints are shown: (a) with regular distance computation (static vessels), and (b) the brain-shift aware risk map computed by the simulation. We can see that the green areas, corresponding to safe insertion points, are narrower and less numerous using our risk map. Only the areas that would be safe even with a brain shift are kept. However, sufficient number and surface of green areas are still present.

On Fig.6, the final result of the automatic optimal trajectory planning, including several constraints other than distance to the vessels, is shown for the template. We can notice that even with the restriction of the safe areas due to our risk map, an optimal trajectory can still be found within the range of the average angles relatively to AC/PC that are used as a basis in clinical routine (around $60°$ in antero-posterior and $30°$ latero-median axis).



(a) Without brain shift (b) With brain shift

Fig. 6: Optimal trajectory (red cylinder): trajectory satisfying at best the combination of soft constraints. In green the best zones, in red the zones to avoid.

4 Conclusion

In this paper we described a physics-based method for simulating deformations of cerebral structures and landmarks caused by the brain shift during deep brain stimulation surgery, according to a position of the burr hole and an estimation of the CSF loss. More particularly, we estimated the movement of the vessels which need to be avoided during the insertion of the electrode. We emphasize that our method does not pretend to provide an exact estimation of the brain deformation or vessel motion at the pre-operative planning step, as it is not possible to anticipate the exact CSF loss before the surgery, or other physiological parameters. To compensate for some uncertainties in the simulation (such as exact CSF loss), and to account for other possible errors (such as segmentation of the vessels and other structures on the patient data), we proposed to embed both vessel motion and estimated error into an advanced distance map. This map was used in a path planning software to produce optimal electrode placements.

The results of our experiments show the benefits of such a simulation, as it does not restrict too much the possible insertion areas but provides safer trajectories regarding the possibilities of brain shift. In the future, we will continue improving the simulation and planning methods. In particular we plan to better determine the influence of the CSF loss (as done in [5]) through additional studies. We also plan to rely on intra-operative images to assess our prediction for the brain shift and vascular motion, and use it to adjust the planned trajectory just after skull opening.

Acknowledgment The authors would like to thank the French Research Agency (ANR) for funding this study through the ACouStiC project.

References

1. Benabid, A., Chabardes, S., Mitrofanis, J., Pollak, P.: Deep brain stimulation of the subthalamic nucleus for the treatment of parkinson's disease. The Lancet Neurology 8(1), 67–81 (2009)
2. Bériault, S., Subaie, F., Mok, K., Sadikot, A., Pike, G.B.: Automatic trajectory planning of DBS neurosurgery from multi-modal MRI datasets. In: MICCAI 2011. LNCS, vol. 6891, pp. 259–266. Springer (2011)
3. Brunenberg, E., Vilanova, A., Visser-Vandewalle, V., Temel, Y., Ackermans, L., Platel, B., ter Haar Romeny, B.: Automatic trajectory planning for DBS: A feasibility study. In: MICCAI'2007. LNCS, vol. 4791, pp. 584–592 (2007)
4. Duriez, C., Dubois, F., Kheddar, A., Andriot, C.: Realistic haptic rendering of interacting deformable objects in virtual environments. Visualization and Computer Graphics, IEEE Transactions on 12(1), 36–47 (2006)
5. Elias, W., Fu, K., Frysinger, R.: Cortical and subcortical brain shift during stereotactic procedures. Journal of Neurosurgery: Pediatrics 107(5) (2007)
6. Essert, C., Haegelen, C., Lalys, F., Abadie, A., Jannin, P.: Automatic computation of electrode trajectories for deep brain stimulation: a hybrid symbolic and numerical approach. IJCARS pp. 1–16 (2011)
7. Felippa, C., Haugen, B.: A unified formulation of small-strain corotational finite elements: I. theory. Computer Methods in Applied Mechanics and Engineering 194(21), 2285–2335 (2005)
8. Ferrant, M., Nabavi, A., Macq, B., Jolesz, F., Kikinis, R., Warfield, S.: Registration of 3-d intraoperative mr images of the brain using a finite-element biomechanical model. IEEE Transactions on Medical Imaging 20(12), 1384–1397 (2001)
9. Letteboer, M., Willems, P., Viergever, M., Niessen, W.: Brain shift estimation in image-guided neurosurgery using 3-d ultrasound. Biomedical Engineering, IEEE Transactions on 52(2), 268–276 (2005)
10. Miyagi, Y., Shima, F., Sasaki, T.: Brain shift: an error factor during implantation of deep brain stimulation electrodes. Journal of Neurosurgery 107(5), 989–997 (2007)
11. Shamir, R., Tamir, I., Dabool, E., Joskowicz, L., Shoshan, Y.: A method for planning safe trajectories in image-guided keyhole neurosurgery. In: MICCAI 2010. LNCS, vol. 6363, pp. 457–464. Springer (2010)