Survey of Computer-Aided Brain Surgery Tools

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Abstract

In this paper we investigate the interfering of computer systems in the process of neurosurgery. We survey the state-of-the-art algorithms and techniques that are used in the brain diseases diagnosis and surgery planning. These algorithms include image processing techniques, visualization of multi dimensional data, and navigational systems.

1. Introduction

Computer-assisted brain surgery revolutionized the diagnosis and treatment of deep lesions in the brain. Today, it is an irreplaceable tool for treatment of brain tumors, epilepsy, movement disorders and other conditions.

The first step in computer-assisted brain surgery is to gather detailed images of the brain using MR, CT, PET and other imaging technologies. The imaging is done with reference points so that the brain is mapped in three dimensions.

Computer systems reconstruct these images into detailed 3-D models of the patient's brain, which highlight critical structures in the brain along with abnormalities. The model allows the neurosurgeon to plan the safest and least invasive route possible to treat the problem. During the operation, the system guides the surgeon precisely to the target.

Computer-assisted brain surgery has expanded the capabilities to treat disease more safely and accurately. Computer-assisted surgery usually means a smaller incision and less risk of injury to critical brain structures. As a result, patients typically experience less postoperative discomfort, blood loss and anesthesia time and shorter hospital stays than with a traditional craniotomy.

In the rest of this paper, we are going to explore the state of the art tools and algorithms used to perform the different stages of the computer-aided neurosurgery. The paper is organized as follows; section 2 is a discussion about the most relevant brain scans and the different types of information provided by each format. Section 3 describes different techniques that are used to analyze the patients' data. These techniques span the image processing and classification areas. Then in section 4, we surveyed the latest visualization techniques that build 3-D models for the patient's brain with high accuracy and low computing time. Planning for the neurosurgery by locating the target area and finding the optimal path to reach this point is discussed in section 5. Section 6 discussed the interfering of computer systems during the operation itself and the advantages of using robots to help the surgeon in handling the critical areas in the brain. Finally a conclusion for the whole paper is presented in section 7.
2. Medical Imaging Devices Used in Neurosurgery

The main imaging scans that are used in neurosurgery diagnosis are MRI, CT, fMRI, and DTI. Each of them has its points of strength and its shortages. They are complementary and the surgeons need the data that are determined by all of them to get both the big picture and the fine details of the patient's case.

2.1 Magnetic Resonance Imaging (MRI) scan

MRI uses magnetic fields to generate images of the brain. Using powerful software, MRI scans outline the normal brain structures in great detail, as well as provides information about physiology and chemistry. Sometimes a special dye is injected into the bloodstream to make tumors more distinguishable from healthy tissue (MR angiography). MRI is more sensitive than CT scanning for confirming the presence of a brain tumor [1].

2.2 Computerized Tomography (CT) scan

Computed tomography (CT) scanning, also called computerized axial tomography (CAT) scanning, is a medical imaging procedure that uses x-rays to produce detailed, two-dimensional images of the brain [2].

A CT imaging system produces cross-sectional images or "slices" of areas of the body. These cross-sectional images are used for a variety of diagnostic and therapeutic purposes.

A CT scan is painless and generally takes less than 10 minutes. While MRI is often the preferred imaging tool, CT can be very helpful in certain types of tumors, especially ones close to or involving bone. CT is superior to MRI in viewing bone areas.

2.3 Functional Magnetic Resonance Imaging (fMRI) scan

Functional magnetic resonance imaging (fMRI), gives a clearer picture of the brain in action and what brain tissue is relevant to accomplishing a given task, such as raising a hand or reading a sentence. Basically, fMRI detects changes in the brain's blood flow that occur when performing specific tasks. The result is a color-coded image that shows surgeons areas of the brain where permanent injury should be avoided. Although there's general understanding of where these important brain centers are, they vary by individual [3].

2.4 Diffusion Tensor Imaging (DTI)

Diffusion tensor imaging (DTI) is a magnetic resonance imaging (MRI) technique. The main area in which diffusion tensor imaging (DTI) is used is when imaging white matter of the brain. The way in which axon bundles are oriented determines how
water flows: i.e. parallel bundles of axons and their associated myelin sheaths make diffusion of H2O molecules easier along the main direction. This property can be imaged and measured with diffusion tensor imaging. Basically, magnetic field variations of the MRI magnet are applied in at least six different directions, which makes it possible to calculate a tensor for each voxel that shows the three dimensional shape of the diffusion pattern. With DTI white matter lesions can be found that do not show up on other MRI/imaging techniques, and can also be used to localize tumors. To do this, the brightness and mean diffusivity are measures used in a clinical setting. Diffusion tensor imaging data can also be used to track a fiber, or path, through which information travels in our brain. As such, DTI can perform a tractography within white matter and track the path of our neural impulses from the brain, down to the spinal cord and into the peripheral nerves. Combining DTI data with the computational methods of MR tractography, neuroscientists can estimate the locations and sizes of nerve bundles (white matter pathways) that course through the human brain [4].

3. Analysis of the Medical Data

Acquiring medical data such as CT and MR perfusion data is essential for diagnosing different diseases e.g., ischemic stroke diagnosis, the assessment of different types and stages of tumors, and the detection and diagnosis of coronary heart disease (CHD).

Perfusion data is dynamic contrast-enhanced image data. It consists of a sequence of images, acquired after a contrast agent bolus is applied [5].

Visual exploration of perfusion data is not an easy task. Firstly, the acquired images are of questioned quality as they exhibit various artifacts. Secondly, there is no absolute scale for the intensity values exists. Moreover, five to eight parameters are needed to be derived for each voxel of the perfusion data. The correlation between these parameters as well as the local distribution of single perfusion parameters is essential for the explanation of the data [5].

3.1 Medical Data Parameters

In this section, we are going to explore the most common parameters extracted from the acquired images that are used for diagnosis purposes.

Modern CT and MRI devices can measure the effects of perfusion in high spatial and temporal resolution. In perfusion imaging, the distribution of contrast agents (CAs) is registered to assess blood flow and tissue kinetics. The point in time when the signal enhancement actually starts is represented by CA arrival, whereas TimeEnd refers to the end of the first CA passage. The average intensity before CA arrival is represented by the Baseline [6].

The most important perfusion parameters that are used for diagnosis are:
Peak Enhancement (PE); which is the maximum value normalized by subtracting the baseline.

Time To Peak (TTP); which is the point in time where PE occurs, normalized by subtracting the CA arrival time. This parameter allows assessing whether blood supply is delayed in a particular region. If the peak is not a significant maximum or the temporal resolution is low, the TTP value is not expressive. The signal change in the interval between CA arrival and TTP is referred to as wash-in, whereas the signal change in the time between TTP and TimeEnd is referred to as wash-out.

Integral; for a certain time interval (often representing one cycle, or pass, of blood flow), the area between the curve and the baseline, which is the approximated integral, is computed. Together, PE and Integral allow one to assess whether the blood supply is reduced in a particular region. Reduced and delayed blood supply is a strong indicator for a damaged region.

Mean Transit Time (MTT); In the time interval used for the integral calculation, MTT specifies the point in time where the integral is bisected. It is normalized by subtracting CA arrival.

The Slope; characterizes the steepness of the curve during wash-in. Depending on the temporal resolution, different regression methods, such as the Gamma-Variate and a linear fit, are used to characterize the curve progression.

The DownSlope; characterizes the steepness of the descending curve during wash-out and is computed similar to the Slope.

There exist various software packages that are used to analyze perfusion data for selected pixels and regions as well as the display of parameter maps. As examples for these packages; the SIEMENS Syngo, Neuro Perfusion software, and Philips CT perfusion software.

3.2 Preprocessing Perfusion Data

Due to the special nature of the images acquired from the patients, special treatments to the images are needed before we can use it to extract information from them.

The most common techniques applied to preprocess the perfusion images are motion correction, temporal denoising, and calibration of signal intensities. Brief description is illustrated below.

A. Motion Correction

Motion correction is used to ensure that the voxel with coordinates (x,y,z) at time t1 corresponds to the voxel with coordinates (x,y,z) at time t2. It is needed because the intervoxel correspondence is hampered due to breathing, patient movement, muscle relaxation, or heartbeat. To solve this problem elastic registration algorithms which considers local transformation are used. A registration algorithm proposed in [7] used
normalized mutual information as similarity measure, is considered a basic algorithm in this area of applications.

B. Temporal denoising

Acquired images exhibit high-frequency noise so smoothing is needed in the temporal dimension for accurate analysis. One of the effective algorithms is proposed in [8], the authors introduced an appropriate filter based on partial differential equations, which simulate a diffusion process.

C. Calibration of signal intensities

Another important aspect of the perfusion data; is the signal intensity. Every signal (e.g. MRI, CT) is measured in different units. So, we need to calibrate the raw signal intensities versus CA concentration. For example, as proposed in [9] the gradient-echo MR can be calibrated based on the assumption of a linear correspondence between the signal intensity and the CA concentration.

3.3 Techniques of Perfusion Data Analysis

After we enhance the quality of the medical data, we come to the point that we want to analyze these data, trying to extract valuable information and diagnose the patient's case. In this section we will explore some fundamental techniques [10] that are used to analyze the perfusion data.

A. Subtracting Images

This is a straightforward technique that can provide valuable information for diagnosis. It is used to visually detect abnormalities. This technique depends on injecting the patient with CA and then subtracting the images at different points in time. Comparing the images helps in determining the suspicious regions. The subtraction is depicted the intensity difference between the two corresponding pixels of two images, each image is acquired at different point in time. If the subtraction leads to negative values, it means that the pixels are not correspondent to each other and so motion correction is needed. This is a simple technique that does not need time consuming computations or complex user interaction. One problem with this technique is how to choose the right points in time for subtracting the images.

B. Multi-Parameter Maps

A Parameter map depicts the perfusion parameter value in a pixelwise manner. It is displayed as a color coded image. In order to provide the user with more illustrating tool, multi-parameter maps are used where simultaneous parameters are visualized. Different approaches are used for multi-parameter maps such as combining isolines and color coding, colored height fields, and exploration of multiple parameter images with lenses. These tools are reported to be of great help in diagnosis because it integrates information from more than one perfusion parameter in one image.
C. Statistical Analysis

A different approach is used in analyzing the medical data, which is the statistical analysis. Well known techniques in the literature of pattern recognition and artificial intelligence are used in classifying MRI data. For example, Chen et al. [11] proposed a fuzzy c-means clustering technique that identifies characteristic kinetic curves from MRI data. Also Nattkemper et al. [12] developed Self Organized Maps (SOM) to time curve features MRI data. Using artificial neural networks and clustering techniques which combine supervised and unsupervised techniques in classification of perfusion data are an active research area.

4. 3D Visualization of the Medical Data

A recent GPU-based approach that is developed by Johanna Beyer [13] for multi volume brain surface visualization begins by applying the skull peeling algorithm. The target of the skull peeling is to remove the occlusions of the points that have similar intensities (like bones and skin) and occlude the brain. The results obtained from skull peeling are saved to be used later as segmentation masks. The segmentation mask can tell us which voxel belongs to what object.

After visualizing the inside of the skull in the previous step, surgeons now in need to determine the functional areas in the brain.

In Beyer’s work [13]; he combined the fMRI and MRI data together by using multi volume blending. Each volume has its own individual transfer function. The volume contributions are combined during ray-casting by applying the transfer functions of all volumes at each sample location and combining the classified values. For visualizing functional data such as fMRI along with anatomical data, the fMRI values can be used for color classification while the anatomical data determines the opacity values.

Rieder et al. [14] proposed a new visualization technique that enables the surgeon to visualize both anatomical and functional data together. The basic idea is to have two views; internal view and external view for every multi modal dataset where each point in the first view corresponds to a point in the second one.

The internal view contains all the functional areas and the fiber tracts and the lesion. The external view contains the skull, the brain, and the functional areas. Both views are depicted in figure 1.
They used two-dimensional transfer function, the first is to visualize the opaque lesion structures and the second is to visualize the transparent anatomy. The authors combine different methods to enhance the visualization results, based on the distance between the to-be rendered voxel and the region of interest (ROI). Any voxel that is far enough from the ROI is discarded, that leads to better viewed images as non important objects are not shown.

The authors use multimodal data and offer distance-based enhancements of functional data and lesions and allow the visual exploration of the surgical approach to the structure of interest by advanced clipping and cutaway tools.

5. Planning for the Neurosurgery

Planning to the neurosurgery consists of two main steps. First, locate the functional areas in the brain. Second step is automatic path planning for the neurosurgery with minimal interaction from the surgeon. It is all about minimizing the risk of neurosurgeries by providing accurate images to the patient's brain, so that the surgeon can plan and train to the operation before doing it in real.

5.1 Locating the Region of Interest

One of the state-of-the-art methods is introduced in Beyer's thesis [13]. He proposed to apply segmented multi volume rendering. First, he performs a prior segmentation for the regions of interest, and then he applies different transfer functions and rendering mode for each region. The transfer function and the rendering mode are set according to the ID of the object. This method so far doesn't give good results especially if the objects are small size, where staircase effect appears in the rendered image. To solve this problem, he performs smoothing rendering. This is done during ray casting. For each sample, the gradient is computed in the positive and the negative directions to guess whether a new object exists or not. This depends on the fact that the gradient is high at the boundaries where sharp change in the intensities occur. When a boundary detected, its intensity is compared to the current object and to its adjacent (neighbor) object then it is assigned to the most similar.

Beyer's work gives good results according to his reported figures. He introduces four different visualization techniques; skull peeling, multi volume blending, segmented
multi volume rendering, and smoothing segmented multi volume. They vary according to the need of the surgeon. The performance ranges from 10 to 35 frames per second. The best images are achieved by the smooth segmented multi volume. The main problem with this method is its need to specify a lot of parameters which can change the results dramatically. These parameters should be set by the user such as the transfer function, the rendering mode, and the value of the boundary.

Another visualization technique is proposed by Brecheisen et al. [15]. Their main contribution is visualizing the multi modal medical data interfering with geometric shapes (e.g., surgical tools, reference grids, 3D measurement widgets) using flexible GPU-based multi volume ray casting.

The algorithm consists of a combination of two algorithms; depth peeling and GPU-accelerated ray casting. It simply renders the front face and store the fragment depth and color. The rest of faces entering the loop are compared to the stored depth, if the coming one is less than the stored one this new fragment is discarded. This depth peeling is followed by ray casting from the first layer to the second layer.

To solve the problem of identifying an object within the volume data we have, the authors view the problem as follows: there is an intersection between an object and other regions in the rendered volume. They propose a set of solutions that can be applied interchangeably: Priority selection, Opacity-weighted average, 2D intersection transfer function, and Intersection color. The difference between them is illustrated in figure 2.

![Figure 2. Different intermixing schemes: (A) priority selection where volume 1 has priority, (B) opacity-weighted average, (C) intersection color (magenta) and (D) 2D intersection transfer function [15].](image)

The authors used their proposed technique to detect a tumor within a dataset of fMRI and DTI images. The tumor is treated as a geometrical surface that intersects the data volumes. Their result as reported in [15] is shown in figure 3.
Figure 3. Multimodal view of head, tumor (T1-weighted MRI), cortical activations (fMRI) and fiber tracts (DTI) [15].

Though the results shown in their paper are pretty good, this technique is not used yet in clinical applications and so it is not tested by enough datasets with different cases to ensure its reliability. We also note that this algorithm behaves the best when the number of depth layers is few, however when layers increase ray casting iterations increase and the performance dramatically decays.

5.2 Safest Path Planning

Brain Surgery Path Planning System is the most important part of The Computer-Assisted Surgery. The relevance for automated path planning becomes clear in the work of Brunenberg et al. [16]. Their partnering neurosurgeons estimate a time gain of 30 minutes during pre-operative planning when using the authors’ method for automated trajectory proposition, which effectively means that the planning time is halved. A segmentation of anatomy is performed in terms of blood vessels, ventricles and sulci of the cortex. An Euclidean distance map allows the calculation of paths with maximum distance to critical structures and thus minimal risk.

Rieder et al. [14], proposed a technique to suggest the safest path to the damaged area in the brain without putting the functional areas at risk. After visualization phase is completed as discussed in section 4, the surgeon now can search for the optimal path between the point of incision and the ROI point. In the internal view, the path is represented by a line connecting the two points, while in the external view it is represented by a cylinder. The path is very flexible, the view is updated accordingly, and the path thickness (cylinder radius) and direction can be changed.

The beauty in their method is that the surgeon can explore the path while observing the functional areas around the path at the same time. After the path is computed and visualized as shown in figure 4, they add landmarks to the brain and the skull to give more support for the surgeons.
Regarding the visualization methods, the paper didn’t actually present a new technique although they combine previously known enhancement methods in one integrating system. The authors assumed that the path to the region of interest should be a straight line. Their system needs to be more generalized to make it possible for the user to explore more complicated forms of paths, putting into consideration that a tumor can exist in a deep difficult area in the brain and the surgeon must take more than straight line move to reach it. Also, it will be more convenient if the system enable the user to compare between different paths at the same time to choose the safest path in case there is no optimal path.

6. Robot NeuroNavigation

The last point that the computer is interfering in the process of neurosurgery is during the surgery itself. Research projects are investigating the possibility to use robots to perform the tasks defined by the surgeon inside the patient's brain during the surgery.

6.1 Da Vinci System

The most well known robotic system that is used in many hospitals around the world is Da Vinci teleoperated system [17]. It consists of three components: a surgeon’s console, a patient-side robotic cart with 4 arms manipulated by the surgeon (one to control the camera and three to manipulate instruments), and a high-definition 3D vision system. Articulating surgical instruments are mounted on the robotic arms which are introduced into the body through cannulas. The device senses the surgeon’s hand movements and translates them electronically into scaled-down micro-movements to manipulate the tiny proprietary instruments. It also detects and filters out any tremors in the surgeon's hand movements, so that they are not duplicated robotically. The camera used in the system provides a true stereoscopic picture transmitted to a surgeon's console.

We described in brief Da Vinci robotic system as it is a general surgery robotic system. Though it proves its success and was used in some neurosurgery cases.

6.2 ROBOCAST
A very large and complex project named ROBOCAST [18, 19] is aiming to design and implement an integrated robot-assisted system that is capable of keyhole neurosurgery. Its goal is to holding instruments and inserting them in the brain with smooth and precise movement according to surgeon’s needs. This task is accomplished through intelligent system that is able to understand and manage the surgeon’s inputs together with diagnostic information from the patient and moreover with data reporting the 3D position of the operating device in the Operating Room.

The core of this system is the trajectory computation; where automatic trajectory is computed based on a risk atlas. This risk volume is computed from a head MRI that incorporates major risk factors. First, the blood vessels are manually segmented. Then distance map is computed on the unified segmented volumes using the method suggested by Danielson P. E. [20]. The risk volume is then computed as the inverse of the distance map such that a voxel that is further from the segmented zones is assigned with a lower risk value.

After computing the robot path, we come to the details of the navigation system. Navigation systems for intra-operative guidance require pose estimation of both patient and instruments. ROBOCAST used optical tracking for validation of robot and probe positions. The tracking system consists of a n-occular synchronized camera system, using linear, CCD or matrix cameras. In order to determine the pose of an instrument or patient, a marker body has to be rigidly attached to the target object. This marker body typically consists of a set of fiducials, which are either light-emitting or retro-reflective. During the process of tracking a target, the n-occular camera system generates 2D images of the fiducials. From the imaged 2D-marker position, the 3D position of the markers, the marker body and eventually of the tool can be determined.

6.3 NeuroArm

NeuroArm [21] is a recent teleoperated anthropomorphic robot from a University of Calgary led consortium. The MRI compatible robot (up to 1.5 Tesla magnetic field) is made for stereotaxy and microsurgery. Beyond motion scaling and high definition visual feedback, the neuroArm is able to provide very accurate 3D information of its two 7 DOF arms. It uses three displays to give a complete visual coverage on the operating environment, showing in parallel the 3D stereoscopic view of the operation, the MR image of the patient and the control panel.

NeuroArm is a MRI-compatible image-guided computer-assisted device specifically designed for neurosurgery. It performs both microsurgery and biopsy-stereotaxy applications. The system includes a workstation, a system control cabinet, and two remote manipulators mounted on a mobile base. For biopsy-stereotaxy, either the left or right arm is transferred to an extension board that attaches to the OR table and the procedure is able to be performed inside the MRI bore.
NeuroArm includes two MR compatible manipulators with end-effectors that interface with microsurgical tools. It includes filters to eliminate unwanted tremors. End-effectors are equipped with three-dimensional (3D) force-sensor, providing the sense of touch. The surgeon seated at the workstation controls the robot using force feedback hand controllers. The workstation recreates the sight and sensation of microsurgery by displaying the surgical site and 3D MRI displays, with superimposed tools.

There is no wide use of neuro-robotic system in the operation room till now. The reasons are that they did not give enough advantages to the users with respect to the inherent disadvantages. These were mainly the high cost, the long time required for setting up, the huge size and the poor integration within the standard instrumentation present in the operating room.

7. Conclusions

Computer systems play distinct important roles with respect to the support of neurosurgery operations starting from imaging devices and ending by robotics surgery.

Special software packages and hardware are needed to perform such tasks in real time and with high accuracy. In our survey paper we focused on the techniques of image processing and visualization of multimodal data. They are effective tools and widely used by surgeons to get more comprehension of the patient's case.

Computer-aided neurosurgery tools are of great value to the patients' sake. It enables the doctors to acquire data of different formats and register them in one image. Analysis techniques can inform the doctors with even more knowledge and give them diagnosis options. Planning and training for the surgery is possible thanks to the 3D visualization techniques. The computer-aided neurosurgery tools can be divided into two categories; preoperative tools and intra operative tools.

Tools used in the pre-operative stages are highly accepted by the users although they complain from the complicated interfaces in some cases, and also from having to input so many parameters to the software they use.

While intra-operative interference is still unacceptable by the neurosurgeons. Most existing systems are considered experimental at their preliminary phase and lack enough reliability.

Till now and according to our knowledge, there is no one integrating computer system that can do all the functions required to perform the different stages of the neurosurgery.

We can summarize the main functions that the computer systems can help within in the process of neurosurgery as depicted in Table 1.
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