Virtual reality presurgical planning for cerebral gliomas adjacent to motor pathways in an integrated 3-D stereoscopic visualization of structural MRI and DTI tractography

Tian-ming Qiu · Yi Zhang · Jin-Song Wu · Wei-Jun Tang · Yao Zhao · Zhi-Guang Pan · Ying Mao · Liang-Fu Zhou

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Abstract
Objective Resection of gliomas invading primary motor cortex and subcortical motor pathway is difficult in both surgical decision-making and functional outcome prediction. In this study, magnetic resonance (MR) diffusion tensor imaging (DTI) data were used to perform tractography to visualize pyramidal tract (PT) along its whole length in a stereoscopic virtual reality (VR) environment. The potential value of its clinical application was evaluated.
Methods Both three-dimensional (3-D) magnetic resonance imaging (MRI) and DTI datasets were obtained from 45 eligible patients with suspected cerebral gliomas and then transferred to the VR system (Dextroscope; Volume Interactions Pte. Ltd., Singapore). The cortex and tumor were segmented and reconstructed via MRI, respectively, while the tractographic PTs were reconstructed via DTI. All those were presented in a stereoscopic 3-D display synchronously, for the purpose of patient-specific presurgical planning and surgical simulation in each case. The relationship between increasing amplitude of the number of effective fibers of PT (EPT) at affected sides and the patients’ Karnofsky Performance Scale (KPS) at 6 months was addressed out.
Results In VR presurgical planning for gliomas, surgery was aided by stereoscopic 3-D visualizing the relative position of the PTs and a tumor. There was no significant difference between pre- and postsurgical EPT in this population. A positive relationship was proved between EPT increasing amplitude and 6-month KPS.
Conclusions 3-D stereoscopic visualization of tractography in this VR environment enhances the operators to well understand the anatomic information of intra-axial tumor contours and adjacent PT, results in surgical trajectory optimization initially, and maximal safe tumor resection finally. In accordance to the EPT increasing amplitude, surgeon can predict the long-term motor functional outcome.

Keywords Diffusion tensor imaging · Glioma · Outcome · Tractography · Virtual reality

Abbreviations
DEC Directionally encoded color
DTI Diffusion tensor imaging
EPT Effective fibers of pyramidal tract
fMRI Functional magnetic resonance imaging
HGG High-grade glioma
KPS Karnofsky Performance Scale
LGG Low-grade glioma
MRI Magnetic resonance imaging
PT Pyramidal tract
ROI Region of interest
VR Virtual reality

Tian-ming Qiu and Yi Zhang contributed to this paper equally.

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Surgical treatment of cerebral glioma involving eloquent area is always a challenge for neurosurgeons. Risk increases in cases of which the glioma is located closely to the central gyri and subcortical motor pathways [15, 24]. Information regarding the infiltrative tumor and invaded motor cortex and subcortical motor pathway is critical in both surgical decision-making and outcome prediction. However, it is often difficult to visualize the relationship between lesions and pyramidal tracts (PTs). Any methods that can increase neurosurgeons’ understanding of the anatomy or enhance the safety of resection will be welcomed [30].

Conventional magnetic resonance imaging (MRI), functional MRI, and magnetoencephalography, together with neuronavigation, are of great value in the localization of the sensorimotor cortex and the lesions [7, 8, 11]. Nevertheless, they have limitations for PTs depiction. Recently, fiber tracking algorithms become a unique technique to trace brain pathway in vivo with diffusion tensor imaging data. A number of researchers have used diffusion tensor imaging (DTI) tractography to map subcortical PTs, including tract origination in the primary motor cortex, convergence in the centrum semiovale, the posterior limb of the internal capsule, and the cerebral peduncles [4, 23, 33]. Its estimation of PT’s orientation and strength is increasingly accurate; therefore, there have been widespread potential implications in the field of surgical planning for several types of brain tumors. Our preliminary study has already introduced the clinical feasibility of such procedures [19, 30].

However, information of depth would not be shown clearly if the fiber tracts were rendered by lines with the constant width without visualizing the tumor and peritumoral tissue synchronously. Recently, a stereoscopic three-dimensional (3-D) virtual reality (VR) system was applied to integrate multimodality medical images, including MR T1-weighted image (T1WI), T2-weighted image (T2WI), and DTI tractography [13, 21, 27, 31]. Usually, T1WI and T2WI data sets were used to delineate tumor stereoscopically and provide anatomical information. DTI data set can be used to perform tractography within white matter. Fiber tracking algorithms can be used to trace a fiber along its whole length (e.g., the PT, through which the motor information transits from sensorimotor cortex to the spinal cord) [13]. Thus, the cortex, tumor, and the tractographic PT can be reconstructed and visualized in a stereoscopic 3-D display synchronously. In addition, an interactive controller was employed to interact with this VR system. Using this controller, the virtual cranium model that comprises cortex, tumor, and whiter matter tracts can be exposed and manipulated freely. The aim of this study was to comprehensively assess the VR presurgical planning, which depends on the DTI tractography, for surgical rehearsal of cerebral gliomas with PT involvement and its effects on decreasing motor deficits, predicting life quality.

Patients and methods

Patient population

Between March 2007 and May 2008, 45 patients with suspected cerebral gliomas involving PTs were enrolled in this study. Eligible patients were aged 4–70 years with admitting diagnosis of single, unilateral, supratentorial primary glioma. The lesions were involved in PTs, comprising cortical regions in the sensorimotor areas, cortical regions adjacent to the central gyrus, subcortical regions with an infiltrative progression along the PTs, and temporal or insular lobes in relation to the internal capsule. No contraindications for MRI scan were present. The exclusion criteria were as follows: patients with secondary or recurrent gliomas, patients with contraindications for MRI scan, and patients for whom initial muscle strength grade of the affected extremities was 0/5 (no contraction at all). This study included 19 female and 26 male patients with a mean age of 46.0±17.98 years (range, 4–70 years). All patients were eligible for surgery based on clinical aspects and imaging evaluations. For histopathological diagnoses, the World Health Organization (WHO) classification of tumor of the nervous system (2007) was used (Table 1).

3-D MRI data set acquisition

The routine 3-D MRI data set was acquired with a 3.0-T whole-body MRI scanner (General Electric Medical Systems, GE Signa VH/i) using the T1-weighted 3-D fast spoiled gradient-recalled sequence after intravenous contrast administration (gadolinium diethylenetriamine pentaacetic acid). The parameters were as follows: repetition time (TR), 11.7 ms; echo time (TE), 5.1 ms; flip angle, 20°; thickness, 1.25 mm; pixel matrix, 320×224; field of view (FOV), 240×240 mm; number of excitations (NEX), 1. Totally, 80 to 150 contiguous axial slices were acquired for complete coverage of the tip of the nose and the top of the head in approximately 10 min. The fluid attenuation inverse recovery (FLAIR) T1WI (fast spin-echo sequence; TR, 2,025 ms; TE, 15 ms; inversion time (TI), 860 ms; flip angle, 90°; echo train, 10; FOV, 240×240 mm; matrix size, 320×224; section thickness, 2 mm; NEX, 2; axial section) or FLAIR T2WI (spin-echo sequence; TR, 8,500; TE, 120; TI, 2,250 ms; flip angle, 90°; FOV, 240×240 mm; matrix size, 320×224; section thickness, 2 mm; NEX, 2; axial section) of
the brain were acquired whenever the operating neurosurgeon or the attending neuroradiologist considered them to be appropriate, which were primary for low-grade (WHO I–II) gliomas (LGGs) with non-enhancing lesions.

**DTI data set acquisition**

The DTI data set was acquired in the corresponding time period, covering the entire brain volume with the following parameters: single-shot spin-echo echo planar imaging sequence; TR, 8,000 ms; TE, 84 ms; axial section thickness, 5 mm; section space, 0 mm; matrix size, 128×128; FOV, 240×240 mm; NEX, 1. The number of diffusion encoding directions for each slice was 25. Usually, 29 axial slices were acquired for complete coverage of the cerebra in approximately 5 min.

**Working in VR environment**

Each set of individual 3-D MRI and DTI data sets were transferred into the VR system (Dextroscope, Volume Interactions Pte. Ltd., Singapore) through a compact disk. In brief, volume rendering was constructed to generate a patient-specific 3-D stereoscopic cranium model. The virtual cranium model was displayed on a monitor (1,024×768 pixels) and reflected via a mirror into the user’s stereoscopic glasses. The electromagnetic sensors conveyed the interaction of the hands with the computer. The operator held an interactive controller with 6° of freedom in the left hand and a stylus in the right hand. By using various registration and segmentation tools (e.g., cloning, extracting, contouring, and so on) and visualization and virtual surgical instruments (e.g., picking, cropping, cutting, and drilling), the anatomic structure of interest was extracted and displayed in a stereoscopic 3-D display.

**Fiber tracking**

To aid in the stereoscopic visualization of the fiber tracts, we used the Fiber Tracking module of the VR system. Firstly, registration was performed between DTI and 3-D MRI Data sets.Registration is the process of correctly positioning and orientating two objects in relation to each other. Secondly, fiber generation was selected to adjust the parameters for fiber tracking. Constantly, the fractional anisotropy (FA) threshold value was defined as 0.18 for tracking. Tracking stopped when the FA value was below the defined threshold. The lengths ranged between 0 and 400 to generate fibers in proper size. Maximum deviation angle was set at 40° to control the curvature of fibers. Thirdly, an Add tool was used to add a region of interest (ROI), the size of which could be adjusted. Three paired ROIs were put on symmetric sides of the axial, in which, one was on the level of cerebral peduncles, another was on the level of posterior limb of internal capsule, and the third was beneath the motor cortex (Fig. 1a–c). Intersection mode was selected to refine the fiber tracts that pass through all the intersect ROIs simultaneously, which assured to be the PTs in this study. Finally, fiber tracts are displayed on a directionally encoded color (DEC) map, in which, red indicates directions in the x-axis (left–right), green indicates directions in the y-axis (anterior–posterior), and blue indicates directions in the z-axis (head–foot), respectively. PTs were primarily displayed in blue (Fig. 1d).

**Segmentation of glioma**

Segmentation tools were great aids to extract the tumor from the brain tissue on 3-D MRI, which enabled operator to observe the spatial relationship between the tumor and other components. Two main tools were used to perform the segmentation of tumor. One is the Contour Editor tool that was used when the surfaces are not clearly defined and automated techniques are unable to produce good results. This manual extraction method was used to extract low-grade gliomas in this study. The other is the Extract Component tool which was an aid to extract the well-defined tumor within the segmentation box automatically.

**Presurgical planning**

An individual presurgical project was meticulously planned in each case. Fiber tracking and segmentation of gliomas were performed to acquire better understanding of anatomical relationship between the tumors and tracts (Fig. 2a, b), including the direction of the PT to the tumor, how the lesion invaded the PT, and the distance between them. All those information helped us in determining the patient’s position, surgical approach, and possible extent of the tumor.

<table>
<thead>
<tr>
<th>Histological diagnoses and WHO grading (2007)</th>
<th>Total</th>
<th>Right side</th>
<th>Left side</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilocytic astrocytoma I</td>
<td>1 (2.22%)</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Astrocytoma II</td>
<td>15 (33.33%)</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>Oligodendroma II</td>
<td>7 (15.56%)</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Ependymoma II</td>
<td>2 (4.44%)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Anaplastic astrocytoma III</td>
<td>6 (13.33%)</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Anaplastic oligodendroma III</td>
<td>4 (8.89%)</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Gliosarcoma IV</td>
<td>1 (2.22%)</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Glioblastoma multiforme IV</td>
<td>7 (15.56%)</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Non-glioma</td>
<td>2 (4.44%)</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>45 (100%)</strong></td>
<td><strong>24</strong></td>
<td><strong>21</strong></td>
</tr>
</tbody>
</table>
resection. During VR presurgical planning, operator held a 6-D controller in the left hand, while a stylus in the right hand, using different virtual surgical instruments to rehearse the operation. Operator visualized the anatomical relationship between the lesion and PT (Fig. 2c), measured in-between distance (Fig. 2d) and designed various surgical approaches by using the tools (e.g., picking, cropping, cutting, drilling, etc.). In the end, an optimal patient-specific plan would be determined.

**Perioperative evaluations**

All patients adopted both clinical and early (within 72 h) postoperative MRI examinations to evaluate the postoperative motor function, the extent of tumor resection, and modality and integrity of the PTs.

**Effective fibers of pyramidal tract calculation**

In the course of PT tractography, original DTI data set of DICOM3.0 format was transferred into the personal computer. Post process was conducted, using the application software Volume-One 1.72 (VOLUME-ONE developers group) and dTV II (Image Process and Analysis Laboratory, The University of Tokyo, Japan), to achieve separately the FA map and DEC map. In this study, tractography was mainly focused on the PTs delineation. We adopt the axial FA map through internal capsule for reference, put seed points at bilateral posterior limbs of the internal capsule (the blue parts on DEC map), and set the radius at 3.5 mm. Therefore, all patients' selected seed points on images were guaranteed constant. Meanwhile, both the central lobule and cerebral peduncle were set as the target areas. A computer was used to separately auto-trace tracts. Those PTs reaching both central lobule and cerebral peduncle simultaneously were defined as effective fibers of pyramidal tract (EPT), which were shown on the maps. The end-trace condition defined in this study was FA <0.18, or steps >160, or the angle between two steps >40°. By the software, we can simulate to draw the tracts automatically and calculate the numbers of them, which we regard as EPT. EPT calculation was
conducted before and after operation and compared with each other.

**Motor strength evaluations**

Motor strength in each patient was graded, before and after operation, for upper and lower extremities by using the Medical Research Council Scale of 0–5 [18] as follows: 5/5 = normal, full range of motion, full resistance; 4/5 = full range of motion, some resistance; 3/5 = full range of motion with gravity; 2/5 = full range of motion without gravity; 1/5 = slight contraction, no movement.

**Follow-up monitoring**

Two out of 45 patients whose final histological diagnoses confirmed non-gliomas were excluded from follow-up monitoring. Three glioblastomas out of the 43 patients were excluded from statistical analyses because of early progression within 6 months. In the remaining 40 patients, the follow-up period ranged from 6 to 12 months (median 8 months). The Karnofsky Performance Scale (KPS) was adopted for grading functional status at the 6-month evaluation. The follow-up data were based on the responses of patients and their relatives to questionnaire forms, which were completed on-site (recommended to all patients at enrollment) or by telephone (if an on-site visit was impossible). Data regarding the patients’ functional status were evaluated by two independent neuro-oncologists, who were not members of the VR working team and were blinded to the result of EPT calculation.

**Statistical analyses**

SPSS for Windows Ver.13 was used to self-pair t test the chased EPT at the affected side before and after operation and to rank sum test the change of motor strength and the EPT increasing amplitude. We used EPT increasing amplitude at affected sides and the patients’ KPS at 6 months to carry out bivariate correlation analysis. A p value of 0.01 or less was accepted as statistically significant.

**Results**

**Presurgical planning**

For all 45 patients, tractography were generated and visualized in the VR environment. On the axial DEC
map, the anterior limb of internal capsule was normally green, containing mainly front-back frontopontine tract and anterior thalamic radiations. The posterior limb of internal capsule was marked blue, which represented the vertical projection of corticospinal and corticoumlinear tracts. The PTs were clearer as shown on the stereoscopic 3-D tractography assigned in blue based on the dominant head–foot direction of the fibers. Likewise, the destruction, extrusion, and displacement of PTs appeared obviously in the affected side. Therefore, PTs in the normal and affected side had showed a sharp contrast. Tumors were extracted successfully using the segmentation tool. Operators visualized the anatomical relationship between the lesion and PTs, measured in-between distance, and rehearsed different surgical approaches by using the different tools. As a result, an optimal patient-specific plan was decided for each case.

The DTI-based functional navigation was conducted for glioma resection during surgical procedure, which had been reported in previous published paper [5, 26].

Perioperative assessment

Gross total tumor resection was confirmed by early postoperative MRI in 33/45 (73.33%) patients, while subtotal tumor resection was indicated in 6/45 (13.33%) patients (Table 2). On the affected side, no significant change of integrity of the PTs was noted, in comparison between presurgical and postsurgical EPT calculation ($t=1.418$, $p=0.163$).

Follow-up outcome

In all patients, 7/45 (15.56%) of the patients improved in motor function, while 30/45 (66.67%) had no change (Table 3). Forty patients have a KPS follow-up survey at 6 months after operation to evaluate their long-term quality of life. Of the patients, 34/40 (85.00%) had a high KPS score (80–100) at 6 months (Table 4).

EPT increasing amplitude as a predictor for long-term motor function

EPT on affected side is 160.56±26.66 before operation and 153.33±42.13 after operation. Increasing amplitude of EPT was calculated for each case. In 7/45 (15.56%) cases, we found that the EPT on affected side increased more than 10% (EPT increasing amplitude>10%). Meanwhile, in another 7/45 (15.56%) cases, the EPT on affected side decreased more than 10% (EPT increasing amplitude<−10%; Table 5). The changes of motor strength are strongly correlated with the EPT increasing amplitude ($p=0.257$). A bivariate correlation analysis verified that 6-month KPS score was strongly correlated with EPT increasing amplitude ($r=0.584$, $p<0.001$).

Illustrative case

A 48-year-old man presented with worsening seizures on the right side for approximately 2 months. At admission, neurological examination showed no paresis of right extremities, grade V muscle strength, and negative Babinski’s sign on both sides. MRI scans revealed a hypo-intense lesion in the left central lobe involving the PTs with mass effect and no enhancement (Fig. 3). Before fiber tracking, we defined the FA threshold value as 0.18 for tracking fibers and maximum deviation angle as 40°. Three ROIs were put on each side of the images: one on the levels of the cerebral peduncles, the posterior limb of internal capsule, and the apex of the central lobe. After fiber tracking and segmentation of tumor, a stereoscopic 3-D image was visualized via the user’s stereoscopic glasses. In this case, the PT were anterior and external to the tumor and closely surrounding the tumor with no distance apart (Fig. 5a). We determined prone position after several head positions rehearsal (Fig. 4a–c.). The EPT on left side calculated before operation is 175. Gross total tumor resection and precise preservation of the PT were accomplished during the DTI-based neuronavigation surgery (Fig. 4d–f) and verified by early postoperative MRI (Fig. 5b). EPT was then 167. The patient experienced transient decreased muscle strength on the right lower extremities during the first week after operation and was released 1 month later. The final histological diagnosis was infiltrating astrocytoma (WHO grade II). Neither adjuvant radiotherapy nor chemotherapy was conducted after the operation. Postoperative MRI and DTI images obtained 3 months after surgery showed no tumor progression and complete normalization of the PT configuration (Fig. 5c). The EPT was 170 then. The 6-month KPS score of this patient was 100. The patient showed no motor weakness or tumor progression during his 12-month follow-up analysis.

Discussion

Virtual reality system for planning neurosurgery

The neurosurgeon today has a wide range of preoperative imaging modalities available with the quick development of neuroimaging. Advancing technology has promoted better means of understanding neurosurgical anatomy and approaches [5, 26]. Ideal presurgical planning requires being virtual but realistic [10, 22]. Developing technology applied to obtaining information regarding not only shear anatomy of the brain but mostly its inherent functions has significantly impacted with the way surgery for these invasive tumors is conducted. The Dextroscope enables us to preoperatively reconstruct the anatomy of the lesion to be
approached in relationship to the actual cranial and cerebral anatomy of the patient. By moving the 3-D images with the hands, we can view the tumors and PTs from any direction, virtually position the patients’ head, and simulate intra-operative viewpoints. It provides a comprehensive and detailed understanding of the anatomical and pathological 3-D spatial relationships. Traditional VR system could not help neurosurgeons visualize the white matter [20, 31]. A 3-D stereoscopic visualization system was developed, integrated with structural MRI and DTI tractography. Glioma, brain tissues, and pyramidal tracts can be 3-D stereodisplayed and manipulated by 3-D controller to design a suitable neurosurgical trajectory, because this VR technology allows neurosurgeons to look at fiber tracts and tumors in a different plane [13].

Pyramidal tractography

The current pyramidal tractography technology is not mature enough, lacking a unified and standardized setting of tractography parameters. Regarding pyramidal tract DTI of white matter fiber tracts, different researchers choose various tracer methods and termination conditions [6, 9, 28, 34]. Meanwhile, their set FA termination figures vary from 0.12 to 0.24, and termination angle vary from 35° to 50°. Various tractography parameter and tracer methods lead to different pyramidal tractographies. Neurological prognosis based on imaging, as a result, has different evaluating conclusions. Therefore, large sample size for prospective contrast study is required in order to evaluate and standardize various parameters in pyramidal tractography.

For this study, the FA tracer termination figure is set at 0.18, and termination angle is set at 40°, as most authors have used.

Designating the ROIs is of great importance, too. In our study, we had three ROIs based on the anatomical principles of motor pathway. Tracts that pass through the cerebral peduncle, the posterior limb of internal capsule, and the motor cortex simultaneously are certainly PTs.

Quantification of PTs

Quantitative tissue characterizations of PTs affected by intracranial lesions that infiltrate, destroy, or otherwise affect the white matter have been more difficult. Some authors used the average of the number of fibers passing each pixel or voxel, over a selected set of voxels, either as a two-dimensional ROI or a 3-D volume of interest, respectively [3, 17, 25, 33]. In our study, we used a computer to separately auto-trace tracts from posterior limb of internal capsule, and the motor cortex simultaneously are certainly PTs.

Table 2

<table>
<thead>
<tr>
<th>Extent of tumor resection</th>
<th>Total</th>
<th>LGGs</th>
<th>HGGs</th>
<th>Non-glioma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross total resection</td>
<td>33 (73.33%)</td>
<td>18 (72.00%)</td>
<td>14 (77.78%)</td>
<td>1 (50.00%)</td>
</tr>
<tr>
<td>Subtotal resection</td>
<td>6 (13.33%)</td>
<td>3 (12.00%)</td>
<td>2 (11.11%)</td>
<td>1 (50.00%)</td>
</tr>
<tr>
<td>Partial resection</td>
<td>5 (11.11%)</td>
<td>3 (12.00%)</td>
<td>2 (11.11%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Biopsy</td>
<td>1 (2.22%)</td>
<td>1 (4.00%)</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
</tr>
</tbody>
</table>

* LGG low-grade glioma, HGG high-grade glioma

Table 3

<table>
<thead>
<tr>
<th>Postoperative motor function</th>
<th>Total</th>
<th>LGGs</th>
<th>HGGs</th>
<th>Non-glioma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improvement</td>
<td>9 (20.00%)</td>
<td>4 (16.00%)</td>
<td>5 (27.78%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Unchanged</td>
<td>30 (66.67%)</td>
<td>18 (72.00%)</td>
<td>11 (61.11%)</td>
<td>1 (50.00%)</td>
</tr>
<tr>
<td>Deterioration</td>
<td>6 (13.33%)</td>
<td>3 (12.00%)</td>
<td>2 (11.11%)</td>
<td>1 (50.00%)</td>
</tr>
</tbody>
</table>

* LGG low-grade glioma, HGG high-grade glioma

Table 4

<table>
<thead>
<tr>
<th>KPS score at 6 months</th>
<th>Total</th>
<th>LGGs</th>
<th>HGGs</th>
</tr>
</thead>
<tbody>
<tr>
<td>80–100</td>
<td>34 (85.00%)</td>
<td>21 (84.00%)</td>
<td>13 (86.67%)</td>
</tr>
<tr>
<td>50–70</td>
<td>4 (10.00%)</td>
<td>3 (12.00%)</td>
<td>1 (6.67%)</td>
</tr>
<tr>
<td>0–50</td>
<td>2 (5.00%)</td>
<td>1 (4.00%)</td>
<td>1 (6.67%)</td>
</tr>
</tbody>
</table>

* LGG low-grade glioma, HGG high-grade glioma

* Three HGG patients with early progression, and two non-glioma patients were excluded from long-term follow-up monitoring

Table 5

<table>
<thead>
<tr>
<th>Change of motor strength</th>
<th>EPT increasing amplitude</th>
<th>&lt;−10%</th>
<th>−10%–10%</th>
<th>&gt;10%</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weakened</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>No change</td>
<td>1</td>
<td>27</td>
<td>2</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Improved</td>
<td>0</td>
<td>4</td>
<td>5</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>7</td>
<td>31</td>
<td>7</td>
<td>45</td>
<td></td>
</tr>
</tbody>
</table>

* Change of motor strength

Acta Neurochir
study [19], which suggested a clear relationship between EPT on the affected side and the patient’s long-term prognosis.

In this study, we tried to look for an index to evaluate and compare the pre- and postoperative PTs. The increasing amplitude of preoperative EPT and postoperative EPT was calculated for each case. We found most of those patients whose EPT increased more than 10% had better motor function postoperatively. Meanwhile, those patients whose EPT decreased more than 10% had worse motor function postoperatively. The changes of EPT suggested a clear relationship with the changes of motor function pre- and postoperatively. To some extent, EPT can reflect the status of PTs, although the EPT is not the exact number of real PTs.

There is a positive relationship between EPT increasing amplitude and 6-month KPS of the patients. Higher EPT increasing amplitude suggested higher KPS after operation. So EPT increasing amplitude can be regarded as a long-term predictor after operation. But in this study, EPT did not give any objective evidence that VR assists or improves outcome.

Application prospects of DTI-based VR environment

VR environment has improved the neurosurgeon’s preoperative anatomic understanding of the relationship between cerebral gliomas and PTs. It is probably a promising tool for safe, minimally invasive, glioma resection [16, 32]. As we had a clear relationship of the tumor and PTs, we were able to plan a surgical approach unambiguously and precisely. It can help neurosurgeons control the extent of tumors resection. The information of the relationship and distance between glioma and PTs enabled the neurosurgeons to remove the tumor more confidently. On one hand, we had a high proportion of total resection of tumor in the end, because it never occurred that tumor was subtotally or partially resected for worrying about damaging the PTs. On the other hand, as to those patients whose PTs went through the tumor, we resected the tumor partially to preserve the residual PTs. Later adjuvant radiotherapy or chemotherapy was conducted after the operation. We have used this integrated 3-D stereoscopic visualization of MRI and DTI tractography to determine the least invasive trajectory while affording maximum surgical outcome.

In the near future, VR environment integrated with 3-D MRI and DTI tractography will probably be used in many different intracranial diseases with PT involved, including cavernous malformation, aneurysm, brain stem lesions, etc. [2, 17, 29, 33]. It can be used not only in the patient-specific presurgical planning but also in the decision of treatment.

The limitation and prospect of the study

The lack of virtual soft-tissue deformation made it difficult to get a feedback of tactile sensations in this system. The operators had to imagine and estimate the degree of soft-tissue deformation and brain shifting during rehearsal. An endoscopic view along the presurgical approach is unable to attain, which limited neurosurgeons to plan a more intuitive presurgical trajectory. More technologies for reciprocating tools are expected to appear in the development of VR system.

Although DTI tractography used in this study is FT-based other than FA-based (2-D) technique with delineating white matter tracts in 3D, it inherits the drawbacks of single-shot echo planar imaging, being prone to susceptibility distortion artifacts and underestimation of whole white matter tracts. More sophisticated technique, such as extended streamline two-tensor tractography, may delineate the putative motor fibers.
Fig. 4 Presurgical planning for the illustrative patient and surgical reality. 

a–c Presurgical planning. 

a After drilling the bone by the virtual tool, the central sulcus (yellow arrow) is displayed. 

b Segmentation of the tumor and tractography show that the tumor (yellow circle) and PTs (black arrow) are in close relationship. The PTs are anterior and external to the tumor. We simulated the operation in prone position of the patient. 

c Virtually resecting the tumor from cutting open the postcentral gyrus and protecting the PTs and central lobe well. 

d–f Surgical reality. 

d Prone position was determined in the operation. 

e Showing the central sulcus (yellow arrow). 

f Tumor totally is removed and PTs, and central lobe is protected well.

Fig. 5 3-D presurgical images and postsurgical images of the illustrative patient. 

a Presurgical images showing the PTs anterior and external to the tumor. 

b 3-D images 3 days after surgery showing the PTs. 

c 3D images 3 months after surgery showing the normal structures of PTs.
A marked shifting and deformation of major white matter tracts because of tumor removal were visualized when comparing the preoperative and intraoperative fiber tracking [14]. This aspect can only be circumvented with the use of intraoperative MRI done with the purpose of reacquiring the same sequences enabling the reconstruction of the white matter fibers as surgery goes along. There is nothing in this technique which enables the surgeon to better differentiate between normal and abnormal tissue. This problem may be solved by intraoperative MRS. There is nothing in this VR system updating him on the level of function of the tissue being manipulated. This can only be pursued with the use of DBS [1, 12, 17].

Conclusions

Our experience with this 3-D stereoscopic visualization of tractography in this VR environment confirmed the importance of patient-specific presurgical planning. It helps the neurosurgeons well understand the spatial relationship of gliomas and adjacent PTs. Simulation of the operation results in surgical trajectory optimization initially and maximal safe tumor resection finally. Surgeons can predict the long-term motor functional outcome by presurgical and postsurgical EPT counting.

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Statement of authorship  This prospective clinical study was approved by local ethics committee before commencing.

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References


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Comment

This article demonstrates the use the authors have found for preoperative planning and rehearsing of surgery of intra-axial cerebral tumors based on virtual reality technology. These are exciting times for Neurosurgery. Developing technology applied to obtaining information regarding not only shear anatomy of the brain but mostly its inherent functions has significantly impacted with the way surgery for these invasive tumors is conducted.

Most information regarding preoperative location of cerebral function is provided by MRI-based technology. That is the case for DTI, tractography, functional MRI, and all adjuncts being developed from here on.

The Dextroscope is an interesting add-on. It enables us to preoperatively reconstruct the anatomy of the lesion to be approached in relationship to the actual cranial and cerebral anatomy of the patient. What has been done here is to add up the information depicting the anatomy of the white matter tracts of the brain namely the pyramidal tracts. The authors then preoperatively assess the EPTs, that is, the number of fibers actually conveying information in a continuous way along the whole cerebral motor pathway and compare this number before and after surgery. Not unexpectedly, patients who end up with higher EPTs seem to fare better from the motor standpoint.

As the authors point out, there are several limitations to the transposition of this information directly into surgery. Fiber tracking technology is still quite dependent on the mathematical algorithm chosen for its representation. Second, there is no way one can depend exclusively on this information during surgery because of the shift produced by the manipulation of the brain and the CSF spaces. This aspect can only be circumvented with the use of intraoperative MRI done with the purpose of reacquiring the same sequences enabling the re-reconstruction of the white matter fibers as surgery goes along. This is still a morose and complex technique, and it was not applied in the current series.

Finally, there is nothing in this technique which enables the surgeon to better differentiate between normal and abnormal tissue and certainly nothing updating him on the level of function of the tissue being manipulated. This can only be pursued with the use of DBS. All in all, this virtual reality technology seems to play an interesting part in teaching residents as well as in helping out surgeons actually plan their best trajectory and strategy for a specific case. However, the same comments which apply to the use of neuro-navigation are also appropriate regarding this technology. These techniques demonstrate the immense steps taken to help localize anatomy and function within the brain. Their use is ever so more important if based on a sound and strong traditional apprenticeship of the anatomy of the brain based on repeated laboratory cadaver dissections.

For all the above reasons, I think it is a little far-fetched to try to pass the idea that the use of the Dextroscope separates from intraoperative functional imaging and deep brain simulation is a recommendable solution for patients with this type of tumors. Just out of curiosity I would ask the authors to explain what they think is the application of this technique for aneurysms, as stated in the text.

The authors should consider shortening the length of the text and clearing some of the issues raised above.

Maybe this can be turned into a technical report. As it is I think the article does not add much to previous articles published on the matter and has the risk of conveying the idea that the use of the Dextroscope is a safe way to avoid intraoperative injury to deep eloquent areas of the brain. I think we should wait for possible changes and reconsider then.

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