

Virtual Reality and 3D Simulation in the Treatment of Pediatric Patients with Central Nervous System Tumors

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Abstract: Pediatric central nervous system tumors are the primary solid malignancies in children and remain a leading cause of mortality in infancy. Advances in pediatric neuro-oncology, driven by molecular oncology research, emphasize the critical need for high-quality pathological tissue to support advanced molecular investigations. However, the vast heterogeneity of these tumors requires precise discrimination of collection sites, aligning with preoperative imaging data. Surgical resection, a pivotal step in diagnosis and treatment, could result in potential morbidities influencing children's neurological status. This, in turn, affects the feasibility of subsequent oncological treatments, influencing overall prognosis and quality of life. To address these challenges, technological tools enhance neurosurgeon orientation in pre-surgical planning and resection. While stereotactic navigation systems reduce morbidity, limitations persist in providing only two-dimensional anatomical information. Recent developments in 3D surgical simulation and virtual reality revolutionize procedural planning, offering real-time integration with intraoperative navigation systems. Beyond surgery, virtual reality has potential in case discussions, preoperative planning, and operative guidance, aiming to improve care and patient outcomes. The virtual reality experience, coupled with detailed anatomical visualization, facilitates meticulous surgical strategy planning for minimal invasiveness. Despite expanding literature on virtual reality applications in neurosurgery, pediatric neurosurgical oncology experiences remain limited. Scientific evaluation of simulation systems' impact on techniques and outcomes, combined with advances in neuroimaging, offers promise for adapting surgical approaches based on neoplastic brain lesion behavior.

In conclusion, incorporating 3D surgical simulation and virtual reality technologies in pediatric neurosurgical oncology holds substantial benefits, offering improved procedural planning, enhanced precision, and patient-specific adaptation. Despite limited reported experiences, the compelling advantages underscore the need for further exploration and consideration in the evolving landscape of pediatric neuro-oncology.

Keywords: Pediatric brain tumors, Neurosurgical oncology, Virtual reality, 3D simulation, Pediatric neurosurgery research.

1. INTRODUCTION

Neoplasms of the central nervous system are the most frequent solid tumors in childhood and the leading cause of death from tumors at this age. Pediatric neuro-oncology has made significant progress in the last decade, mainly thanks to advanced diagnostic and therapeutic tools imported from research programs in the field of molecular oncology [1-3].

One of the fundamental steps underlying this innovative approach to treat brain tumors is the collection of good quality pathological tissue, and due to its documented spatial heterogeneity, the possibility to precisely discriminate collection sites allowing for the correlation with preoperative imaging data [4-6]. This innovative approach has had major positive implications at all levels of care, including pre-surgical

and surgical management, two extremely important steps in the treatment path of these patients.

The unique phase of surgical resection is the first step in diagnosis and treatment, and at the same time allows the collection of pathological tissue essential for advanced molecular research [4-7]. However, morbidity and unexpected complications deriving from the surgical procedure can negatively impact the neurological status of these children both on the short term and permanently [7-8]. Temporary impairment of neurological functions has the potential to condition the feasibility of the subsequent oncological treatment plan, negatively impacting on cure rates. In addition, permanent disability will reduce the chances of future that is not dependent on other and a satisfactory life [9].

In this scenario, advanced technological tools improving the orientation of the neurosurgeon both during planning of the surgical procedure and during resection are vital both for clinical outcomes and the quality of collected pathological tissue [10-12].

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In the management of the pre-surgical and surgical phases, availability of detailed anatomical and functional planning tools allows for the performance of very complex procedures, ensuring an optimal sparing of neurological function [13, 14].

Modern surgical practice has been developed with an excellent containment of functional risk; nonetheless, it offers an extraordinary growth potential [10, 12, 14]. Development of this potential includes innovative techniques and instruments that not only provide delicate neural tissue handling, but improvement of intraoperative and perioperative patient care and refinement of patient specific approaches. At the same time, an undeniable contribution depends on the possibility of identifying the exact position of anatomical and pathological structures of interest and appreciating their mutual relationships in the preoperative and intraoperative phases [15, 16]. In fact, the possibility offered by stereotactic navigation systems to have reputable points that favor the spatial orientation of the surgeon markedly reduces surgical morbidity even in the most complex cases [16, 17]. Presently, even the most advanced navigation systems offer a two-dimensional visualization of anatomical information with limited possibilities of integrating real-time volumetric information obtained during surgical planning into the surgical resection phase [18].

2. 3D SURGICAL SIMULATIONS

The very recent availability of 3D surgical simulation systems has been a great contribution to procedural planning [19]. These systems allow for the reprocessing of imaging data and for better defining, through virtual reality (VR), the relationships between pathological tissue and normal nervous structures [16]. All these data can be integrated in real time with intraoperative navigation systems, and through augmented reality the surgeon can visualize an overlap between the direct intraoperative microscopic view and previously planned 3D visual data with consequent improvement of the intraoperative orientation, and lastly increased precision during the procedure [13, 14, 16]. Real life and virtual morphological data can therefore be matched to functional information obtained by intraoperative mapping and monitoring, further enhancing intraoperative orientation and preservation of neurological functions [20].

Potentially, VR has many clinical and research applications to be used for case discussions, preoperative planning, and operative guidance, with the

final aim to improve quality of care and patient quality of life [15, 21].

The immersive experience offered by VR technology coupled with the possibility to visualize in high definition a number of anatomical details not usually available would allow better planning of the surgical strategy that contributes to the minimal invasiveness of surgical approaches [11, 15, 22]. It is foreseeable that this would lead to further improvement in surgical results. In addition to the obvious clinical advantages, formal documentation of this data would be an important scientific contribution to the pediatric neurosurgical field. The availability of a patient specific virtual model allows the fine tuning of surgical planning to the exact spatial scenario that will be encountered during the surgical procedure, reducing the number of uncertain variables that might impose adaptation of planned surgical steps to the conditions of the real surgical field [16].

In fact, during surgical procedures, operators integrate their general anatomical knowledge with what is observed in real time during the dissection. The possibility of having detailed patient-specific anatomical information that can be integrated with the intraoperative visualization and navigation instruments considerably increases the quantity and quality of the data on which surgical judgment is based throughout the procedure [13, 14, 17, 20].

The final result would be much similar to VR applications currently used in the aviation field, where pilots can progressively familiarize themselves with specific spatial scenarios and environmental situations, reducing the amount of cognitive resources needed to manage these aspects during real-life duty and improving their performance both in expected and unexpected conditions.

An example of microscopic intraoperative vision coupled with the preoperative virtual model is represented in Figure 1.

3. DISCUSSION

Clinical advantages of VR applications in neurosurgery have increasingly been documented in the literature, especially regarding the facilitation of case discussion, training of younger surgeons, planning of complex surgical procedures, and intraoperative integration with neuronavigation and augmented reality applications [15, 16, 20, 21, 12-14]. Surprisingly, there is scarcity of experiences reported in

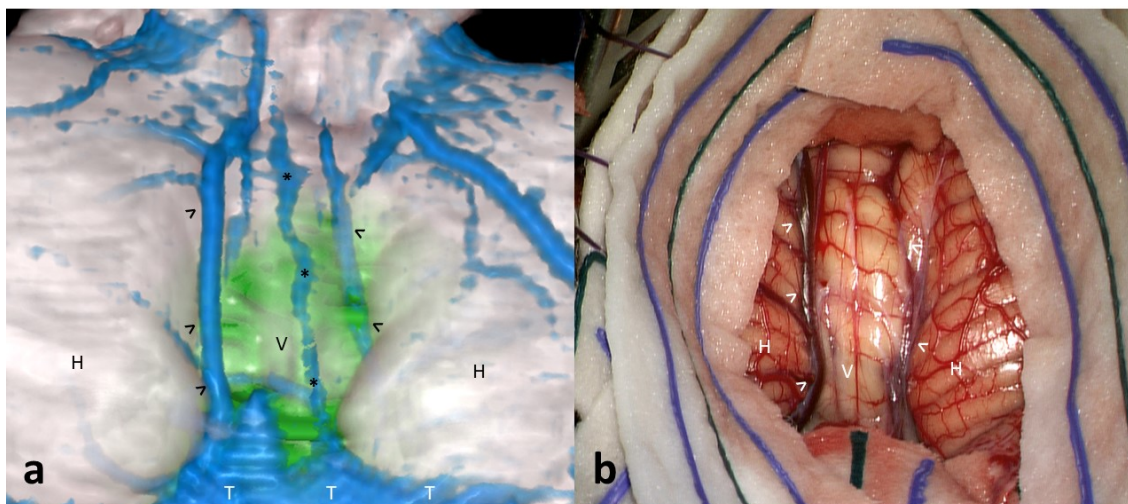


Figure 1: Preoperative 3D/VR reconstruction (a) of a vermian glial tumor and microscopic intraoperative view (b). In the microscopic view, the presence of tumor might be suspected due to pale appearance of the cerebellar vermis (V), compared to cerebellar hemispheres (H). The virtual model clearly shows in green color the precise extension of the tumor below the cerebellar surface. The superficial paravermian veins (arrowheads) are demonstrated both on the virtual and real life views, showing the perfect correspondence of their course on the cerebellar surface. The virtual model is also showing a dural venous channel (asterix), not visible in the microscopic view because the dura has already been opened and reflected towards the transverse sinuses (T).

the literature in the pediatric setting, with no data regarding the particular scenario of pediatric neurosurgical oncology [23-25].

From a scientific point of view, the formal measurement of the impact of simulation systems on different variables related to the surgical technique and obtained clinical results is of particular interest. Furthermore, the evaluation of the surgical conduct in the presence of the simulation system promotes clinical training, specifically steepening the learning curve, and most importantly increasing patient safety [26].

In addition, modern neuroimaging techniques offer the possibility of gathering numerous biological information related to neoplastic brain lesions [27]. The possibility of identifying areas with potentially different biological behavior during surgery would allow surgeons to adapt the surgical technique for better accuracy and plan targeted tissue sampling. The achievement of this objective would not only improve the quality of the tissue available for biological studies but would also contribute to the further development of advanced imaging techniques, thus providing an objective response to the neuroradiological data not currently available. Specifically, through this approach, we could contribute to the study of tumor heterogeneity, further promoting advances in understanding the individual profiles of tumor cells [28-30].

Rehearsal of selective tissue sampling using virtual models might improve precise targeting of desired tumor tissue, assisting surgeons whenever direct intraoperative vision offers little information in confirming correct the target approach [13, 16, 18].

Finally, improvement of the instrumentation supporting "augmented reality" visualization represents one of the most promising aspects of VR in neurosurgery [13, 31]. The integration in real time of direct visual information with that derived from patient-specific simulations would allow a previously unknown precision of surgical gesture, especially in the neurosurgical field where close spatial relationships of normal structures often impose the use of narrow surgical corridors for which the correct orientation of the patient's head in the pre-surgical phase is of vital importance. In the same way, the visual applications can provide unobstructed access to the surgical area, usually unintentionally blinded from the operator, as these pathological processes often hide inside or beyond tumors, such as the course of cranial nerves and vascular structures. In detail, these particular structures that must be spared would have greater chances to be preserved through augmented reality visualization. The development of these innovative visualization applications marks a step forward in the field neurosurgery [16, 18, 20].

From the patient side, it would be interesting to evaluate how the perception of the procedure and the

anxiety linked to it by the parents of the patient would change. When the time comes for discussing and thus deciding whether or not the child should be subjected to neurosurgical procedures, the shared vision of radiological images is always a significant help for proxies to adequately perceive expected clinical benefits and surgical risks. VR has the potential to support the discussion of the case with the patients/parents, providing them with the greatest possible understanding of what could lie ahead.

Neoplasms of the central nervous system are the most frequent solid tumors in childhood and the leading cause of death from tumors at this age [1]. Pediatric neuro-oncology has made significant progress in the last decade, mainly due to advanced diagnostic and therapeutic tools introduced from research activities in the molecular oncology field [32]. The application of this innovative approach provided for significant changes at all levels of care, specifically in reference to neurosurgery on pre-surgical and surgical phases, both of which are extremely important steps in the clinical management of the patient. The most recent 3D surgical simulation system has contributed greatly thus far to procedural planning. Processing imaging data and better defining pathological tissue and normal nervous structure relationship, by means of VR, are concrete examples of the effectiveness of these systems [16-20]. Data can then be processed and integrated in real-time with intraoperative systems and planned 3D visual data for surgery precision. VR has provided clinical and research applications: to implement the anatomo-clinical information available during preoperative planning; to support the discussion of a patient case with the child and parents; to evaluate the surgical conduct in the presence of the simulation system, including accuracy; to contribute to the study of tumor heterogeneity; to develop innovative visualization applications [33].

We have previously reported [34] on the advantage of a VR system in the exquisite setting of pediatric neurosurgical oncology. The highest advantage, as perceived by operators, was found in younger children, deep supratentorial locations and glioma histologies, all conditions in which intraoperative orienteering might be challenging due to scarcity of anatomical landmarks. Despite no formal evaluation of clinical benefit in pediatric neurosurgical oncology, preliminary data both from children and adult series support the concept that this should be strongly considered [11, 12, 22, 23].

Potential limitations to use of 3D/VR applications include the paucity of medical grade commercially

available systems, the high cost of these solutions and the need for a precise operational paradigm to seamlessly integrate neuroimaging processing in the clinical flow. Specific studies addressing the cost-effectiveness of virtual reality models in pediatric neurosurgery are missing. Our unpublished data do not show a significant impact on traditional outcome variables, including operation time, neurological outcome, blood loss and reoperation rates [34]. However, randomization for such an intervention is virtually impossible for ethical reasons and pediatric brain tumors include such a heterogeneous population with so many different variables concurring to the final outcome that we foresee the impact of any systematic intervention would be challenging to prove.

To better include VR modeling the patient journey, we strongly advocate the involvement of neuroradiologists in the quality check of elaborated models, to ensure a reliable reference during the virtual case rehearsal and intraoperative assistance. This would also naturally result in improvement of source imaging techniques, leading to refinement of virtual models.

CONCLUSIONS

In summary, the application of advanced technological tools, especially VR, in pediatric neuro-oncology holds great potential to improve surgical outcomes, enhance patient safety, and contribute to research efforts in understanding brain tumors. While experiences in the pediatric neurosurgical oncology field are limited in the literature, the benefits of using VR in this context are promising and warrant further consideration and exploration.

DECLARATIONS

Ethics Approval and Consent to Participate

Not applicable

Consent for Publication

Not applicable

Availability of Data and Materials

Not applicable

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Authors' Contributions

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