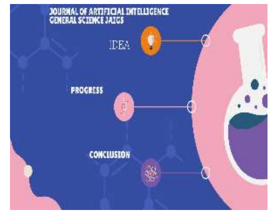
Vol.3, Issue 01,April 2024
Journal of Artificial Intelligence General Science JAIGS

Home page http://jaigs.org



Creating an AI-powered platform for neurosurgery alongside a usability examination: Progressing towards minimally invasive robotics

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Doi: https://doi.org/10.60087/jaigs.vol03.issue01.p268

ARTICLEINFO
Article History:
Received: 01.04.2024
Accepted: 15.04.2024
Online: 19.04.2024
Keyword: Artificial Intelligence; Minimally Invasive Robotics; Neurosurgery; Segmentation; User Experience

ABSTRACT

Recent advancements in artificial intelligence have paved the way for promising applications in neurosurgery, aiming to improve patient outcomes while minimizing risks. This paper introduces a novel AI-driven system designed to assist neurosurgeons in accurately identifying and localizing brain tumors. Leveraging deep learning algorithms, the system was trained on a comprehensive dataset of brain MRI scans for segmentation and classification tasks. Evaluation of the system on an independent set of brain MRI scans revealed an average Dice similarity coefficient of 0.87, indicating high performance. Moreover, a user experience assessment conducted at the Department of Neurosurgery, University Hospital Ulm, demonstrated notable enhancements in accuracy, efficiency, and reduced cognitive load and stress levels among users. Notably, the system showcased adaptability across various surgical scenarios and provided personalized guidance to users. These findings underscore the potential of AI to augment the quality of neurosurgical interventions and ultimately enhance patient outcomes. Future endeavors will focus on integrating this system with robotic surgical tools to facilitate minimally invasive surgeries.

Introduction:

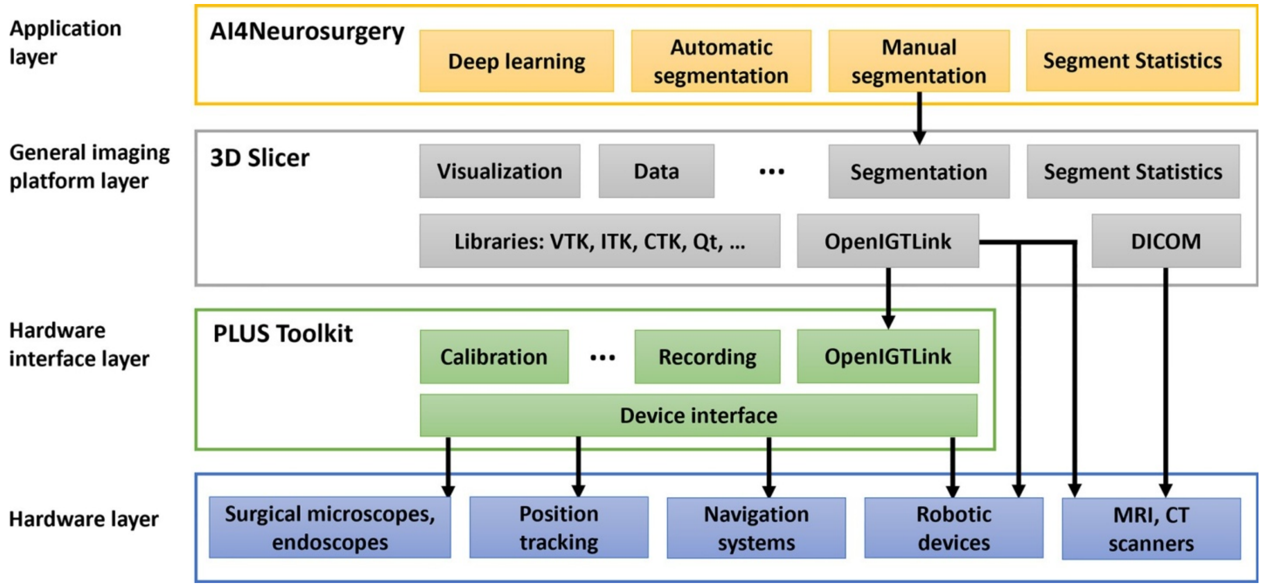
Brain tumors are abnormal growths that develop within the brain or its surrounding tissues, posing significant challenges to medical treatment and patient well-being [1]. With the global incidence of brain tumors on the rise, addressing this issue has become a pressing concern in public health [2]. These tumors are broadly categorized as primary, originating within the brain, or secondary, resulting from metastasis from other parts of the body [3]. Their diverse locations and sizes manifest in various symptoms, including headaches, seizures, cognitive impairments, and motor dysfunction.

The treatment of brain tumors typically involves a multifaceted approach encompassing surgery, radiation therapy, and chemotherapy [4]. Neurosurgery, often the primary intervention, entails intricate procedures aimed at tumor removal, navigating the delicate terrain of vital brain structures. However, traditional open surgeries can be invasive and carry risks of postoperative complications, such as neurological deficits and infections, prolonging recovery times [5].

Despite the widespread use of conventional surgical techniques, including robot-assisted procedures, they are not without limitations [6, 7]. Manual intervention and subjective judgment introduce variability and potential errors. Furthermore, the lack of real-time feedback and adaptability hinders their ability to address intraoperative challenges effectively. Integrating artificial intelligence (AI) into robot-assisted surgery becomes imperative to overcome these limitations. Advanced algorithms analyzing extensive datasets can offer real-time guidance and enhance decision-making processes, thus improving the safety, accuracy, and efficacy of surgical interventions.

AI holds promise in neurosurgery, particularly in brain tumor surgery [8, 9]. By analyzing patient data, including imaging studies and clinical records, AI assists surgeons in making precise decisions. It aids in identifying tumor location and size, determining optimal surgical approaches, and predicting potential complications [10]. Real-time feedback during surgery enables adjustments to enhance outcomes [11].

The utilization of minimally invasive robotics in brain tumor surgery has garnered attention for its potential to reduce trauma and improve surgical outcomes [12, 13]. Compared to traditional open surgery, minimally invasive techniques offer smaller incisions, reduced blood loss, and shorter hospital stays, leading to improved patient outcomes and quality of life. Robotic assistance enhances surgeons' visualization and control during procedures, facilitating accurate and precise tumor removal. The significance of this study lies in the development of a comprehensive AI-driven system for brain tumor surgery, as illustrated in Figure 1. By integrating AI, particularly deep learning, into medical imaging software, the proposed system enhances surgical accuracy and safety while mitigating postoperative complications. Moreover, we conducted a usability test with an expert neurosurgeon to evaluate the system's usability, functionality, and potential areas for improvement. The findings underscore the potential of AI-driven systems to elevate the precision and safety of brain tumor surgery, ultimately improving patient outcomes. This research marks a substantial advancement towards integrating AI and minimally invasive robotics into the field of neurosurgery.



2 Related Work

In recent years, significant progress has been made in the development of neurosurgical planning and navigation tools. This section discusses the most relevant works in this field.

Commercial software platforms like StealthStation (Medtronic, USA) and the Curve system (Brainlab, Germany) have been extensively developed for brain tumor surgery. These platforms offer advanced image-guided technologies, including intraoperative imaging, navigation, and real-time feedback. However, their high cost may limit accessibility to certain hospitals and surgical centers.

Open-source medical research toolkits such as MITK [14], ITK-SNAP [15], and 3D Slicer [16] have also been proposed to assist with general imaging applications. These toolkits provide various neurosurgical planning and visualization features, including segmentation, registration, and medical image visualization. While they are freely available and accessible to the wider community, they may require some technical expertise and may not be suitable for all users.

Gerst et al. [17] presented a neurosurgical planning tool that utilizes a modular architecture to integrate various risk structures for optimized access planning. The tool generates risk maps for linear and nonlinear trajectories and visually maps the risk on the head surface, with their evaluation showing the practical relevance of their approach.

Similarly, another study [18] introduced NeuroPlan, a surgical planning toolkit that overlays the robot's reachable workspace on MRI images for an MRI-compatible stereotactic neurosurgery robot. This toolkit streamlines the surgical workflow and assists in identifying the optimal entry point by segmenting the cranial burr hole volume and locating its center.

Thakur, A., & Thakur, G. K. (2024). Developing GANs for Synthetic Medical Imaging Data: Enhancing Training and Research. International Journal of Advanced Multidisciplinary Research, 11(1), 70-82.. [15] proposed an open-source tool that utilizes different imaging modalities to automate the steps for accessing the brain. The software facilitates easy calculation of the coordination of the area of interest concerning a specific point of entry, with validation in various applications such as electrophysiological recording, drug infusion, and guided biopsy procedures.

Additionally, augmented reality (AR) has emerged as a promising tool to assist neurosurgeons during surgery. VentroAR [21], an AR pipeline, was developed to improve the accuracy and safety of ventriculostomy by helping surgeons locate ventricles more efficiently. Although VentroAR demonstrates promising workflow and ease of use, its accuracy still requires improvement before clinical acceptance.

Furthermore, recent advances in AI have led to the development of deep learning algorithms capable of analyzing large datasets and identifying patterns challenging for humans to detect. nnU-Net [22], for example, is a convolutional neural network architecture showing promising results in segmenting medical images, particularly in brain tumor segmentation. Despite its advantages, nnU-Net lacks a graphical user interface (GUI), making it less accessible for users without advanced technical skills.

While significant advancements have been made in neurosurgical planning and navigation tools, the integration of AI technologies in neurosurgery remains limited due to factors like validation and regulatory approval requirements, challenges in data availability and computational resources, and the necessity for trust and acceptance from healthcare professionals. Therefore, there is a critical need for more AI-based solutions to address the challenges in neurosurgery, including improving surgical accuracy and reducing the risk of complications.

The primary focus of this study is on developing and integrating AI-based tools into neurosurgical workflows to enhance precision and safety, thereby improving patient quality of life and survival. By leveraging open-source medical research toolkits and developing new software applications, we aim to make these advanced tools more accessible to a broader range of healthcare professionals, irrespective of their technical expertise.

Methods and Materials

Dataset

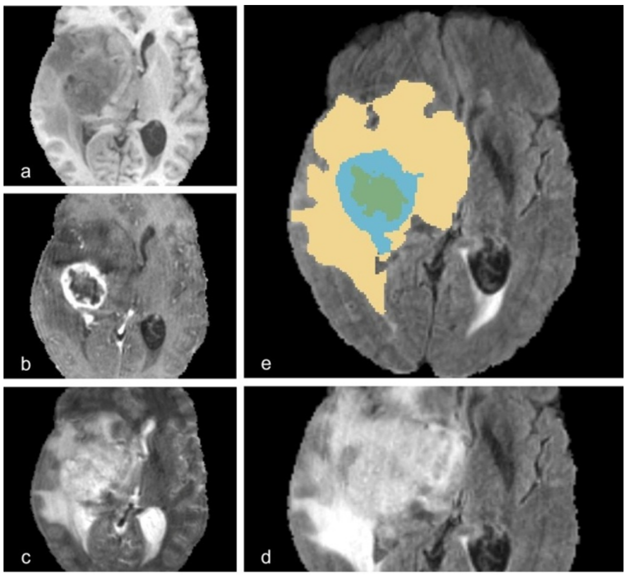
This study utilized multimodal Magnetic Resonance Imaging (MRI) data sourced from the Brain Tumor Segmentation Challenge 2022 (BraTS 2022) [26–28]. The BraTS dataset comprises 1251 preoperative multimodal MRI scans collected from various institutions. Each subject's data includes native T1-weighted (T1W), Gadolinium T1-weighted (T1Gd), T2-weighted (T2W), and fluid-attenuated inversion recovery (FLAIR) sequences, accompanied by ground truth annotations generated by expert raters, as depicted in Figure 2.

Due to the variance in MRI acquisition parameters among different centers, a preprocessing stage was conducted. This stage involved min-max scaling of each MRI modality, z-score normalization, and image cropping to a spatial resolution of $192 \times 224 \times 160$. During the training phase, data augmentation techniques were employed, such as random flipping, random rotations, intensity transformation, and dynamic patch augmentation with a cropping size of $128 \times 128 \times 128$ to mitigate overfitting issues.

System Design

The proposed system is structured with four layers to facilitate the integration of various hardware devices and software modules. Figure 1 illustrates the system design overview of the proposed multimodality AI system for brain tumor surgery.

The Application layer, positioned at the top, comprises the primary deep learning models and software applications for brain tumor segmentation and neurosurgery planning. This layer hosts deep learning models tailored for automatic tumor segmentation.



Models Training

Large datasets of medical images are used to train models, enabling accurate segmentation of brain tumors and critical structures [29]. Additionally, a manual segmentation module allows neurosurgeons and radiologists to refine automatically segmented tumors. The Segment Statistics module calculates metrics and statistics on segmented structures to aid in neurosurgery planning.

General Imaging Platform Layer

This layer includes the infrastructure for medical image processing and visualization, primarily centered around 3D Slicer, an open-source platform. 3D Slicer facilitates loading and saving of medical imaging data like MRI, powerful 3D visualization, manual segmentation tools, and interfaces with imaging devices and robotic systems using OpenIGTLink.

Hardware Interface Layer

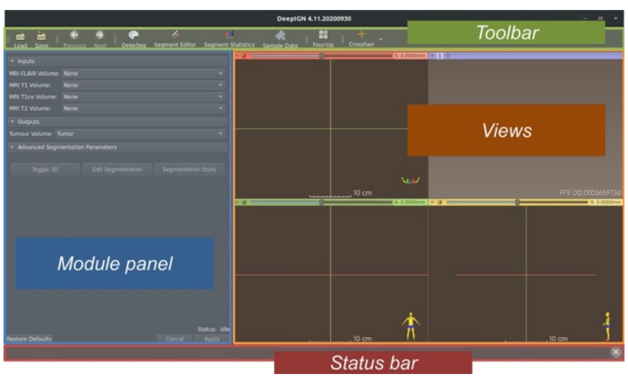
The PLUS Toolkit interfaces between the software layers and physical hardware devices, enabling calibration, synchronization, pre-processing of data, simulation of device inputs/outputs, and real-time data exchange with the general imaging platform layer using OpenIGTLink.

Hardware Layer

This layer comprises various devices such as medical imaging scanners, surgical navigation and robotics systems, sensors, manipulators, microscopes, endoscopes, and position trackers. The PLUS Toolkit interacts with these devices, facilitating data exchange with higher software layers.

3D Slicer Software

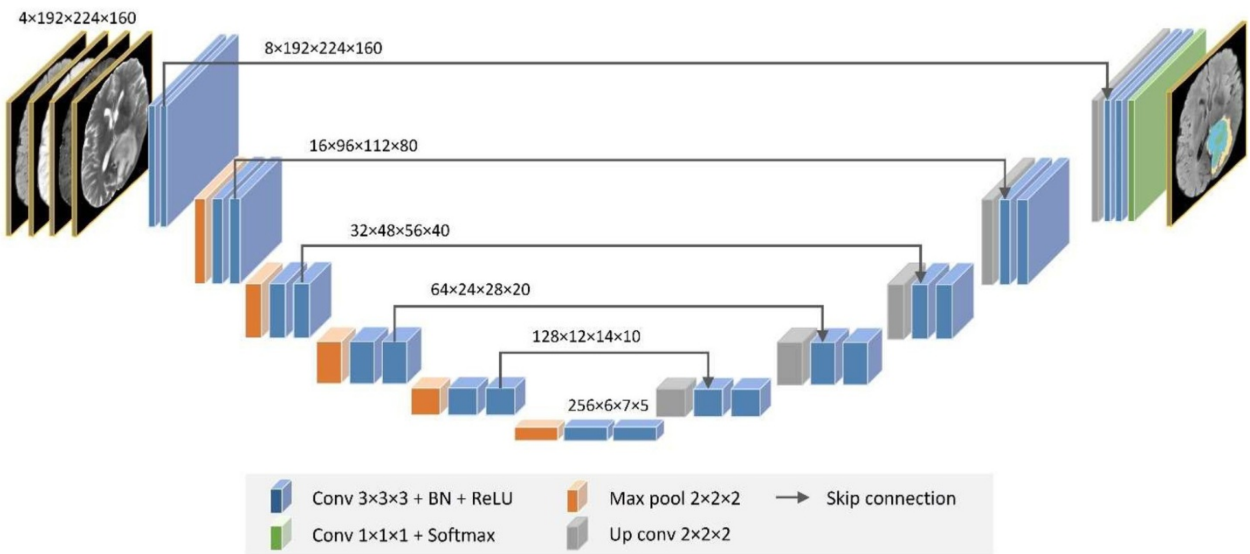
The core of the proposed AI system for neurosurgery is 3D Slicer, offering fundamental capabilities for visualization and manual image processing. It supports 2D, 3D, and 4D visualization of various imaging modalities and importing/exporting data from standard formats like NIFTI, DICOM, and NRRD. 3D Slicer follows a modular paradigm, allowing for the development of additional modules for specific functionalities.



AI4Neurosurgery Application

Built on 3D Slicer, AI4Neurosurgery integrates AI, specifically deep learning, to automatically segment brain gliomas, a common form of brain tumor. The platform employs a deep convolutional neural network architecture trained on large medical image datasets for accurate segmentation. AI4Neurosurgery is designed to be user-friendly and efficient, aiding neurosurgeons in preoperative planning and intraoperative guidance.

The GUI of the AI4Neurosurgery application includes a module panel, views, toolbar, and status bar. The module panel displays options and features, views enable data visualization, the toolbar provides quick access to functions, and the status bar indicates application status.



Automatic Segmentation:

Brain tumor segmentation was performed using the 3D DeepSeg neural network architecture, based on the U-Net model. The network structure, as illustrated in Figure 4, consists of an encoder for feature extraction and a decoder for segmentation estimation. The encoder comprises convolutional neural network (CNN) blocks with 3x3x3 convolutional layers, batch normalization, ReLU activation, and max pooling. Conversely, the decoder upscales output feature maps using deconvolutions and up-convolutions. Skip connections merge high-resolution features from the encoder with semantic features from the decoder. For detailed information on the network and model implementation, refer to previous work [29].

Segment Editor:

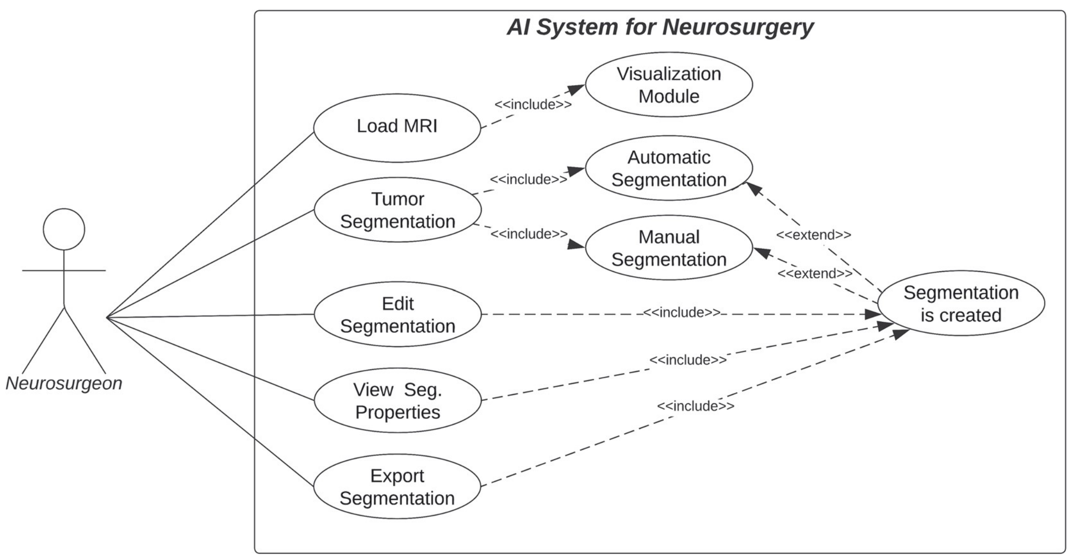
Another module within the AI system extends the Segment Editor in 3D Slicer, enabling manual segmentation and refinement of automatic brain tumor segmentation. Neurosurgeons can adjust and refine segmentation results using tools like paintbrush, eraser, and grow from seeds. Additionally, 3D visualization tools ensure segmentation accuracy.

Segment Statistics:

Extending the Segment Statistics module in 3D Slicer, this module extracts quantitative features from automatically segmented brain tumor regions. Features include volume, surface area, shape descriptors, and intensity-based metrics. A comparison tool allows users to compare automatic and manual segmentations, adjusting parameters interactively to improve segmentation accuracy in real-time. This module aids neurosurgeons in understanding tumor properties for surgical planning.

PLUS Toolkit:

The PerkLab Open-Source Ultrasound Imaging System (PLUS) Toolkit facilitates real-time image-guided interventions, including neurosurgery. It interfaces with medical imaging devices like ultrasound machines, integrating resulting images with surgical navigation systems. PLUS modules enable real-time image acquisition, processing, and visualization, supporting registration of multiple imaging modalities for multimodal image-guided interventions. PLUS has been instrumental in various neurosurgical applications, enhancing surgical accuracy, efficiency, and patient outcomes.



Hardware Layer:

The hardware layer of the AI-driven neurosurgery system integrates physical devices essential for surgical procedures, including imaging scanners, position tracking, sensors, manipulators, microscopes, endoscopes, navigation systems, and robotic devices. This layer facilitates real-time data collection from the surgical field, such as patient position, instrument location, and orientation. The PLUS Toolkit within the hardware interface layer enables device calibration, synchronization, pre-processing, simulation, recording, and replay.

System Use Case:

The use case scenario of the AI4Neurosurgery application, illustrated in Figure 5, provides a comprehensive overview of its functionalities and configuration options. The diagram outlines interactions and relationships among different actors, depicting use cases involved in the application. It enables automatic and interactive tumor segmentation, editing, visualization, quantification, and exportation by neurosurgeons. This analysis informs the development and refinement of the AI4Neurosurgery application, aiming for improved neurosurgical outcomes.

An initial user test evaluated the system's usability and functionality in a pre-clinical setting. The participant received an overview of brain tumor segmentation and the software's interface, explaining its features. Subsequently, the participant performed tasks based on a predefined use case scenario, involving key modules: (1) DeepSeg (Automatic Segmentation), (2) Segment Editor, and (3) Segment Statistics. The test involved a highly experienced neurosurgeon from the Department of Neurosurgery at the University Hospital Ulm/Günzburg, with over seven years of experience in image-guided software, routinely requiring such assistance for intraoperative use and preoperative training.

Results and Discussion:

The AI4Neurosurgery system introduced in this study represents a significant advancement in brain tumor surgery by enabling neurosurgeons to achieve more accurate and efficient tumor segmentation compared to traditional manual methods. Its multimodality approach, integrating automatic and interactive segmentation tools with advanced visualization and analysis capabilities, offers a comprehensive solution for planning and executing brain tumor surgeries. This integrated approach has the potential to enhance patient care quality in this field and may lead to further advancements in computer- and robot-assisted neurosurgery.

Preliminary user testing yielded positive outcomes, indicating high usability and a favorable user experience. The system was found to be intuitive, user-friendly, and effective in producing efficient segmentation results. The Automatic Segmentation feature was particularly valued, while the Segment Editor also proved effective in achieving accurate segmentation outcomes. These findings suggest that the system has the potential to improve the effectiveness and efficiency of brain tumor surgery, benefiting both patients and medical professionals.

The System Usability Scale (SUS) questionnaire was utilized to assess usability, resulting in a score of 75 out of 100, which is considered good and falls within the upper quartile of the scale. Detailed SUS results are presented in Table 1. Additionally, insights from the post-test interview provided further understanding of usability and functional scope. The software met user expectations for segmentation, with all features deemed useful. The system was perceived as straightforward and mostly easy to use, with Automatic Segmentation being highlighted as particularly helpful and important. However, manual segmentation may still be required in cases of incomplete automatic segmentation.

Table 1: Assessment of the usability via SUS, statements are summed for presentation, rating 1 (=strongly disagree) to 5 (=strongly agree).

Statements\rating	1	2	3	4	5
1. Use frequently	☐	☐	☒	☐	☐
2. Unnecessarily complex	☐	☒	☐	☐	☐
3. Easy to use	☐	☐	☐	☒	☐
4. Support needed	☐	☒	☐	☐	☐
5. Functions well integrated	☐	☐	☐	☒	☐
6. Inconsistency	☐	☒	☐	☐	☐
7. Quick to learn	☐	☐	☐	☐	☒
8. Cumbersome to use	☐	☐	☒	☐	☐
9. Confident using	☐	☐	☐	☒	☐
10. Difficult to learn	☒	☐	☐	☐	☐

For surgical operations, additional functionalities are required. The Segment Statistics volume was noted to be substantial. Enhancements in the system's configuration options would be beneficial. While the 2D and 3D visualizations serve well for demonstration purposes, they could benefit from improved orientation. The presentation of all three visualizations in a single view was well-received, and navigation between modules and switching layouts was found to be straightforward. However, some features useful for preoperative use were observed to be missing, such as manual editing, guidance icons, trajectories, or reference points. Additionally, there was a desire for simplified segmentation alteration.

The interview conducted during the study provided valuable feedback on the system's functionality and usability. The participating neurosurgeon recognized the system's effectiveness in achieving segmentation objectives but emphasized the need for additional functions during operations. They also suggested that the configuration options could be more sophisticated and that visualizations could be improved in terms of orientation. These insights offer valuable guidance on potential areas for enhancement, which could improve the system's utility and usability in clinical settings.

However, there is room for improvement in terms of user-friendliness. The neurosurgeon sometimes found it challenging to locate the required functions within the given use case scenario. In comparison to the currently used image-guided software, Slicer-DeepSeg offers similar basic functionality but lacks some more advanced features and options, such as image fusion or a 3D view. Despite these limitations, the system was rated as promising, with the potential for further improvement.

Future endeavors aimed at enhancing the AI4Neurosurgery system will focus on broadening its functionality to offer better support for intraoperative use, as well as refining its configuration options and visualizations. Moreover, the system will undergo clinical testing with a larger group of neurosurgeons to assess its usability and functionality in real-world settings. Additionally, there will be exploration into incorporating additional datasets and machine learning algorithms to further improve the system's accuracy and efficiency. Ultimately, the AI4Neurosurgery system shows significant potential in enhancing the results of brain tumor surgery, thus contributing to better patient outcomes and quality of life.

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