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Original Article

Impact of Neuronavigation on Surgical Outcomes in Intra-axial Brain Lesions Resection: A Pilot Study in a Limited Resource Setting

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BACKGROUND: Neuronavigation (NNAV) is an essential neurosurgical tool, yet its cost often limits its use in resource-limited settings. This pilot study reports our initial experience with NNAV in intra-axial brain lesion surgery.

OBJECTIVE: To report our first formal use of NNAV and assess its impact on patient outcomes.

METHODS: Sixteen adult patients with weakly or non-enhancing intra-axial brain lesions underwent NNAV-assisted surgery to optimize resection safety and radicality. We evaluated the surgeon's subjective experience and measured objective variables including Karnofsky Performance Status (KPS), Extent of Resection (EOR), complication rates, blood loss and hospital stay. Statistical analyses were conducted to assess outcomes.

RESULTS: Surgeons reported positive experiences, highlighting improved accuracy in localizing challenging lesions and mitigating brain shift. The average EOR was 64.51%, with a gross total resection rate of 31.25%. Preoperative KPS averaged 86.25, improving to 91.25 postoperatively. The immediate post-surgery complication rate was 37.5%, remaining unchanged for three months. The average hospital stay was 5.69 days, and the mean blood loss was 387.50 ml. Strong positive correlations were found between preoperative KPS and both postoperative KPS (r = 0.735) and EOR (r = 0.794), suggesting that healthier patients achieved better outcomes. Tumors in opercular and temporal regions negatively impacted KPS change, and a gradual learning curve using the NNAV was observed.

CONCLUSION: NNAV enhanced surgical precision, contributing to improved outcomes and reduced complications. Further research with larger samples is needed to confirm these findings and assess the long-term benefits of neuronavigation.

KEYWORDS: Extent of resection, Intra-axial brain tumor, Karnofsky performance status, Low-grade glioma surgery, Resource-limited setting.

INTRODUCTION

Neuronavigation (NNAV) systems have revolutionized neurosurgical procedures by enhancing the precision of brain tumor resections. These advanced systems integrate preoperative imaging data with real-time surgical navigation, allowing surgeons to accurately localize and resect brain tumors. However, a significant challenge with NNAV is brain shift, which can gradually degrade navigational accuracy throughout the surgical process.[1] In our resource-limited institute, the question arose whether the sole use of a neuronavigation device is sufficient to maximize the safety and radicality of intra-axial brain surgery or if it is only useful during the initial stages of surgery, such as preoperative planning and localization.

In resource-limited settings, the adoption of advanced, costly technology can be difficult. Although neuronavigation is a basic tool in the neurosurgical suite, its implementation can be challenging due to its cost and logistical constraints, especially when it is typically used in conjunction with additional expensive neurosurgical tools, such as intraoperative neuromonitoring (IONM) and cortical mapping. Despite these challenges, the capacity of NNAV to improve surgical outcomes and reduce complications makes it a potentially valuable investment.

This pilot study aimed to report our first experience using a neuronavigation device to operate on patients undergoing maximal safe resective surgery for intra-axial brain lesions in a resource-limited setting at Ain Shams University Hospitals in Cairo, Egypt. Due to constrained resources, we assessed the predominant use of neuronavigation as the main neurosurgical tool used intraoperatively, and we assessed its value subjectively based on the surgeon's impressions and objectively by measuring different surgical outcomes. Intraoperative ultrasound (IOUS) assistance was used when needed, but no additional neurosurgical tools [e.g., IONM, awake surgery, cortical mapping, fluorescein guidance, or intraoperative computed tomography (CT) or magnetic resonance imaging (MRI)] were employed.

PATIENTS AND METHODS

A prospective analysis, from 2018 to 2023, was conducted

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on sixteen patients fitting the inclusion criteria who underwent brain tumor resection with neuronavigation alone, with or without the use of intraoperative ultrasound (IOUS). Key variables assessed included preoperative and postoperative Karnofsky Performance Status (KPS), tumor volume, extent of resection (EOR), postoperative complication rate, total blood loss, length of hospital stay, and patient demographics. Statistical analyses included descriptive statistics, Chi-square and ANOVA tests, Spearman correlation, and regression analysis. The collected data were revised, coded, tabulated, and introduced to a personal computer using the Statistical Package for Social Science (SPSS 25). Statistical analyses were performed on MS Excel (Microsoft Corp, Redmond, WA, USA). Data was presented and suitable analyses were conducted according to the type of data obtained for each parameter. Mean, standard deviation (± SD), and range were used for parametric numerical data, while median and interquartile range (IQR) were used for non-parametric numerical data. Frequencies and percentages were calculated for categorical data. Spearman's rank correlation coefficient was employed to evaluate the relationship between ordinal variables, and chi-squared tests of independence were conducted to investigate the association between categorical variables. The level of significance was set at $P > 0.05$ for non-significant (NS) results and $P < 0.05$ for significant (S) results. All procedures performed in the study involving human participants were approved by the research ethics committee of the Ain Shams University (ASU) Faculty of Medicine, reference number: FMASU MD 187/2021. All participants provided informed written consent to participate in the study. All patients were consented to the surgical procedure and publication.

Patient Selection

We included consecutive patients, aged 16 years or older, undergoing NNAV-guided brain surgeries for lesions that are intraxial, weakly, or non-enhancing on preoperative conventional MRI that mimic the appearance of a diffuse glioma (low grade, non-ring enhancing). Redo surgeries were excluded only if the previous pathology was a high-grade lesion. De novo patients were not excluded based on their postoperative histopathological results (e.g., high-grade glioma or metastasis) if their preoperative MRI fitted the inclusion criteria. All our pathological analysis was based on the WHO 2007 and 2021 classification of brain tumors, according to the date of the pathological result (before or after the WHO 2021 CNS tumor classifications)[2]. We aimed to select patients with lesions for which the use of NNAV was crucial and that was hard to localize and/or demarcate intraoperatively using the standard surgical white light and microscope.

The surgeon aimed to use NNAV guidance (BrainLab® Kick, Munich, Germany) throughout the entire surgical procedure to achieve maximal safe resection. This started with preoperative planning, followed by the most aesthetic skin incision, and the smallest acceptable craniotomy and durotomy. The surgeon then proceeded to localize the epicenter and the perimeter of the lesion and marked both using virtual NNAV waypoints. These points acted as virtual "post-fences" to assist during resection. Major vessels, eloquent areas, and tracts were also marked and named, noting their proximity to the lesion. Throughout the resection process, the surgeon regularly checked and noted the navigational accuracy, and the effect of brain shift by comparing NNAV points to real fiduciary points (canthi, auditory meatus, skull points) and estimated the depth and extent of resection (EOR). Surgeons halted resection once maximal safe resection was achieved. The aim was safe gross total resection (GTR) of the seen lesion and the corresponding signal abnormalities on the preoperative MRI (any enhancing areas on T1 weighted MRI or FLAIR sequence MRI). When further assistance was needed, IOUS (BK5000, BK Medical®, General Electric, USA) was incorporated into the navigation system to recheck and correct for brain shift, as well as to check for residual lesions. We measured the EOR by doing a volumetric analysis using the semi-automatic segmentation software Horos™ (GNU Lesser General Public License, Version 3.0 (LGPL 3.0) by manually delineating the tumor region of interest (ROI) in each MRI slice then the software computed the total volume of the tumor using a preset algorithm.

MRI sequences used to calculate the preoperative and postoperative tumor volumes were the ones with the maximum tumor size that can be visualized. Usually, FLAIR weighted sequences for weakly or non-enhancing lesions, or the contrast-enhanced T1 weighted sequences for non-ring enhancing lesions.

The extent of tumor resection was presented as a percentage as per the equation previously described by Smith, et al[3]:

EOR percentage = [(preoperative tumor volume – postoperative tumor volume)/ preoperative tumor volume] × 100

Objective Assessment of the NNAV on Surgical Outcome:

The study's primary outcome was the extent of tumor resection measured via volumetric analysis within three days and/or at three months postoperative and the frequency of gross total resection achieved. Additionally, the secondary outcomes were the navigational accuracy (localization and effect of brain shift), the patient's three-month Engel class (for epileptic patients), the patient's three-month Karnofsky Performance Scale (KPS), and the frequency of postoperative complications [immediate (within the first three days) and persistent postoperative complications (remained till at least three months)].

Subjective Assessment of NNAV Accuracy:

In addition to the forementioned secondary outcomes, we also aimed to subjectively assess the NNAV's performance during the procedures by asking the operating surgeon a series of dichotomous questions. The surgeon's response was based on the NNAV's reliability in localizing the tumor, marking critical structures, and achieving the planned resection. Our questions queried the following. First, navigational accuracy: comparison of NNAV points to real fiduciary points and evaluation of any discrepancies. Second, effect of brain shift: monitoring the impact of brain shift on NNAV accuracy and its adjustments during surgery. Third, overall utility: evaluation of the NNAV's contribution to the surgical process, including its role in planning, localization, and resection.

RESULTS

Demographics and Descriptive Results

Our cohort comprised sixteen patients with weakly enhancing intra-axial brain lesions with various pathologies. It included nine males and seven females. The age of the patients ranged from eighteen to fifty-two years, with an average age of 37.38 years. The median age was thirty-nine years, and the standard deviation (SD) was 11.22 years, indicating a wide variation in patient ages. Tumors were mostly located in the frontal lobe (37.5%), followed by Peri-Rolandic (25%), fronto-temporal-insular (FTI) (18.7%), temporal (12.5%), and opercular (6.25%). tumor laterality was slightly skewed, with nine tumors on the left hemisphere and seven on the right side. A summary of our cohort demographics and descriptive results were shown in **(Table 1).**

The pathological diagnoses in our study included anaplastic astrocytoma (6, 37.5%), diffuse astrocytoma in 2 patients (12.5%), glioblastoma in 6 patients (37.5%), anaplastic oligodendroglioma in one patient (6.25%), cerebral cavernous malformations in 2 patients (12.5%), metastatic carcinoid in one patient (6.25%), ganglioglioma in one patient (6.25%), and Dysembryoplastic-Neuroectodermal tumor (DNET) in 2 patients (12.5%). This demographic and clinical summary highlights the diversity of the patient sample in terms of age, tumor locations, and pathologies, providing a broad basis for analyzing surgical outcomes and treatment efficacy.

The most common clinical presentation was seizure activity at the time of diagnosis in 12 cases (75%). Regarding the three-month Engel classification, the distribution of outcomes was as follows, 25% of patients were classified as Engel Class one, indicating no postoperative seizures; 31.25% were classified as Engel Class two, indicating rare postoperative seizures; 18.75% were classified as Engel Class three, indicating a significant reduction in seizure frequency but not complete freedom; and 25% were classified as Engel Class four, indicating no substantial improvement or an increase in seizure frequency.

Neuronavigation and Tumor Visibility

Tumor visibility by the standard surgical white light was assessed and categorized into three groups: not visible (the tumor is completely not visible on the surface and the surgeon can't localize it by just the naked eye), suspiciously visible (the surgeon is suspicious, but not certain, about a cortical area that might be abnormal, e.g. discoloration, change in appearance or consistency, light reflection on the cortical surface), and fully visible (in which the surgeon can easily see and clearly demarcate the lesion from the surrounding brain tissue). Among the patients, 25% (4 out of 16) had tumors that were not visible to the naked eye. Most patients, 43.75% (7 out of 16), had suspiciously visible tumors. Additionally, 31.25% (5 out of 16) of the patients had tumors that were fully visible to the naked eye. Regarding the surgeons' assessment of the NNAV during the surgery, neuronavigation was considered essential for localization in 68.75% (11 out of 16) of the cases. In contrast, for 31.25% (5 out of 16) of the cases, neuronavigation was not deemed essential. The NNAV was able to accurately localize the epicenter of the lesion as well as demarcate the borders in all the lesions. The accuracy of the NNAV was checked throughout the procedure, by checking fiduciary points (skull points, canthi, auditory canal, major sulci, and gyri). The navigation wasn't affected by brain shift in all cases and the accuracy did not falter in all cases except in one case. This highlights the importance of neuronavigation in accurately localizing tumors during surgical procedures for most patients.

Objective Assessment of Surgical Outcomes

Our primary objective was the EOR and GTR. The average calculated Extent of Resection (EOR) is 64.51% with a standard deviation of 35.19%, while the median EOR is 78.11%, indicating that half of the patients achieved an EOR of 78.11% or higher. The Gross total resection (GTR) rate was 31.25%, highlighting that complete resection was achieved in about one-third of cases. The EOR for each patient was calculated and plotted in **(Figs. 1,2)** to visualize the change in EOR per patient. We then proceeded to analyze several factors that could be of value in comparison to the EOR. Firstly, the Extent of Resection (EOR) was subdivided into four categories and the distribution of patients within these categories was: partial resection (PR) (0-50%) in six patients (37.5%), subtotal resection (STR) (51-75%) in two patients (12.5%), near total resection (NTR) (76-98%) in three patients (18.75%), and gross total resection (GTR) (99-100%) in five patients (31.25%). Most of our patients fell in the PR group, followed by the GTR group, the NTR group, and finally the STR group.

Concerning the learning curve of our operating

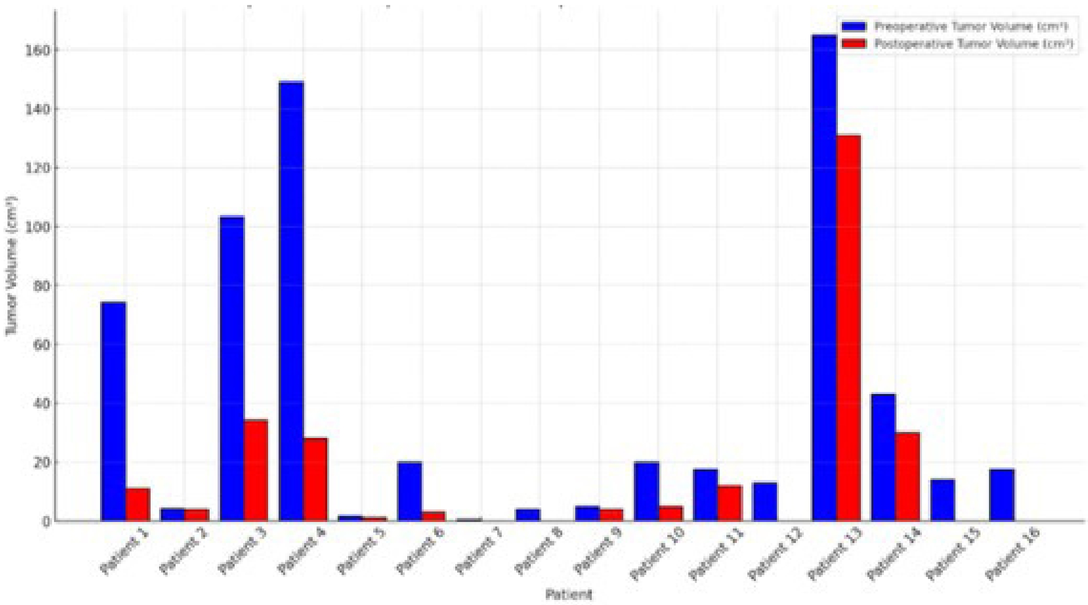

Fig 1: Preoperative (blue) and postoperative (red) tumor volumes for each patient in the cohort.

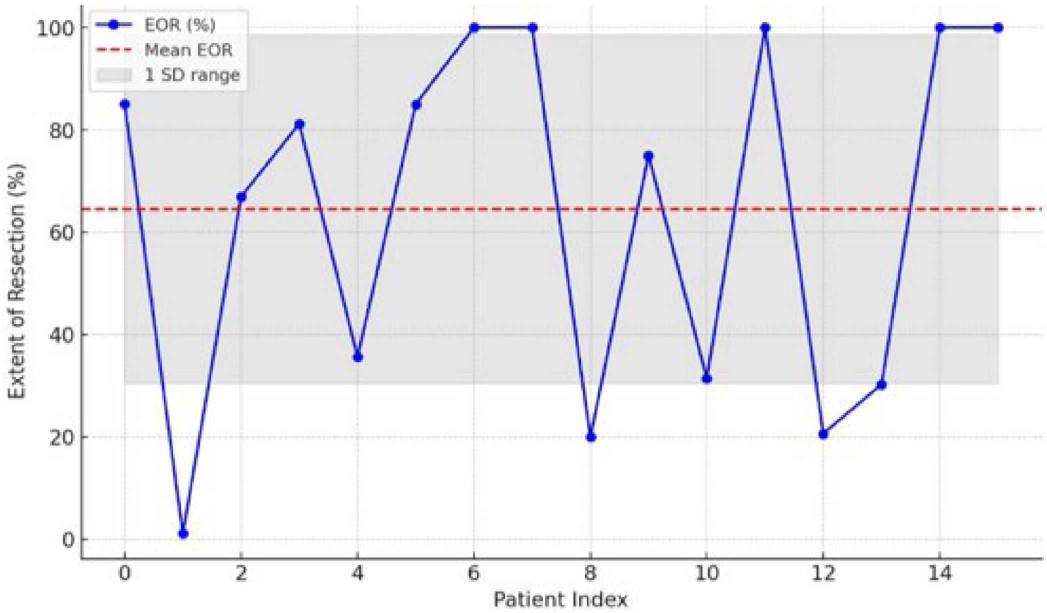

Fig 2: This is a plot displaying the variance in the EOR (Blue) percentages among patients. The blue circles, connected by lines, represent individual EOR values. The red dashed line indicates the mean EOR. The gray-shaded area shows one standard deviation above and below the mean.

staff, there was a noted improvement in the time required for patient positioning, skin registration, and troubleshooting. However, the objective assessment of the EOR trend over time did not show a significant change, which can be partially attributed to the small sample size and the low frequency of such patients compared to the relatively long study's time frame. To analyze the EOR trend over time, we conducted a linear regression analysis that revealed a slope of 0.0015 and an intercept of -1044.89 **(Fig. 3)**, indicating a very slight increase in the EOR over time. This suggested that, on average, the EOR had been increasing marginally with each subsequent surgery. However, this intercept value lacks practical interpretability. The small slope value signified that the observed trend in EOR is very subtle, implying minor improvements in EOR over time, potentially due to improved surgical techniques, better utilization of neuronavigation systems, or increased surgeon experience.

Secondary objective was to assess the impact of

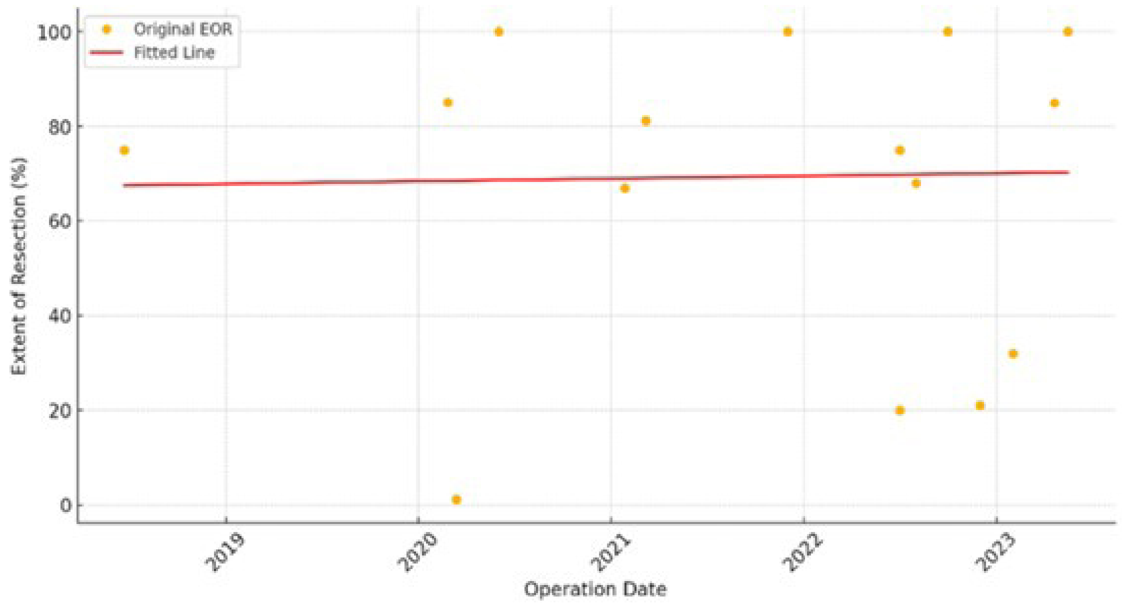

Fig 3: Plot showing the EOR values (yellow dots) and the fitted linear regression trend line (red). The yellow dots represent the EOR percentages for each case. The red line represents the fitted linear regression line representing the EOR trend over time.

neuronavigation on the patient's clinical status. We started by assessing the functional status of the patient, the complications rate, and finally the measurement of blood loss and hospital days. First,, to assess the functional status of patients, we used the Karnofsky Performance Scale (KPS). We measured the preoperative KPS and compared it to the postoperative KPS, calculating the change in KPS for each patient. The mean preoperative KPS was 86.25 with a standard deviation of 10.88. The mean postoperative KPS was 91.25 with a standard deviation of 9.57. The mean change in KPS was a five-point increase in the KPS. With a standard deviation of 12.11. These results suggested that most patients experienced an improvement in their functional status following surgery **(Fig. 4).**

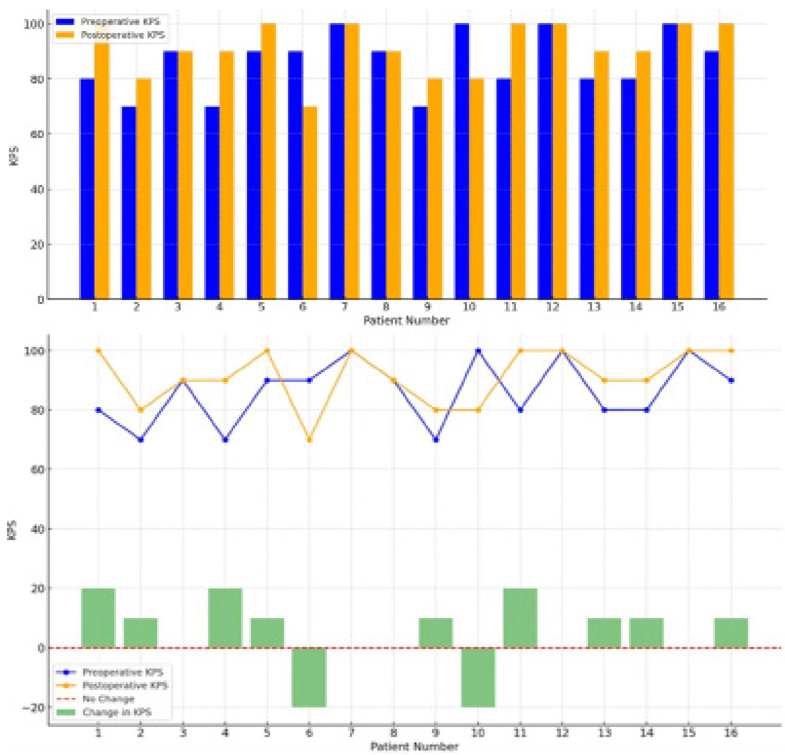

Fig 4: Karnofsky Performance Status (KPS) for each patient (Preop in Blue, Postop in Yellow), along with the change in KPS. (Green bars). The dotted red line represents no Change in KPS. Preoperative KPS scores are represented by the blue bar and line, while postoperative KPS scores are represented by the orange bar and line. The change in KPS, depicted by the green bars, represents the difference in KPS from preoperative to postoperative status for each patient, with positive values (above the red dashed line) indicating improvement and negative values (below the red dashed line) indicating a decline. The red dashed line at y=0 represents no change in KPS.

Overall, most patients had positive outcomes, indicated by the average increase in KPS of five points, while a few experienced a decline. This suggested that surgical intervention was beneficial in enhancing the patients' functional status as seen in the KPS box plot **(Fig. 5).** Although our statistical analysis did not show significance between the change in KPS and the EOR, the Spearman correlation analysis showed a strong correlation between them. Regarding our complication rates, the immediate postoperative complication rate was 37.50%, indicating that over one-third of patients experienced complications shortly after surgery. The three-month postoperative complication rate was also 37.50%, suggesting that these complications might have long-lasting effects.

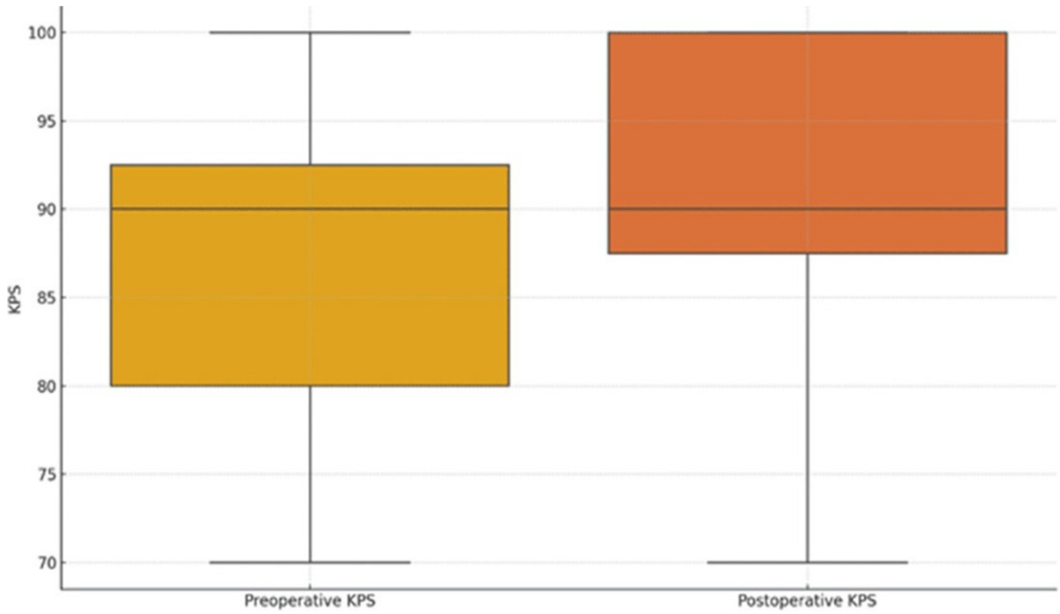

Fig 5: Box plot showing the preoperative (yellow) and postoperative KPS (orange) distribution for all patients.

We then assessed the relationship between each EOR subcategory and potential KPS improvement. The mean Karnofsky Performance Status (KPS) values for each Extent of Resection (EOR) subcategory were as follows: for patients in the Partial Resection (PR) category (0-50% EOR), the mean preoperative KPS was 73.33 and the mean postoperative KPS was 79.17, resulting in a mean KPS change of 5.83. In the Subtotal Resection (STR) category (51-75% EOR), the mean preoperative KPS was 85.00 and the mean postoperative KPS was 77.50, with a mean KPS change of -7.50. For the Near Total Resection (NTR) category (76-98% EOR), the mean preoperative KPS was 81.67 and the mean postoperative KPS was 90.00, resulting in a mean KPS change of 8.33. In the gross total resection (GTR) category (99-100% EOR), the mean preoperative KPS was 92.00 and the mean postoperative KPS was 95.00, with a mean KPS change of 3.00. These values highlighted the varying degrees of functional improvement or decline associated with different levels of tumor resection. An ANOVA test was conducted to determine if the mean KPS change between categories was significant. The ANOVA test did not reveal statistically significant differences in the mean KPS changes across the different EOR categories, with an F-statistic of 2.15 and a p-value of 0.147. After investigating the relationship between EOR categories and the change in KPS, we proceeded to investigate the different mean KPS categories (preoperative, postoperative, and change) and their correlation with EOR. We created a correlation matrix for the mean KPS categories and EOR. The resulting correlation coefficients provide insights into the relationships between preoperative KPS, postoperative KPS, EOR, and change in KPS, helping to understand how these variables interact with each other in the context of surgical outcomes. The correlation matrix analysis revealed the following correlation coefficients: preoperative KPS and postoperative KPS (r=0.735), preoperative KPS and EOR (r=0.794), postoperative KPS and EOR (r=0.839), KPS change and EOR (r=-0.078), preoperative KPS and KPS change (r=-0.506), and postoperative KPS and KPS chacge (r=0.212). This indicates a strong positive correlation between Preoperative KPS and postoperative KPS, Preoperative KPS and EOR, and postoperative KPS and EOR, as well as a moderate negative correlation between KPS change and preoperative KPS.

Our final analysis was the amount of blood loss (ml) and duration of hospital stay (days) amongst our cohort **(Fig. 6).** On average, patients spent 5.69 days in the hospital post-surgery, with a standard deviation of 2.73 days. The mean blood loss during surgery was 387.50 ml, with a standard deviation of 379.69 ml. our results revealed significant variability in blood loss among patients, with amounts ranging from as low as 50 ml in patient Seven to as high as 1500 ml in patient Three. Most patients experienced blood loss around 500 ml, with only a few exceptions exceeding this amount. Hospital stay ranged from two days (patient seven) to 13 days (patient Six), and showed a relatively even distribution, with a slight concentration around five to six days. Key observations include patient three, who despite having the highest blood loss of 1500 ml, had a relatively short hospital stay of four days, and patient six, with moderate blood loss of 250 ml, experienced the longest hospital stay of 13 days, indicating other factors may have influenced the extended stay. Patient seven, who had the least blood loss of 50 ml, also had the shortest hospital stay of two days, suggesting a straightforward recovery.

We further investigated the relationship between the amount of blood loss and the length of hospital stay by doing a correlation analysis. The calculated correlation coefficient between blood loss and hospital days was -0.072, indicating a very weak negative correlation, suggesting no significant relationship between the amount of blood loss during surgery and the length of hospital stay.

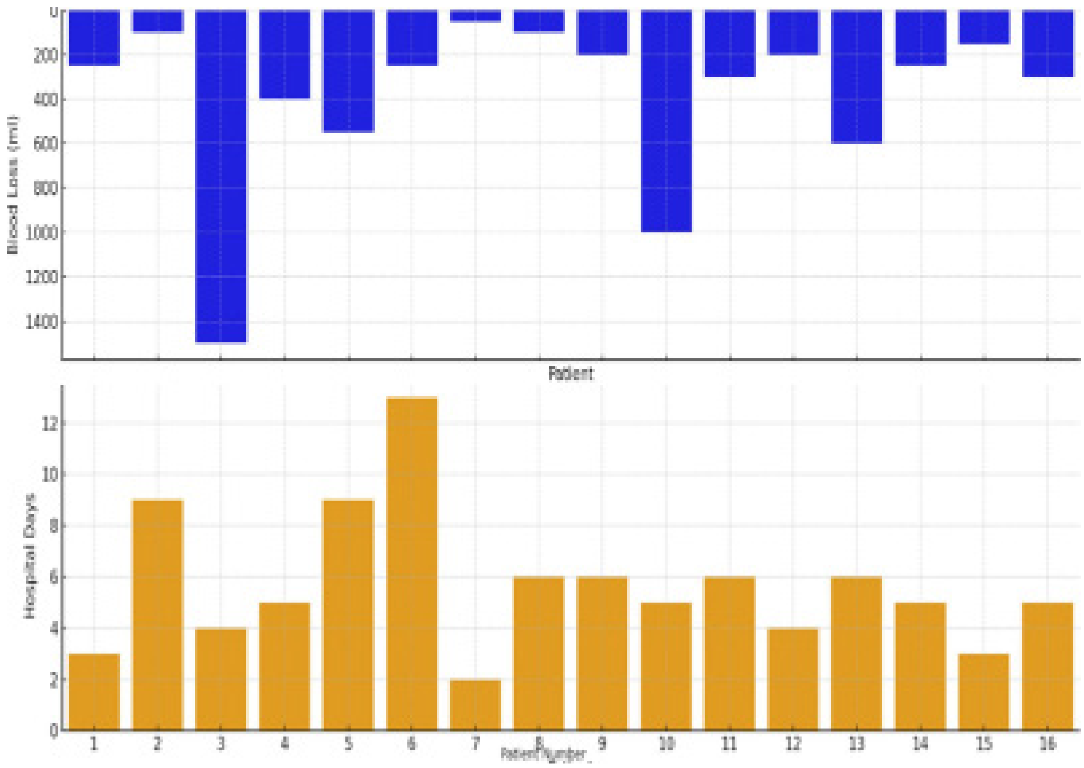

Fig 6: The mirrored bar plot above presents blood loss (blue bars) and hospital days (yellow bars) for each patient in the cohort. Blood loss shown above the horizontal axis in blue and hospital days below the axis in orange.

Table 1: Summary of our demographics

Variable	Value
Total patients	16
Sex	9 males, 7 females
Age range (years)	18-52
Average age (years)	37.38
Median age (years)	39
Age standard deviation	11.22
Brain locations	Frontal: 6, FTI: 3, Peri-Rolandic: 4, Temporal: 2, Opercular: 1
Tumor side	Right: 7, Left: 9
Tumor pathology	Anaplastic astrocytoma (6), Diffuse astrocytoma (2), Glioblastoma (1), Anaplastic oligodendroglioma (1), Cerebral cavernous malformations (2), Metastatic carcinoid (1), Ganglioglioma (1), and DNET (2)
WHO Grades	WHO Grade 1 (5), WHO Grade 2 (2), WHO Grade 3 (7), WHO Grade 4 (1)

FTI: fronto-tempro-Insular. DNET: Dysembreoplastic neuroepithelial tumor, WHO: World Health Organization.

Due to the study time frame the pathological classification and reporting as per the WHO 2016 and 2021.[3]

DISCUSSION

Our study highlighted key findings regarding neuronavigation (NNAV)-guided surgical outcomes for intra-axial weakly enhancing brain lesions in a resource-limited neurosurgical setting. Starting with how the NNAV assisted us in lesion localization, tumor visibility by the naked eye under standard surgical white light varied, with 25% of tumors not visible, 43.75% partially visible, and 31.25% clearly visible. Thus, neuronavigation was considered essential for tumor localization in 68.75% of the cases, indicating that nearly 70% of the surgeries required NNAV assistance for safe tumor resection.

Moreover, the NNAV's accuracy was maintained throughout the procedures, unaffected by brain shift in all but one case. In that instance, a significant error in navigational accuracy was detected early during the resection process, requiring the use of an intraoperative ultrasound to semi-automatically correct the brain shift and allow further resection. Surgeons subjectively reported an overall positive attitude toward using neuronavigation, reflecting its perceived utility and reliability in aiding tumor localization. This widespread acceptance highlights the importance of neuronavigation in achieving precise tumor localization, particularly in cases where the tumor is not easily visible under standard surgical lighting.

After assessing the NNAV's usefulness subjectively, we proceeded to objectively assess its effect on surgical outcomes by measuring several variables and comparing them to similar studies in the literature. Although half of our cohort had an extent of resection (EOR) above 78.11% (median EOR), the mean EOR achieved in this study was 64.51%, with a standard deviation of 35.19% and a wide variance, suggesting a substantial spread in EOR values and reflecting highly variable surgical outcomes. This variability can be attributed in part to the heterogeneity of several factors (patient status, tumor characteristics, and surgeon's experience) and the small sample size that accentuated this variability.

When compared to the literature, our EOR and GTR rates showed some discrepancies from other results reported. For instance, Valdivia et al.[4] reported a higher mean EOR of 84% and a GTR of 56%, using other tools with the NNAV, such as fluorescein "5-ALA" and cortical mapping guidance, which significantly improved outcomes as per their univariate and multivariate analyses. Willems et al.[5] achieved a comparable calculated mean EOR of contrast-enhancing tumor tissue of approximately 71% but a lower GTR rate of 13% (three out of 23 patients in the neuronavigation group). This EOR percentage variability, spanning almost two decades, suggests that over the years, the EOR of surgeries conducted with NNAV on intra-axial lesions might be influenced by several factors, such as tumor characteristics, surgical techniques, and intraoperative decision-making. Moreover, we can infer that NNAV alone might not be sufficient to achieve radiological radicality.

In our study, the immediate postoperative complication rate was 37.50%, and the three-month postoperative complication rate remained the same, indicating that these complications might lead to permanent neurological deficits. However, the complication rate was not significantly correlated with either blood loss or hospital stay. Patients spent an average of 5.69 days in the hospital post-surgery (SD=2.73 days), and the mean blood loss during surgery was 387.50 ml (SD=379.69 ml). Although we had a higher complication rate, our blood loss and hospital days were much lower than the range reported by a study by Akyuz and Kadioglu.[6] (Approximately 13 days and 900 ml), which compared NNAV versus. non-NNAV meningioma surgery and found statistical significance in the use of neuronavigation for improving blood loss, surgical time, and postoperative hospital stay. The weak correlation coefficient between blood loss and hospital days supports the idea that blood loss during surgery does not significantly impact the length of hospital stay. Instead, other factors such as the patient's overall health, the complexity of the surgery, and post-surgical complications may play a more influential role. This analysis highlights that while monitoring blood loss is important, it may not be the primary determinant of hospital stay duration. It also underscores how NNAV can help decrease blood loss and hospital days.

Although we had a relatively high complication rate and a low GTR rate, most patients either maintained or improved their KPS, with a mean five-point increase in the postoperative KPS (SD=12.11), with only two patients showing a decline. This result prompted us to delve further into the relationship between KPS change and various study variables. Consequently, we conducted multiple linear regression analyses to examine predictors affecting KPS change. Significant predictors were preoperative KPS and postoperative KPS, with coefficients of -1.0000 ($P < 0.05$) and 1.0000 ($P<0.05$), respectively. This indicates that higher preoperative KPS is associated with less improvement, as patients with better initial functional status have less room for noticeable improvement. While lower postoperative KPS is associated with greater improvement, highlighting successful recovery and functional gains post-surgery. Other predictors, including final EOR percentage, tumor size, patient age, hospital days, immediate postoperative complications, and tumor location, were not statistically significant. The initial linear regression model had a high R-squared value of 1.000, which indicated potential overfitting due to multicollinearity among predictors. By addressing multicollinearity and removing these predictors, the revised model resulted in a more stable and interpretable model, with a moderate fit and an R-squared value of 0.663. Significant effects were postoperative KPS and certain tumor locations on KPS change. Specifically, significant negative impacts on KPS change were observed for the opercular tumor location ($P = 0.037$) and temporal tumor location ($P = 0.017$). These findings can be attributed to the proximity of these locations to eloquent cortices involved in speech processing, such as Broca's and Wernicke's areas, along with the connecting tracts and language streams within the temporal lobe. These findings suggest that tumor location, particularly in areas close to eloquent cortices, significantly impacts functional outcomes post-surgery.

The correlation matrix between the KPS categories and the EOR suggests that while the extent of resection is crucial for achieving oncological goals, it may not directly translate to functional improvement. Therefore, surgical planning should consider not only the aim of maximal resection but also the preservation of neurological function to optimize overall patient outcomes. The results align with existing studies that highlight KPS scores and functional status as major predictors of outcomes.[7-9] Improving preoperative functional status is essential, and the relationship between EOR and functional improvement is complex and influenced by multiple factors. For example, patients with higher preoperative KPS are more likely to maintain their functional status post-surgery, while those with lower preoperative KPS have more potential for improved KPS change. One variable that we aim to assess and evaluate further, which has been mentioned in the literature as a better prognostic indicator of outcome,is the residual tumor volume rather than the EOR or GTR. While we initially planned to measure and incorporate this variable into our results, we were impeded by our small sample size which led to insignificant findings. [10] However, further investigations are being planned at our institution to confirm the powerful effects of residual tumor volume, as opposed to EOR, among other variables, in larger cohorts.

Limitations

The main limitation of our study is the small sample size, which limited our ability to draw significant statistical conclusions regarding other study objectives (e.g., WHO grades, isocitrate dehydrogenase (IDH) mutation status, etc.), thereby limiting appreciable conclusions.

Another limitation was the absence of randomization; we could not randomize the population into the NNAV group versus. the non-NNAV group due to ethical reasons. In line with other non-randomized studies using historical controls, we compared our EOR results to the literature. However, in doing so, sample heterogeneity cannot be fully excluded. Moreover, our radiology-based selection process resulted in a heterogeneous group of intra-axial pathologies. This heterogeneity, encompassing different pathologies, sizes, sites, and proximity to eloquent cortical and subcortical areas, limited the availability of homogeneous data for significant statistical analysis.

Furthermore, there might be bias from a potential learning effect. Even though all main surgeons had previous experience with NNAV-guided resections of intra-axial brain lesions, there might be bias in the learning curve while using the NNAV. As it is a newly introduced device to our institute, the earlier patients in the study had a less "NNAV-experienced" surgeon, in contrast to the patients near the end of the study.

Moreover, we only followed the patients for a short term, the longest follow-up period was six months. Thus, we were not able to withdraw intermediate or longer-term outcomes, such as permanent neurological deficits, survival rates, and oncological outcomes. Finally, we did not conduct a formal financial analysis to evaluate the cost-effectiveness of the neuronavigation device or compare it to other intraoperative modalities, such as intraoperative ultrasound combined with an ultrasonic aspirator. However, we anticipate that, in the long term, with proper training, improved patient selection, and optimized resource allocation, neuronavigation will prove cost-effective. To statistically validate its cost-effectiveness and compare its financial value in a resource-limited setting, we plan to conduct a formal efficiency study in the future. This will help us better allocate resources to meet patient needs, such as choosing between IOUS and NNAV.

CONCLUSION

Our study assesses neuronavigation in intra-axial brain surgery within a resource-limited setting. NNAV improved tumor localization and resection accuracy, particularly for hard-to-see lesions. NNAV use was correlated with better preoperative and postoperative KPS scores. Patients with higher preoperative KPS achieved greater resection and maintained better outcomes, while those with lower KPS showed greater improvement potential. However, the use of NNAV alone was insufficient for tumors near eloquent regions, potentially requiring adjunct tools like IOUS to improve safety and radicality.

The study highlights the need for complementary techniques (e.g. awake surgery and/or cortical mapping) and future research focusing on larger cohorts, advanced predictors (e.g., preoperative language function metrics), and refined patient selection protocols to improve postoperative recovery and functional outcomes in resource-constrained neurosurgical settings.

List of abbreviations

5-ALA: 5-amino levulinic acid.
ANOVA: Analysis of variance.
ASU: Ain Shams University.
CNS: Central nervous system.
CT: Computerized tomography.
DNET: Dysembryoplastic-neuroectodermal tumor.
DTI: Diffusion tensor imaging.
EOR: Extent of resection.
FLAIR: Fluid attenuated inversion recovery.
FMRI: Functional magnetic resonance imaging.
FTI: Fronto-tempro-insular.
GTR: Gross total resection.
IDH: Isocitrate dehydrogenase.
IONM: Intraoperative neuromonitoring.
IOUS: Intraoperative ultrasound.
IQR: Interquartile range.
KPS: Karnofsky performance status.

MRI: Magnetic resonance imaging.
NNAV: Neuronavigation.
NS: Nonsignificant.
NTR: Near total resection.
PR: Partial resection.
ROI: Region of interest.
S: Significant.
SD: Standard deviation.
SPSS: Statistical package for social science.
STR: Subtotal resection.

Disclosure

The authors report no conflict of interest in the materials or methods used in this study or the findings specified in this manuscript.

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