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ORIGINAL RESEARCH

Evaluation of the Use of Intraoperative Neuronavigation in the Surgery of Brain Tumors: Single Center Experience and Retrospective Analysis of 172 Cases

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ABSTRACT

Neuronavigation systems are computer-assisted procedures that use preoperative imaging data to ensure accurate anatomical orientation and safe resection during surgery. Despite their widespread use in neurosurgery, evidence of their effectiveness and reliability remains limited. This study aimed to examine the need for neuronavigation systems in patients with intracranial tumors, their relationship with tumor location and size, and their limitations. A retrospective analysis was conducted on 172 patients with intracranial tumors who underwent surgery using neuronavigation systems at our clinic between January 2021 and October 2023. Patients were classified based on tumor size into two groups: those with tumors <3 cm and those with tumors ≥ 3 cm. Further classification was done according to tumor locations such as supratentorial, infratentorial, and skull base, as well as based on superficial and deep-seated tumor locations. The need for neuronavigation systems was assessed using a scoring scale ranging from 0 to 2 assigned during surgery. Of the patients, 49.4% were male and 50.6% were female, with a mean age of 52.9 ± 16.2 years (range 2–80 years). The mean total score for neuronavigation system use was significantly higher in patients with tumors <3 cm and those with deep-seated tumors (p = 0.003). The need for neuronavigation was less in infratentorial tumors. Identifying anatomical and vascular structures during surgery was the surgical stage with the greatest need for neuronavigation use (n=172, 100%). Multivariate binary logistic regression analysis revealed that tumor size ≥3 cm and superficial location were risk factors determining the need for neuronavigation systems. İdentifying anatomical and vascular structures in supratentorial and deep-seated tumors, and evaluating surgical resection in tumors <3 cm are the areas where the use of neuronavigation systems is necessary.

Keywords: Image-guided surgery. Neuronavigation. Brain tumor surgery.

Beyin Tümörlerinin Cerrahisinde İntraoperatif Nöronavigasyon Kullanımının Değerlendirilmesi: Tek Merkez Deneyimi ve 172 Vakanın Retrospektif Analizi

ÖZET

Nöronavigasyon sistemleri, ameliyat sırasında doğru anatomik oryantasyon ve güvenli rezeksiyon sağlamak için ameliyat öncesi görüntüleme verilerini kullanan bilgisayar destekli prosedürlerdir. Nöroşirürjide yaygın olarak kullanılmalarına rağmen, etkinlikleri ve güvenilirliklerine dair kanıtlar sınırlı kalmaktadır. Bu çalışmanın amacı intrakraniyal tümörlü hastalarda nöronavigasyon sistemlerine olan ihtiyacı, tümörün yeri ve boyutuyla ilişkisini ve sınırlamalarını incelemektir. Ocak 2021 ve Ekim 2023 tarihleri arasında kliniğimizde nöronavigasyon sistemleri kullanılarak ameliyat edilen intrakraniyal tümörlü 172 hasta üzerinde retrospektif bir analiz yapıldı. Hastalar tümör boyutuna göre iki gruba ayrıldı: <3 cm tümörü olanlar ve ≥ 3 cm tümörü olanlar. Ayrıca, supratentoryal, infratentoryal ve kafa tabanı gibi tümör lokasyonlarının yanı sıra yüzeysel ve derin yerleşimli tümör lokasyonlarına göre de sınıflandırma yapılmıştır. Nöronavigasyon sistemlerine duyulan ihtiyaç, ameliyat sırasında verilen 0 ila 2 arasında değişen bir skorlama ölçeği kullanılarak değerlendirilmiştir. Hastaların %49,4'ü erkek, %50,6'sı kadındı ve ortalama yaşları 52,9 ± 16,2 yıldı (dağılım 2-80 yıl). Nöronavigasyon sistemi kullanımı için ortalama toplam puan <3 cm tümörü olan hastalarda ve derin yerleşimli tümörü olanlarda anlamlı olarak daha yüksekti (p = 0.003). Nöronavigasyon ihtiyacı infratentoryal tümörlerde daha azdı. Cerrahi sırasında anatomik ve vasküler yapıların belirlenmesi nöronavigasyon kullanımına en fazla ihtiyaç duyulan cerrahi aşamaydı (n=172, %100). Çok değişkenli ikili lojistik regresyon analizi, tümör boyutunun ≥3 cm ve yüzeysel yerleşimin nöronavigasyon sistemlerine olan ihtiyacı belirleyen risk faktörleri olduğunu ortaya koydu. Supratentoryal ve derin yerleşimli tümörlerde anatomik ve vasküler yapıların belirlenmesi ve <3 cm tümörlerde cerrahi rezeksiyonun değerlendirilmesi nöronavigasyon sistemlerinin kullanımının gerekli olduğu alanlardır.

Anahtar Kelimeler: Görüntü rehberliğinde cerrahi. Nöronavigasyon. Beyin tümörü cerrahisi.

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Image-guided neuronavigation systems (NN) are computer-assisted procedures that aid in planning of a surgical approach to targeted lesion[1–4]. In traditional cranial surgery, intraoperative identification of local anatomical is required to position and reach the target area[5]. This procedure can be complicated and difficult, particularly in deep-seated parenchymal lesions, as it involves working within a broader surgical field and poses a potential risk of injury to functional brain tissue.

The principles of NN, based on the Cartesian coordinate system, were developed in the early 20th century and allowed the surgical target to be determined with minimal margin of error[6–8]. With rapid advances in technology, significant improvements in NN systems have occurred over the last two decades. These advancements have enabled not only accurate intraoperative localization of lesions but also the identification of adjacent anatomical structures, allowing for optimal surgical planning[9]. Consequently, NN has become an indispensable tool for many neurosurgical procedures[3].

However, NN systems are still evolving technologies. The evidence reporting their effectiveness and safety of remains limited[10,11]. During surgery, the drainage of cerebrospinal fluid (CSF) and the displacement of lesioned and non-lesioned brain areas (brain shift) due to tumor resection can alter the preoperatively acquired NN data[10–15]. Additionally, technical implementation difficulties, installation time, and the cost of NN systems cost limit their widespread use[16,17].

In this study, we examined the need and limitations of NN use in the surgical treatment of patients with intracranial tumors in relation to tumor location and size. We also aimed to determine at which surgical stages intraoperative NN is required.

Material and Method

Following approval from the local ethics committee, a retrospective analysis was conducted on 172 cases of intracranial tumor lesions that underwent intraoperative NN (Stealth Station, Medtronic, Minnesota, USA) assisted surgical interventions at our center between 2021 and 2023. All procedures involving human participants were conducted in accordance with the ethical standards of the institutional or national research committee and with the 1964 Helsinki Declaration and its later amendments, or comparable ethical standards. Review of patient files confirmed that all participants provided informed consent.

Patients with intracranial lesions confirmed by pathological diagnoses were included in the study. Exclusion criteria included patients who underwent surgical interventions with NN for reasons other than intracranial tumors, those who did not receive intraoperative NN, and those who underwent biopsy procedures.

The patients' age, gender, presenting symptoms, location and size of the targeted lesion, the need for NN during surgery, limitations of NN use, and related data were retrospectively analyzed. Histopathological diagnoses, preoperative and postoperative Karnofsky Performance Scores (KPS), tumor resection grades, medical complications, intraoperative course, and encountered issues were also identified.

Surgical Procedure

Surgical procedures were performed using the frameless NN system (Stealth Station, Medtronic, Minnesota, ABD). Preoperative axial T2 CISS and axial T1 contrast-enhanced MRI slices with a 1mm slice interval were acquired from all patients and transferred to the surgical NN workstation. Intraoperative data were then recorded using the surface marking technique. Image-patient record fusion was achieved. During surgery, an operating microscope (Leica OH6, Leica Microsystems, Wetzlar, Germany) was used to perform standard microsurgical procedures, and the intraoperative position was periodically checked using the reference probe when necessary.

Assessment of patient groups and the need for NN use

Patients were grouped according to tumor location as follows: supratentorial tumors (STT) (Figure 1), infratentorial tumors (ITT) (Figure 2), and skull base tumors (SBT) (Figure 3). Additionally, patients with tumors reaching the cortical surface were classified as superficial tumors (SFT) and patients with tumors below the cortex were classified as deep-seated tumors (DST). Based on tumor size, they were classified as tumors <3 cm and tumors ≥3 cm (Table I). The NN data and operative notes were retrospectively reviewed to identify surgical stages requiring NN usage. A scoring system was established for the five surgical stages identified, and evaluations were conducted across all groups. These stages were:

1. Planning the skin flap and craniotomy,
2. Identifying anatomical and vascular structures,
3. Determining the cortical incision site,
4. Determining the route to reach the tumor,
5. Evaluating tumor resection.

The assessment was conducted on a 3-point scale. (0: No need for NN usage, 1: NN was used but the procedure could be performed without it, 2: NN usage was necessary). The total score for all five stages ranged from 0 to 10.

The results were analyzed in three ways:

1. Association between tumor size and need for NN use

2. The association between tumor localization and need for NN use

3. Need for NN use in each of the five stages identified during surgery

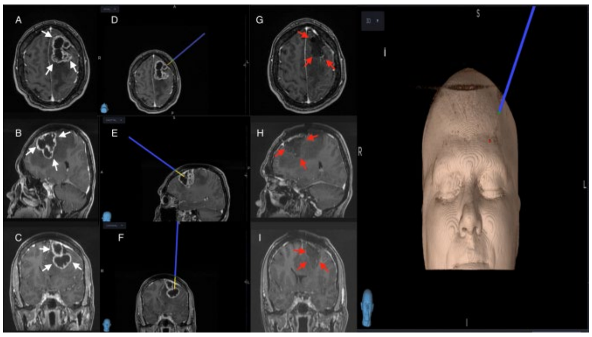

Figure 1.
A patient with supratentorial tumor: preoperative MRI scan, intraoperative neuronavigation and postoperative MRI scan.

***(A-C)** Preoperative MRI scan (axial, sagittal, coronal T1-weighted gadolinium) showed a tumor located in the left frontal region (white arrow indicates tumor). **(D-F)** Intraoperative neuronavigation image (axia, sagittal, coronal T1-weighted with gadolinium). **(G-I)** Postoperative MRI showed total tumor resection (red arrow showed cavity after tumor resection). **(İ)** Neuronavigation image of the skull entry site.*

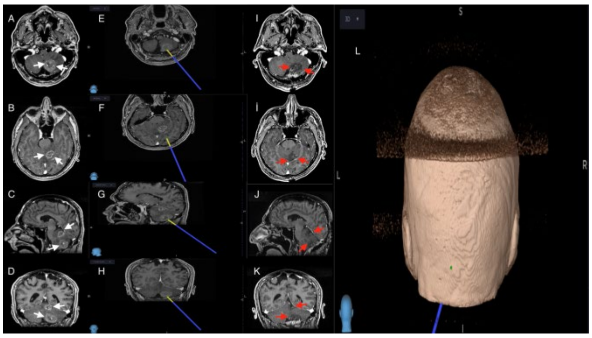

Figure 2.
A patient with tumors located in two different infratentorial areas: preoperative MRI, intraoperative neuronavigation and postoperative MRI scan.

***(A-D)** Preoperative MRI scan (axial, sagittal, coronal T1-weighted gadolinium) showed a tumor located in the left frontal region (white arrow indicates tumor). **(E-H)** Intraoperative neuronavigation image (axial, sagittal, coronal T1-weighted with gadolinium). **(I-K)** Postoperative MRI showed total tumor resection (red arrow showed cavity after tumor resection). **(L)** Neuronavigation image of the skull entry site.*

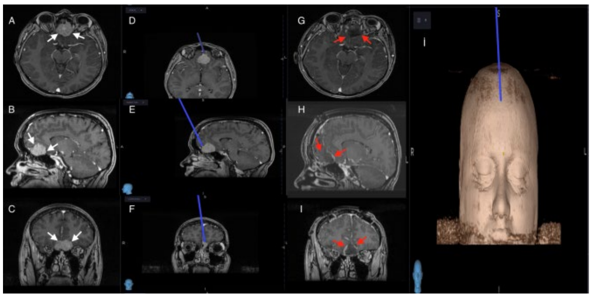

Figure 3.
A patient with a skull base tumor: preoperative MRI, intraoperative neuronavigation and postoperative MRI scan.

***(A-C)** Preoperative MRI scan (axial, sagittal, coronal T1-weighted with gadolinium) showed a tumor in the frontobasal (white arrow showed tumor). **(D-F)** Intraoperative neuronavigation image (axial, sagittal, coronal T1-weighted with gadolinium). **(G-I)** Postoperative MRI showed total tumor resection (red arrow showed cavity after tumor resection). **(İ)** Neuronavigation image of the skull entry site.*

Postoperative evaluation

All patients were monitored in the intensive care unit for at least 24 hours postoperatively. The KPS at the time of postoperative discharge was determined for all patients and compared with the preoperative KPS.

All patients underwent early postoperative cranial CT and follow-up MRI within the first 24 hours after surgery. All neuroimages were reviewed for residual contrast-enhancing tumor tissue. Gross total resection (GTR) was defined as no distinct tumor observed on postoperative MRI. Subtotal resection (STR) was defined as observation of residual tumor exceeding 5% of the total tumor volume.

Results

A total of 172 patients who met the inclusion criteria underwent tumor resection using intraoperative NN. Of these patients, 49.4% of the patients were male and 50.6% were female, with a mean age was 52.9 ± 16.2 years (range 2-80 years). The symptoms, histopathological diagnoses, preoperative and postoperative mean KPS values, resection rates, complications, and classification of the patient groups according to tumor location and size are presented in Table I. In the present study, the deviation from accuracy in calculating the neuronavigation target registration error was found to be an average of 2.4± 0.3 mm.

Table I. General demographic characteristics and clinical conditions of patients.

Variables	(n = 172) (%)
Gender	
Female	87(50.6)
Male	85(49.4)
Mean Age ± SD, years	52.9 ± 16.2
Symptoms at presentation	
Headache	140(81.4)
Nausea and vomiting	52(30.2)
Seizures	37(21.5)
Hemiparesis	30(17.4)
Ataxia and balance disorder	28 (16.3)
Cranial nerve involvement	22 (12.7)
Speech impairment	17(9.9)
Personality disorder	8 (4.6)
Histopathological diagnosis	
Glioblastoma multiforme	50(29)
Metastasis	44(25.6)
Meningioma	33(19.2)
Anaplastic astrocytoma	11(6.4)
Pilocytic astrocytoma	6(3.5)
Oligodendroglioma	5(2.9)
Schwannoma	5(2.9)
Pituitary adenoma	5(2.9)
Epidermoid tumor	4(2.3)
DNET	4(2.3)
Lymphoma	3(1.8)
Ependymoma	2(1.2)
Mean KPS± SD	
Preoperative KPS	88.2±13.4
Postoperative KPS	87.5±14.6
Resection rate	
GTR	133(77.3)
STR	39 (22.7)
Complications	
Seizures	12(6.9)
Hemiparesis	9(5.2)
Infection	5 (2.9)
Intracerebral hematoma	4 (2.3)
CSF fistula	3(1.8)
Location	
Infratentorial	29 (16,9)
Skull base	30 (17,4)
Supratentorial	113 (65,7)
Localization	
Superficial	78 (45,3)
Deep-seated	94 (54,7)
Size (cm)	
<3.00	97 (56,4)
≥3.00	75 (43,6)

SD: Standard deviation, **GTR:** Gross total resection, **STR:** Subtotal resection, **CSF:** Cerebrospinal fluid, **DNET:** Dysembryoplastic neuroepithelial tumor, **KPS:** Karnofsky performance score

The relationship between tumor size and the need for NN use

The independent samples t-test showed that the mean total score of the need for NN use was statistically significantly higher in patients with tumors <3 cm compared to patients with tumors ≥3 cm (p = 0.003). Additionally, the need for NN use in the “evaluating tumor resection” stage was statistically significantly higher in patients with tumors <3 cm (p < 0.001) (Table II). According to multivariate binary logistic regression analysis, tumor size ≥3 cm was a risk factor determining the need for NN use. The total scores increased the risk of not needing intraoperative NN use 4.77-fold at the stage of determining the cortical incision site (p < 0.001, CI;1.80–12.64), 2.73-fold at the stage of determining the route to reach the tumor (p<0.005, CI;1.12–6.69), and 4.44-fold at the stage of evaluating tumor resection (p<0.001, CI;2.20–8.962). These findings were statistically significant (Table III).

The relationship between tumor location and the need for NN use

In the independent samples t-test, the mean total score for the need for NN use was significantly higher in the DST group than in the SFT group (p < 0.001). Additionally, in the "identified surgical stages of defining anatomical and vascular structures, determining the route to reach the tumor, and evaluating tumor resection", the need for NN use was statistically significantly higher in the SFT group (p<0.001) (Table II). However, the need for NN use during "planning the skin flap and craniotomy" was statistically significantly higher in the SFT group than in the DST group (p < 0.001).

According to multivariate binary logistic regression analysis, SFT was another risk factor determining the need for NN use, with total scores increasing the risk of not needing intraoperative NN use 80.10-fold at the stage of determining the "cortical incision site" (p<0.001, CI;9.73–659.73) and 27.69-fold at the stage of "determining the route to reach the tumor" (p<0.001, CI;7.20–106.53). These findings were statistically significant (Table III).

Evaluation of the need for NN use in the surgery of infratentorial tumors, skull base tumors, and supratentorial tumors

A statistically significant difference in female-to-male ratios was found between the ITT, SBT, and STT patient groups (p = 0.023) according to the chi-square test. Moreover, according to the Kruskal–Wallis H test, there were statistically significant differences in age (p = 0.025), mean total score (p<0.001), as well as surgical stages of "planning the skin flap and craniotomy” (p<0.001), “identifying anatomical and vascular structures” (p<0.001), and “evaluating tumor resection” (p = 0.027) between the ITT, SBT, and STT patient groups.

Pairwise comparison of the groups revealed that the median total scores for NN use were significantly higher in the STT and SBT patient groups than in the ITT patient group (p<0.005). Furthermore, when the surgical stages were evaluated, the median scores for NN use for the stages of "planning the skin flap and craniotomy and identifying anatomical and vascular structures" were significantly higher in the STT group than in the SBT group and in the SBT group than in the ITT group (p<0.005). Similarly, the median scores for NN use during the evaluation of tumor resection were statistically significantly higher in the SBT group compared to the STT group (p<0.005). Pairwise comparison of the groups revealed a statistically significant difference in median age (p<0.005). Multivariate binary logistic regression analysis revealed that tumor localization in different intracranial compartments was not a statistically significant risk factor in evaluating the need for NN (Table III).

Table II. Comparison of age, gender and need for neuronavigation use between groups according to surgical stages.

		Infratentorial localization		Skull base localization		Supratentorial localization		Superficial tumor		Deep-seated tumor		<3 cm		≥3 cm	
		n	%	n	%	n	%	n	%	n	%	n	%	n	%
Gender	Male	19	65,5	9	30,0	57	50,4	37	47,4	48	51,1	50	51,5	35	46,7
	Female	10	34,5	21	70,0	56	49,6	41	52,6	46	48,9	47	48,5	40	53,3
	p	**0,023[a]**						0,636[a]				0,526[a]			
		Med.	Q1-Q3	Med.	Q1-Q3	Med.	Q1-Q3	Ort.	SS.	Ort.	SS.	Ort.	SS.	Ort.	SS.
Age		52,00	30,00-60,00	47,50	42,00-61,00	57,00	47,00-64,00	55,40	14,85	50,74	16,94	54,39	14,84	50,87	17,61
p		**0,025[b#]**						0,060[c]				0,156[c]			
Planning skin flap and craniotomy		0,0	0,0-0,0	0,0	0,0-2,0	2,0#	2,0-2,0	1,67	0,75	1,31	0,92	1,48	0,84	1,45	0,89
p		**<0,001[b$]**						**<0,001[c]**				0,815			
Identification of anatomical and vascular structures		2,0	1,0-2,0	2,0	2,0-2,0	2,0	2,0-2,0	1,83	0,38	1,94	0,25	1,91	0,29	1,87	0,34
p		**<0,001[b$]**						**<0,001[c]**				0,403[c]			
Determination of the cortical incision site		2,0	1,0-2,0	2,0	1,0-2,0	1,0	1,0-2,0	0,69	0,61	1,85	0,39	1,40	0,69	1,23	0,85
p		0,113[b#]						**<0,001[c]**				0,136[c]			
Determining the route to reach the tumor		2,0	0,0-2,0	2,0	1,0-2,0	1,0	1,0-2,0	0,68	0,61	1,76	0,50	1,34	0,73	1,17	0,81
p		0,052[b#]						**0,001[c]**				0,160[c]			
Evaluation of the amount of resection		1,0	0,0-2,0	2,0	1,0-2,0	1,0	0,0-1,0	0,71	0,61	1,20	0,86	1,24	0,76	,64	0,71
p		**0,027[b*]**						**<0,001[c]**				**<0,001[c]**			
Total		6,0	3,0-8,0	7,5	6,0-8,0	7,0	6,0-9,0	5,58	2,03	8,05	1,69	7,37	2,18	6,36	2,17
p		**<0,001[b##]**						**0,001[c]**				**0,003[c]**			
Preoperative KPS		80,0	80,0-80,0	100,0	90,0-100,0	100,0	70,0-100,0	87,05	13,69	89,26	13,14	89,48	13,65	86,67	12,98
p		**<0,001[b$$]**						0,164[c]				0,172[c]			
Postoperative KPS		80,0	80,0-80,0	100,0	90,0-100,0	100,0	70,0-100,0	86,15	14,88	88,72	14,39	88,76	14,67	86,00	14,52
p		**0,020[b$$]**						0,292[c]				0,220[c]			

a: Chi-Square Test, b: Kruskal–Wallis H test, c: Independent Samples t-test, KPS: Karnofsky performance score. Pairwise post-hoc test: # Supratentorial localization, Skull base localization, Infratentorial localization,
$ Supratentorial localization > Skull base localization > Infratentorial localization,
* Supratentorial localization<Skull base localization
Infratentorial localization<Supratentorial localization, Skull base localization
$$ Infratentorial localization<Skull base localization

Table III. Multivariate logistic regression analysis of factors affecting the need for neuronavigation use.

	Planning the skin flap and craniotomy		Determination of the cortical incision site		Determining the route to reach the tumor		Evaluation of the amount of resection	
	B	Odds Ratio (CI %95)	B	Odds Ratio (CI %95)	B	Odds Ratio (CI %95)	B	Odds Ratio (CI %95)
Age	**-0,03***	**0,98 (0,95-1,00)**	-0,01	0,99 (0,96-1,02)	0,02	1,02 (0,99-1,05)	-0,01	0,99 (0,97-1,008)
Gender (Male)	-0,14	0,87 (0,42-1,79)	-0,32	0,73 (0,28-1,91)	0,00	1,00 (0,42-2,42)	0,20	1,22 (0,61-2,435)
Size (>3 cm)	0,09	1,09 (0,53-2,26)	**1,56****	**4,77 (1,80-12,64)**	**1,01***	**2,73 (1,12-6,69)**	**1,49****	**4,44 (2,20-8,962)**
Localization (SFT)	-0,70	0,50 (0,23-1,05)	**4,38****	**80,10 (9,73-659,73)**	**3,32****	**27,69 (7,20-106,53)**	0,66	1,94 (0,92-4,087)
STT (Yes)			0,277	1,320 (0,37-4,77)	-0,71	0,490 (0,16-1,47)	-0,05	0,95 (0,43-2,10)
Nagelkerke R Square	0,09*		0,48**		0,38**		0,18**	

SFT: Superficial tumor group. STT: Supratentorial tumor group. Binary Multivariate Logistic Regression Analysis. *<0,05, **<0,01

Postoperative evaluation

According to preoperative and postoperative MRI evaluation, the GTR rate was 77.3% in the present study. In the early postoperative period, surgical intervention was required for significant hematomas at the surgical site in four patients (2.3%). All these patients underwent reoperation to evacuate the hematoma. Additionally, postoperative neurological examination revealed deterioration in nine patients (5.2%) compared with preoperative neurological status. At the one-month follow-up, it was observed that the neurological status of four patients (2.3%) had improved and returned to the preoperative level. Wound site infection was observed in five patients (2.9%). Statistical analysis showed no significant difference between the mean KPS scores of patients at admission (88.2±13.4) and discharge (87.5±14.6). No surgical mortality was observed in this series (Table I)

Statistical Analysis

Descriptive statistical analyses (number, percentage, mean, standard deviation, etc.) were performed to examine the demographic and clinical characteristics of the cases evaluated in the study. The mean age and treatment success between the two groups were compared using the independent sample t-test. Male-to-female ratios between the groups were compared using the chi-square test. The Kruskal–Wallis H test was used to compare age and median NN need scores between the ITT, STT, and SBT groups. Binary comparisons were performed according to the pairwise comparisons test. Binary logistic regression analysis was used to examine factors increasing the risk of not needing NN use in the stages of planning skin flap and craniotomy, determining the cortical incision site, determining the route to reach the tumor, and evaluation of tumor resection. The significance level was set at $p<0.05$ for all analyses. The conformity of the data to normal distribution was checked with Kurtosis and Skewness values (±1.5). IBM SPSS 26.0 program was used for all statistical analyses.

Table IV. Surgical stages requiring neuronavigation.

Surgical stages	Need for neuronavigation use, N(%)
Planning the skin flap and craniotomy	130(75.6)
Identification of anatomical and vascular structures	172(100)
Determining the cortical incision site	142(82)
Determining the route to reach the tumor	138(80.2)
Evaluation of the amount of resection	117(68)

Discussion and Conclusion

The present study supports the idea that NN is a necessary tool in the surgery of intracranial tumors. Our findings indicate that NN was helpful to the surgeon in 140 of 172 patients (81.4%). However, the need for NN use varied depending on tumor location and size. Moreover, NN was not equally necessary at every stage of the surgery. To the best of our knowledge, there is no objective scaling system to evaluate the use of NN based on tumor localization and size in the literature. Our findings can be summarized as follows:

Evaluation of the need for NN use according to tumor size

In the present study, the need for NN use was significantly higher in patients with tumors <3 cm than in those with tumors ≥3 cm in size ($p = 0.003$). When evaluating individual surgical stages, NN use was found to be statistically significantly less necessary in the resection stage in patients with tumors ≥3 cm (Table II). This result is likely due to target deviation during the resection of large tumors caused by brain shift which is a significant factor disrupting surgical orientation during the operation, constituting a major drawback of NN systems[11,13]. Brain shift remains an active area of research today, with physical, surgical, and biological factors contributing to it[11,12,18,19]. For instance, Gerard et al.[11] categorized the causes of brain shift into these three factors, including physical factors that are directly related to the NN system hardware, or patient's position and the effects of gravity. Surgical factors were those related to the use of different surgical equipment, such as retractors, or CSF loss, whereasbiological factors were those related to the use of different drugs (e.g., Mannitol) to manage intracranial pressure during surgery[11]. Dorward et al.[13] reported mean cortical shifts of 4.6 mm after opening the dura and 6.7 mm after completing the surgical procedure. Reinges et al.[10] found lesion volume to be the primary factor affecting brain shift during and after lesion removal. Our multivariate logistic regression analysis revealed that tumor size ≥3 cm significantly increased the risk of data failure in NN use (Table III). Consequently, maintaining NN data was challenging due to the displacement of lesioned and non-lesioned structures during resection, particularly in tumors larger than 3 cm, reducing the need for NN use at this stage.

Evaluation of NN use in deep-seated or superficial tumors

In neurosurgery, a transcortical approach is usually used for deep-seated tumoral lesions. However, if the distance from the brain surface to the lesion is significant, this approach can cause disorientation and even unnecessary brain damage[3]. Wagner et al.[20] reported that NN was most useful in deep and centrally located tumors in functional brain areas. Pinskser et al.[21] reported that NN use in subcortically located tumors in eloquent brain areas could increase safe resection rates. According to the findings of the present study, the overall need for NN use was statistically significantly higher in the DST group (Table III), consistent with the literature. Regarding surgical stages, NN use was significantly less in the SFT group during the identification of anatomical and vascular structures, determination of the cortical incision site, and tumor resection (Table II). We believe that this may be because superficially located tumors can be visualized immediately under the microscope after opening the dura. According to multivariate logistic regression analysis, in DST, NN use was highly valuable in determining the cortical incision site and establishing the route to reach the tumor.

Evaluation of the need for NN use in the surgery of infratentorial tumors, skull base tumors, and supratentorial tumors

There were some differences in the surgical outcomes of the STI, ITI, and LTI groups when evaluating overall total and surgical stages separately.

NN use was higher in the STT group compared to the ITT group (Table II). Wagner et al.[20] reported that NN is a useful tool in the surgery of supratentorial tumors for defining craniotomy flaps, tumor resection margins, or endoscope guidance, especially in elusive brain areas, subcortical tumors, and lesions within the ventricle. In a prospective study comprising 37 cases, Dwarakanath et al.[17] reported that NN use in supratentorial lesions was particularly more helpful in craniotomy planning and delicate procedures such as biopsy or shunt placement compared to infratentorial and skull base lesions. In the present study, multivariate logistic regression analysis did not reveal supratentorial tumors as an independent risk factor for the need for NN use (Table III). However, the need for NN use was significantly higher in the surgical stages of planning skin flap and craniotomy and identifying anatomical and vascular structures (Table II).

In the current study, infratentorial tumors showed a lower need for NN use compared to other compartments (Table II). This difference is likely due to the surgical stage of planning the skin flap and craniotomy. In the surgical planning of infratentorial lesions, paramedian or median incisions are commonly employed, and the smaller working area generally does not require planning the skin incision and craniotomy. The need for NN use in the other surgical stages was similar across different compartments. However, tumor location was not an independent risk factor in multivariate logistic regression analysis for data failure in NN use (Table III).

Many studies indicate that the use of NN offers a high degree of safety in the treatment of skull base lesions[22–25]. The skull base is anatomically extremely comple, containing cranial nerves and major vascular structures. Tumor invasion into bone and critical neurovascular structures further complicates and increases the risk of surgical intervention in this compartment. However, NN use for SBT has advantages compared to tumors in other brain parts [23,26] as SBT are usually firmly attached to the dura and bone, with cranial nerves and major blood vessels in stable and fixed positions in this anatomical region, minimizing brain shift due to CSF drainage[13,23,26]. In a series of 87 patients undergoing surgery for SBT, Kurtsoy et al.[22] reported better anatomical guidance with NN use during skull base surgery, noting effective tumor boundary and critical neurovascular structure visualization. According to their findings, NN was a safe and valuable aid for achieving complete tumor resection[22]. Sure et al.[26] emphasized NN's role in increasing the efficiency and safety in SBT surgery with no significant intraoperative shift during the surgical procedure.

In this study, the need for NN use was statistically significantly higher in the SBT group compared to the ITT group (Table II). Analyzing surgical stages revealed significant differences in the need for NN use during skin flap-craniotomy design and identification of anatomical structures. Additionally, the need for NN use during tumor resection evaluation was significantly higher in the SBT group compared to the STT group.

One of the most important contributions of the present study is determining which surgical stages require the highest need for NN use. Our results showed a consistent need for NN use in all patients during the stage of identifying anatomical and vascular structures (Table IV).

Despite the benefits of using NN during surgery, several challenges exist. First, NN is an expensive method requiring additional equipment beyond standard facilities. Second, NN use requires preoperative data to be loaded onto the NN workstation just before the operation and registered to the references on the patient during surgery, increasing surgical duration. Additionally, the accuracy of registrations is associated with personnel training and requires a learning curve[27,28]. Third, NN systems do not provide real-time image information during surgery[10,29,30], meaning conditions like brain shift can affect intraoperative NN data accuracy [27,28].

Limitations

This study has some limitations. First, it is a single-center retrospective study. Intraoperative NN use was evaluated only according to the location and size of the tumor, without considering pathological diagnoses and total resection rates. The study focused more on the need for and usefulness of NN systems during surgery, not reflecting NN's superiority in terms of total tumor resection rate and survival rates. Furthermore, the degree of the need for NN use was scored by the operating surgeon, and the subjective nature of this assessment may impact the external validity of the study. Therefore, randomized studies on larger samples with more objective criteria are needed to provide definitive answers.

The need for NN use during surgery varies according to both the location and size of the tumor and the different surgical stages. NN use is more effective in STT, DST and tumors <3 cm in size. It also helps the surgeon to identify anatomical and vascular structures during surgery. Larger prospective, randomized studies are needed to evaluate the true efficacy and accuracy of NN systems.

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