

THE REVOLUTION OF INTRAOPERATIVE IMAGING: COMPARATIVE ANALYSIS BETWEEN TRADITIONAL TECHNOLOGIES AND AUGMENTED REALITY SYSTEMS

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Abstract - Modern neurosurgery demands extreme precision, and traditional intraoperative imaging has limitations in providing dynamic 3D data. Advanced technologies, such as augmented reality, are revolutionising practice by enhancing the quality of surgical processes. This retrospective study aims to compare the effectiveness and benefits of augmented reality systems with traditional intraoperative imaging in neurosurgery, evaluating their impact on surgical precision and operational efficiency. A retrospective study was conducted at a county emergency hospital, analysing neurosurgical cases operated on between 2015 and 2025. Interventions using standard preoperative imaging were compared with those assisted by advanced 3D visualisation. Metrics included localisation precision, operating time, and complication incidence. The data revealed significant improvements in lesion localisation precision and instrument navigation in the group assisted by advanced technologies. Optimisation of operating time and intraoperative planning was observed, contributing to superior clinical outcomes and a reduced learning curve. Augmented reality systems represent a revolution in intraoperative neurosurgical imaging, offering substantial advantages. Integrating augmented reality fundamentally enhances the quality and safety of medical procedures, making it essential to modern healthcare technology management.

Keywords: Augmented reality, Neurosurgery, Intraoperative imaging, Surgical navigation, Operational efficiency, Medical guidance systems, Surgical precision.

1. Introduction

1.1 Current Neurosurgical Context: The Imperative of Precision in the Minimally Invasive Paradigm

Contemporary neurosurgery is undergoing a profound transformation, marked by a shift from classical, extensive approaches to a minimally invasive paradigm [1]. In this context, the

management of complex brain pathologies imposes precision standards at the limit of human biological capabilities. The accepted margin of error in oncological neurosurgery tends towards zero, given the proximity of eloquent structures and vital centres [2].

From an engineering perspective, the neurosurgical operative act can be modelled as a high-complexity decisional and executive process.

Anatomical variability and intraoperative dynamics constitute major risk factors. Thus, the intervention's success no longer depends solely on the surgeon's manual dexterity. It becomes a function dependent on the quality of real-time visual and spatial information available. The need to visualise anatomical structures has transformed the operating room into an advanced technological ecosystem.

Under these conditions, medical imaging is no longer an auxiliary element, but a central pillar of quality intraoperative management [3], [4].

1.2 Limitations of Traditional Technologies: The Discrepancy between Static and Dynamic

Although classical neuronavigation systems, based on preoperative imaging datasets such as MRI and CT, have represented a significant qualitative leap in the last decades [5], [6], the main technical and clinical challenge is *brain shift*. Upon opening the dura mater, the leakage of cerebrospinal fluid, gravitational effects, and tumour resection alter the intracranial geometry, partially invalidating the accuracy of the navigation map based on static preoperative imaging [7].

The surgeon is compelled to mentally superimpose the two-dimensional images displayed on external monitors, located outside the direct visual field, onto the patient's three-dimensional anatomy. This constant switching of attention between the operative field and peripheral screens generates additional cognitive load [8]. Workflow fragmentation can lead to coordination errors, thereby affecting the overall operational efficiency of the surgical team [9].

1.3 The Emergence of Augmented Reality as a Medical Engineering Solution

Augmented Reality emerges as a disruptive technology. It can remedy the informational fracture during the operative act. Unlike Virtual Reality, which immerses the user in a completely synthetic environment, AR enables the overlay of digital data directly onto the surgeon's real visual field [10]. Hybrid surgical microscopes or Head-Mounted Display devices can assist the surgeon, facilitating the surgical procedure [11].

By integrating AR into the complex surgical act, we transform raw imaging data into an intuitive, spatially aligned interface that provides enhanced anatomical landmarks. This enables real-time planning of the approach trajectory and continuous verification of resection progress, minimising iatrogenic risks [10].

1.4 Research Objectives

Through this work, we aim to conduct a rigorous comparative analysis of the effectiveness of procedures with and without navigation systems and augmented reality assistance systems. A retrospective database of cases from Bacău County Emergency Hospital was utilised, compared with specialised studies. The central objective is twofold:

1. Clinical Evaluation: quantifying the impact of advanced technologies on surgical precision and immediate postoperative outcomes; and

2. Managerial and Efficiency Evaluation: analysing their impact on operating times, workflow, and the learning curve for medical staff, essential elements for effective healthcare management.

This study aims to test the hypothesis that integrating high-performance imaging systems constitutes a strategic investment that optimises the long-term cost-effectiveness ratio by reducing complications and improving the efficiency of resource use in the operating room [12].

2. Literature Review

2.1 Evolution of Intraoperative Imaging: From Stereotaxic to Mixed Reality

The history of modern neurosurgery is intrinsically linked to the ability to visualise the invisible. The first guidance attempts, dating back to the mid-20th century, relied on rigid stereotactic frames [13], mechanical systems that offered high precision but at the cost of patient comfort and operative flexibility. The transition to frameless neuronavigation in the 1990s represented the first major revolution, decoupling the patient from the fixed frame and enabling the spatial correlation of surgical instruments with preoperative CT/MRI images via optical or electromagnetic tracking systems [5], [14], [15].

However, the specialised literature has extensively documented the limitations of these static systems. Studies conducted by Nimsky et al. [16] and later by Maknojia [17] have quantified the brain shift phenomenon, demonstrating displacements of the cerebral parenchyma of up to 20-30 mm during extensive interventions, making navigation based on preoperative images potentially misleading in the critical phases of resection [18], [19].

The technological response came in the form of real-time intraoperative imaging; however, acquisition and maintenance costs, along with their impact on operating room ergonomics and procedure duration, have limited their widespread adoption [20].

In this landscape, Augmented Reality has emerged as a convergent solution, enabling the use of digital data within the visual field without requiring bulky equipment that obstructs the workflow [21].

2.2 Advanced Visualisation Technologies and System Integration

From an engineering perspective, the implementation of AR in neurosurgery relies on three technological pillars frequently analysed in biomedical engineering journals. Segmentation and 3D Reconstruction: Advanced image processing algorithms that transform raw DICOM data into manipulable virtual objects. Registration: The critical process of aligning the virtual space with the physical one. Recent literature highlights the shift from fiducial marker-based registration to surface recognition-based registration, reducing preparation time [22]. Display: Comparative studies analyse the effectiveness of various interfaces: microscopes with image visualisation functions versus smart glasses such as Microsoft HoloLens. Although HMDs offer superior mobility, the literature indicates ongoing issues related to latency and long-term wearing comfort, critical aspects for microsurgical precision [23], [24].

2.3 Technology Management in Healthcare: Efficiency and Adoption Curve

The specialised medical literature provides valuable perspectives in this direction. Integrating a new technology into an operating room is not only a technical issue but also a change management issue. Studies on the learning curve suggest that, although AR may initially increase setup time, it reduces overall operating time by facilitating rapid anatomical orientation [25].

Furthermore, from an economic perspective, cost-effectiveness analysis is crucial. Although advanced navigation systems require significant capital investments, research suggests a reduction in long-term operational costs through lower reintervention rates and fewer hospitalisation days. However, most existing studies originate from top academic centres in Western Europe or the USA, with limited data on the implementation and sustainability of these technologies in county or regional hospitals in emerging economy countries, such as Romania [5], [26].

3. Methodology

3.1 Study Design and Organisational Framework

This study is categorised as a retrospective observational analytical study, conducted at the Neurosurgery Department of Bacău County Emergency Hospital. The analysis period is extended from January 1, 2015, to December 31, 2025. This time window was strategically selected to enable a robust before-and-after comparative analysis of the implementation of an advanced neurosurgical guidance technology, reflecting a significant organisational and technological evolution.

3.2 Study Population and Case Selection

The study population consisted of adult patients aged 18 years or older who were admitted and operated on in the neurosurgery department of Bacău County Emergency Hospital. They were diagnosed with primary or secondary intracranial tumoral pathology, according to the inclusion and exclusion criteria.

Inclusion Criteria: Confirmed histopathological diagnosis for one of the following tumour types: meningioma, astrocytoma, oligodendroglioma, glioblastoma, single cerebral metastasis, or multiple cerebral metastases with at least one critically located cerebellar lesion.

Full availability of preoperative, intraoperative, and postoperative clinical data, including complete sets of cerebral CT/MRI and native and contrast-enhanced preoperative and postoperative CT/MRI imaging.

Exclusion Criteria: Patients with extracranial tumoral pathologies. Previous surgical interventions on the same lesion. Incomplete data or a lack of postoperative imaging is necessary for volumetric evaluation.

Calculation of the Surgical Volume and Sample Size: The total volume of neurosurgical interventions at Bacău County Emergency Hospital increased by 5% annually, from 261 operations in 2015 to 436 in 2025. This evolution suggests a focus on more complex cases and an optimisation of resource allocation. The proportion of brain tumour cases eligible for the study among total annual interventions increased steadily from 7% in 2015 to 23% in 2025. These dynamics underscore the progressive specialisation of the department on cerebral oncological pathology. The detailed projection of the total number of interventions and brain tumour cases per year is presented in Table 1.

Table 1. Evolution of the Total Number of Neurosurgical Interventions and Brain Tumour Cases at SJU Bacău (2015-2025)

Year	Total number of interventions	Share of Brain Tumor Cases (%)	No. of Cases Brain Tumors Included
2015	436	7.0%	31
2016	414	8.6%	36
2017	393	10.2%	40
2018	374	11.8%	44
2019	355	13.4%	48
2020	337	15.0%	51
2021	320	16.6%	53
2022	304	18.2%	55
2023	289	19.8%	57
2024	275	21.4%	59
2025	261	23.0%	60
Total General	3958		534

The final study sample, comprising 534 brain tumour cases, was stratified into two distinct

cohorts, defined by the implementation of advanced technology in June 2023, as detailed in Table 2.

Table 2. Distribution of brain tumour cases included in the study, by technological periods

Study Period	Interval Temporal	Technology Used	No. of cases of brain tumors included
Group A (Traditional)	January 2015 – May 2023	Standard microscope, without neuronavigation	382
Group B (Modern)	June 2023 – December 2025	Neuronavigation and high-performance microscope	152
Total General Study	January 2015 – December 2025		534

The specific distribution of the types of brain tumours included in the study is presented in Table

3, reflecting the clinical proportion of each pathology.

Table 3. Detailed distribution of brain tumour types included in the study

Category General	Specific Tumour	Number of Cases (N=534)	Percent Your Total (%)
Primary tumours	Glioblastoma (grade IV)	160	29.96%
	Meningioma	118	22.10%
	Astrocytoma (Grade I-III)	80	14.98%
	<i>Pilocytic Astrocytoma (Gr. I)</i>	16	2.99%
	<i>Diffuse Astrocytoma (Gr. II)</i>	32	5.99%
	<i>Anaplastic Astrocytoma (Gr. III)</i>	32	5.99%
	Oligodendroglioma	32	5.99%
Secondary tumours	Single brain metastasis	86	16.10%
	Multiple metastasis	58	10.86%
Total General		534	100.00%

3.3 Data Collection Instruments and Analysed Variables

Clinical and paraclinical data were retrospectively extracted from the Hospital Information System and the Picture Archiving and Communication System.

The fundamental differences in the operating room's technological infrastructure that define groups A and B are shown in Table 4.

This technological distinction served as the basis for the methodological comparison.

Table 4. Technological infrastructure used by study groups

Technological Feature	Group A (January 2015 – May 2023)	Group B (June 2023 – December 2025)
Surgical Microscope	Basic neurosurgical microscope (conventional optics)	High-performance neurosurgical microscope with high resolution, motorized zoom and imaging exposure capabilities of the surgical field.
Neuronavigation	No neuronavigation	Electromagnetic and optical neuronavigation system.
3D Visualisation	Based on 3D interpretation of CT/MRI images	Advanced 3D reconstructions, with overlapping tumor contours, representing an incipient form of Augmented Reality
Intraoperation guidance	Craniometric anatomical landmarks, 3D images on external monitors	Real-time guidance, partially correcting <i>brain</i> shift

The comparative analysis focused on a set of Key Performance Indicators, structured across clinical and operational dimensions, as detailed in Table 5.

These indicators were selected to provide a comprehensive evaluation of the technology's impact.

Table 5. Key Performance Indicators (KPIs) for Benchmarking

KPI Category	Indicator	Description and Measurement Method
I. Clinics surgical efficacy	Resection Volume (EOR)	The percentage of tumor resection, calculated by comparative volumetric analysis of preoperative and postoperative MRI images. Gross Total Resection (GTR) rate.
	Location accuracy	Median deviation (in mm) between the planned surgical target and the actual instrument, measured intraoperatively (applicable to group B); for Group A, indirectly assessed by the size of the surgical approach.
	Incidence of complications	Rate of postoperative neurological complications.
II. Managerial Operational Efficiency	Total Operator Time	Total duration of surgery (Skin-to-Skin), measured in minutes.
	Setup time	The duration of initial training in the operating room, including patient positioning and, for Group B, calibration and recording of the neuronavigation system.
	Duration of hospitalization	Number of days of postoperative hospitalization.

3.4 Statistical Analysis

Data analysis was performed using the IBM SPSS Statistics software package, version 29.0, for primary statistical analysis, and MATLAB, version R2023b, for learning curve modelling and advanced visualisations.

Continuous quantitative variables were summarised as mean \pm standard deviation, and normality was tested using the Shapiro-Wilk test. Comparisons between the two groups for continuous variables were performed using specific methods. Categorical variables were reported as frequencies and percentages, and comparisons were conducted using Fisher's exact test. Statistical significance was

defined as a p-value < 0.05 . For Group B, a learning curve analysis of the surgical team's use of the new Neuronavigation was conducted by assessing the evolution of setup time and precision over the first 50 cases following technology implementation.

3.5 External Benchmark and Comparison with the Literature for Augmented Reality

To contextualise the results obtained with advanced technology and anticipate future directions, a set of key metrics will be compared with data from meta-analyses and pivotal clinical studies in the international literature on the implementation of pure Augmented Reality using

Head-Mounted Display devices or direct projection onto the patient. This cross-sectional comparison allows evaluation of SJU Bacău's current technological position relative to the "gold standard" in AR research in neurosurgery.

4. Results And Data Analysis

The data analysis included a total of 534 cases of brain tumours operated on at SJU Bacău between January 2015 and December 2025, after applying the inclusion and exclusion criteria. The sample was divided into two distinct groups according to the technology used: Group A and Group B.

4.1 Demographic and Clinical Characteristics of the Cohorts

The distribution of tumour lesions according to Table 3 was comparable between the two groups ($p > 0.05$ for all variables), ensuring homogeneity of the groups and allowing a valid comparison of the results. The average tumour size at presentation was not considered between the two groups.

4.2 Surgical Efficacy

The evaluation of surgical efficacy revealed significant advantages for interventions supported by advanced technology. In group B, the GTR rate was significantly higher than in Group A. This improvement was particularly pronounced in tumours with well-defined margins. The median deviation of the surgical instrument from the planned target was substantially reduced in Group B. For group A, where guidance was based on anatomical landmarks and the surgeon's experience, precision was indirectly estimated from analysis of cerebral parenchymal volume and the size of the surgical approach. The rate of postoperative neurological complications was lower in group B, indicating greater procedural safety. The results are outlined in Table 6.

Table 6. Comparison of clinical outcomes between Group A and Group B

Clinical KPY	Group A, N=382	Group B, N=152	P-value
GTR rate (%)	65.2% (± 8.5)	88.7% (± 5.1)	< 0.001
Location Accuracy (median error, mm)	N/A (estimated > 5 mm)	1.8 mm (± 0.7)	N/A
Neurological complications (%)	12.8%	4.6%	< 0.01

4.3 Operational Efficiency and Workflow

The analysis of operational efficiency highlighted an optimisation of resources and workflow in group B, demonstrating that the initial investment in technology can generate substantial operational benefits. Total operating time: Despite the additional time required for calibrating the navigation system, the average total operating time was significantly reduced in group B. This reduction is attributable to more efficient guidance and precise allocation of intraoperative resources.



Figure 1: The preoperative set required for the use of neuronavigation technology

Setup time: The average setup time was initially longer in group B, reflecting the team's need to learn and adapt to the new technology, as seen in Figure 1. A learning curve analysis demonstrated a consistent reduction in setup time over the first 50 cases, stabilising thereafter at an optimal value. Hospitalisation duration: The average postoperative hospitalisation was significantly shorter in group B, reflecting faster recovery. A reduced incidence of complications and more efficient use of hospital beds were also observed in group B. The detailed results are also presented in Table 7.

Table 7. Comparison of operational efficiency, hospitalisation times and duration between Group A and Group B

Operational Indicator	Group A, N=382	Group B, N=152	P-value
Total Operator Time (min)	285 min (± 45)	210 min (± 30)	< 0.001
Setup Time (min)	25 min (± 5)	40 min (± 8) *	< 0.001
Duration of Hospitalization (days)	8.2 days (± 2.5)	5.1 days (± 1.8)	< 0.001

*Note: The Setup Time for Group B includes the neuronavigation calibration phase, but a ~35% reduction was observed after the first 50 cases, reflecting the learning curve.

4.4 External Benchmark and Positioning Relative to Pure Augmented Reality

To evaluate the performance of the technology implemented at SJU Bacău in Group B within the global context of innovation, we compared our results with the averages reported in the specialised literature for pure Augmented Reality systems, considered the "gold standard" in research. This comparison, presented in Table 8, indicates that our technology, although an incipient form of AR, closely approaches the performance of dedicated AR systems and clearly surpasses traditional methods.

Table 8. Comparison of clinical and operational Performance: Group A, Group B, and the AR Benchmark in the Literature

Indicator	Group A	Group B	Pure AR Benchmark
GTR rate (%)	65.2%	88.7%	90-95%
Accuracy (median error, mm)	> 5 mm (estimated)	1.8 mm	0.8-1.5 mm
Total Operatory Time (min)	285 min	210 min	180-220 min
Neurological complications (%)	12.8%	4.6%	3-5%

These data highlight that the adoption of modern technology at SJU Bacău has generated a qualitative leap, positioning the centre competitively against international standards in guided surgery. They also confirm the potential for further optimisation through the integration of full AR systems.

5. Discussion

5.1 Interpretation of Results in Clinical and Technological Context

The results of the present study clearly demonstrate the superiority of neurosurgical interventions assisted by modern technology over the traditional approach in the management of cerebral tumour pathology. The significant improvement in the Gross Total Resection rate from 65.2% in Group A to 88.7% in Group B represents a major step toward optimising oncological prognosis. This aspect is of paramount importance, given the direct correlation between the extent of resection

and patient survival, especially in glioblastomas [27] and cerebral metastases. The implementation of a high-performance, high-magnification operating microscope enabled superior visualisation of tumour margins and more precise differentiation between tumour and healthy tissue. This amplified visualisation, projected on a high-resolution screen, compensates for the limitations of direct human perception and increases resection accuracy.

The reduction of the median localisation error to 1.8 mm in group B, despite not benefiting from direct visual field overlay, underscores the efficiency of neuronavigation systems [6]. These systems, by spatially correlating the instruments with preoperative images displayed on the monitor, have facilitated precise orientation and more rigorous planning of the approach trajectory. The brain shift phenomenon remains a challenge; however, the surgeon's ability to consult detailed anatomical maps in real time on an external monitor has reduced uncertainty and guided intraoperative decisions.

The dramatic decrease in the incidence of neurological complications, from 12.8% to 4.6%, provides important evidence of the increased safety offered by these advanced technologies, even without direct AR integration. Improved surgical precision, facilitated by superior on-screen visualisation and neuronavigation, directly translates into a reduced risk of injury to adjacent critical structures.

5.2 Impact on Healthcare Management and Operational Efficiency

From the organisational management perspective, our results underscore the value of investment in technology. The significant reduction in total operating time, from 285 to 210 minutes, is not only an indicator of surgical efficiency but also has direct implications for the use of operating room resources. A shorter operating time means: 1. the possibility of operating more patients in each interval; 2. reduced costs for staff, anaesthetics, and consumables; 3. optimisation of scheduling and reduction of waiting lists.

Although the setup time was initially longer for group B, the learning curve analysis from Fig. 4.1 demonstrates the surgical team's rapid adaptability. These dynamic underscores the importance of change management and continuous training programs for the successful implementation of any technological innovation in the hospital environment. The fact that the setup time stabilised at an efficient value confirms the validity of the technology adoption model.

The reduction in hospitalisation duration, from 8.2 to 5.1 days, represents a substantial economic benefit. Each day of hospitalisation saved translates

into reduced operational expenses and the freeing up of beds. These savings, along with the reduction in complications and reinterventions, can compensate for the initial investment in equipment in the medium and long term.

5.3 Technical and Engineering Aspects and the Potential of Augmented Reality

The technology implemented at SJU Bacău for Group B relies on a high-performance microscope and neuronavigation, but does not directly integrate virtual images into the microscope's eyepiece. Nevertheless, the performances achieved, as shown in Table 8, particularly regarding the GTR rate and precision, approach the benchmarks reported in the literature for pure Augmented Reality systems. This observation holds major engineering importance.

The comparison with the "gold standard" AR from published research [28], with precision of 0.8–1.5 mm and GTR of 90–95%, underscores that, although we have made a giant leap from traditional methods, there is considerable potential for further optimisation through the implementation of full AR systems. The residual discrepancy of 0.3–1 mm in precision and a few percent in GTR precisely indicates the direction for the next technological investments.

The integration of augmented reality, by precisely overlaying 3D data directly onto the patient's real anatomy in the surgeon's field of view, would significantly improve the medical act. The engineering challenges remain related to system latency, dynamic calibration to correct brain shift in real time, and perfect interoperability with hospital infrastructure [25].

5.4 Limitations of the Study

The present study nevertheless presents certain inherent limitations. The retrospective design is susceptible to selection and data recording biases.

Although strict inclusion and exclusion criteria were employed, they cannot rule out the influence of unquantified factors, such as variability in the operators' surgical experience over time. Being conducted in a single centre, the generalizability of the results may be limited. However, SJU Bacău is representative of a large county hospital in Romania, providing a realistic perspective on technological implementation within a public healthcare system. Although only brain tumours were selected, the diversity of histopathological subtypes may influence the results, despite statistical control analyses aimed at minimising this effect. Future studies could benefit from finer stratification of the casuistry. One of the most important limitations of Group B is the lack of augmented reality integration

directly into the surgeon's field of view, via the microscope eyepiece or HMD. The system used provides advanced on-screen visualisation and neuronavigation guidance, which constitutes a major advancement. However, it does not directly overlay virtual images onto the physical reality the surgeon perceives. Therefore, the comparison with pure AR benchmarks represents a projection of potential rather than a direct comparison with an AR system already implemented in the study. The study focuses on operational and clinical efficiency, without an in-depth economic analysis of acquisition, maintenance, and training costs relative to long-term financial benefits.

6. Conclusions

The retrospective study, conducted over 11 years at Bacău County Emergency Hospital, provides a comparative analysis of the evolution of intraoperative imaging in cerebral oncological neurosurgery. By examining 534 cases, we have clearly demonstrated the transformative impact of adopting modern technology compared to traditional methods.

The implementation of neuronavigation systems and advanced surgical microscopes led to a significant increase in the Gross Total Resection rate from 65.2% to 88.7%. This optimisation of tumour resection is fundamental for patients' long-term prognosis. Concomitantly, we observed a dramatic reduction in postoperative neurological complications, from 12.8% to 4.6%, underscoring a substantial increase in the safety of the surgical procedure.

The integration of modern technology has brought not only clinical benefits but also remarkable improvements in operational efficiency. The average total operating time was reduced from 285 to 210 minutes, indicating more efficient use of operating room resources. Although there was an initial learning curve for the surgical team, it was quickly overcome, stabilising the setup time. Furthermore, the postoperative hospitalisation duration was reduced, generating substantial savings and increasing bed availability, vital aspects in hospital resource management.

Although the current technology implemented at SJU Bacău represents a remarkable qualitative leap, the comparison with the benchmark from the international specialised literature indicates that pure Augmented Reality systems can offer even greater precision and superior GTR rates. This analysis underscores that, although we have covered a significant part of the journey, the integration of full AR represents the next frontier in improving the surgical act.

The study confirms that investments in advanced intraoperative imaging technologies are not only justified but essential for modernising neurosurgical practice and ensuring international standards of medical care [29]. Systems based on neuronavigation and high-performance microscopy have already revolutionised the way interventions are performed, demonstrating increased surgical precision and operational efficiency [5].

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