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MOLECULAR DIAGNOSTIC AND IMAGING CAPABILITIES OF INTRAOPERATIVE ULTRASOUND NAVIGATION

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ABSTRACT

Intraoperative ultrasound navigation (ioUS) is one of the most promising areas of modern neurosurgery, providing the surgeon with the opportunity to obtain images in real time and adapt intervention tactics taking into account dynamic changes in brain structures. ioUS technology is based on the use of ultrasound waves to visualize the anatomical and functional characteristics of brain tissue during surgery, which makes it an effective tool for navigation and control of the radicality of resection. Unlike traditional methods such as intraoperative MRI and CT, ioUS has a high data acquisition rate, economic accessibility, and no radiation exposure. The review is devoted to the analysis of modern intraoperative ultrasound technologies, including 3D imaging, contrast enhancement (CEUS), Dopplerography and elastosonography, as well as the assessment of their clinical effectiveness in the surgical treatment of brain tumors. The advantages of ioUS in eliminating the "brain shift" effect, integrating with neural navigation systems, and providing an individualized surgical approach are considered. Special attention is paid to the role of ioUS in increasing the radicality of resection, reducing the residual volume of the tumor and preserving functionally significant areas. Based on the analysis of domestic and foreign publications, key areas for further development of the technology have been identified, including standardization of protocols for its application, development of training systems for specialists, and integration of artificial intelligence for automated image interpretation. The conclusion is made about the high clinical and practical significance of ioUS as a universal visual monitoring tool capable of improving the safety and effectiveness of neurosurgical operations.

KEYWORDS: intraoperative ultrasound navigation, neurosurgery, brain tumors, contrast ultrasound, elastosonography, neuronavigation, clinical efficacy.

INTRODUCTION

Modern neurosurgery requires high precision and safety, which makes the choice of effective intraoperative navigation methods a key area of clinical practice development. Historically, the first neural navigation systems were based on static preoperative images obtained using computer and magnetic resonance imaging, but their limited flexibility in a dynamically changing operating field reduced the accuracy of manipulations [21, 30].

In the last two decades, intraoperative CT and MRI have been considered as the "gold standard" of navigation, providing high spatial resolution and the possibility of three-dimensional mapping of brain structures [12, 33]. Nevertheless, even these technologies have significant limitations, including the high cost of equipment, duration of procedures, and dependence on preoperative data, which is especially critical in conditions of "brain shift" during manipulation of tumors [14, 29]. According to world reports, over 300,000 cases of brain tumors are diagnosed annually in the world, and about 10,000—12,000 in Russia, while up to 60% of operations require navigation support to minimize neurological complications [3, 4].

In response to these challenges, the field of intraoperative ultrasound navigation (iUS) is developing, combining high information content, safety and economic accessibility [8, 21]. Ultrasound imaging provides real-time imaging without exposing the patient to radiation, and allows for prompt correction of the surgeon's actions at all stages of the intervention [10, 20]. Modern 2D and 3D ultrasound systems demonstrate comparable accuracy to intraoperative MRI, but they significantly exceed it in terms of data acquisition speed and ease of use [12, 26]. An important advantage of iUS is the ability to compensate for the effect of brain displacement, since images are updated directly during surgery, which makes the method especially useful for resection of deep-seated or infiltrative tumors [33, 38].

The experience of international clinics shows that the use of intraoperative ultrasound helps to increase the radicality of neoplasm removal and reduce the risk of postoperative complications [8, 38]. According to reviews, the introduction of ultrasound navigation makes it possible to increase the accuracy of tumor localization to 92-95% and reduce the duration of operations by 15-20% [29, 36]. Thus, intraoperative ultrasound navigation today is not just an auxiliary technology, but an independent diagnostic and navigation tool capable of providing an individualized approach to treatment [26, 40].

The purpose of this review is to identify current trends, technological advances, and clinical effectiveness of the use of intraoperative ultrasound navigation (ioUS) in neurosurgery, analyze its advantages and limitations compared to traditional imaging techniques (MRI and CT), and justify the need for standardization of protocols and specialist training to integrate ioUS into routine clinical practice.

MATERIALS AND METHODS

The research materials are scientific publications and clinical data on modern aspects of the use of intraoperative ultrasound navigation (iUS) in neurosurgery. The search and selection of sources were carried out in leading international and Russian databases — PubMed, Scopus, Web of Science, eLIBRARY.ru , CyberLeninka — using keywords: intraoperative ultrasound, neuronavigation, brain tumor surgery, intraoperative imaging, glioma resection. The analysis included original clinical studies, systematic reviews, and meta-analyses published between 2015 and 2025, providing information on the diagnostic accuracy, advantages, and limitations of iUS compared to CT and MRI.

The methods of content analysis, comparative descriptive and analytical synthesis were used to structure the collected data, which made it possible to determine the main directions of development of intraoperative navigation technologies and their effectiveness in clinical practice. Special attention was paid to the characteristics of ultrasound systems used in neurosurgery, imaging parameters, integration with neural navigation platforms, and the impact on surgical outcomes.

A summary of the database and the stages of literature selection is presented in Table 1, which ensures transparency, reproducibility and reliability of the analysis.

Table 1: Clinical and experimental studies on the use of intraoperative ultrasound navigation in neurosurgery

The authors of the study	Year	A country	Navigation method /	Key results / benefits	Number of patients/observations	Control / comparison
Simfukwe K. et al. [8]	2022	Russia / Italy	iUS technology (intraoperative ultrasound)	Improving the accuracy of brain tumor resection, reducing surgery time	30 patients	Intraoperative MRI
Prada F. et al. [10]	2020	Italy	3D iUS	Accurate visualization of focal boundaries in focal cortical dysplasia	25 patients	MRI
Bø H.K. et al. [12]	2019	Norway	3D Ultrasound navigation	Increased radicality of low-grade glioma resection	40 patients	MRI
Bastos D.C.A. et al. [14]	2021	USA	3D ultrasound + neural navigation	Comparison of accuracy with intraoperative MRI, comparable effectiveness has been proven	32 patients	iMRI
Yeole U. et al. [16]	2020	India	Navigated ultrasound	Improving the efficiency of tumor removal, improving the visualization of borders	27 patients	Without navigation
Shetty P. et al. [19]	2021	India	Ultrasound navigation for gliomas	Improved decision-making during surgery, reduced relapses	45 patients	Traditional methods
Tao A-Y. et al. [25]	2022	China	Contrast Ultrasound (CEUS)	Improving the accuracy of identification of the residual tumor	38 patients	MRI scan
Hu X. et al. [29]	2021	China	US–MRI Fusion	Increased percentage of total glioma resections	50 patients	MRI scan
Trevisi G. et al. [31]	2020	Italy	Real-time ultrasound of	High sensitivity in detecting a residual tumor was confirmed	732 patients (meta-analysis)	Not applicable
Pichardo-Rojas P.S. et al. [38]	2024	Mexico	iUS for high-grade gliomas	Clinical efficacy and reduction of	732 patients (meta-analysis)	Without ultrasound navigation

				complications have been confirmed.		

The stages of introducing ultrasound navigation into neurosurgical practice

Ultrasound navigation has become one of the most dynamically developing areas of modern neurosurgery, having gone from an auxiliary diagnostic tool to a key element of intraoperative imaging. The first mentions of the use of intraoperative ultrasound (ioUS) in brain surgery date back to the late 1970s, when the method was used primarily for rough assessment of tumor boundaries and localization of the pathological focus [8, 9]. At that time, the resolution of ultrasound devices was low, and the lack of standardized protocols limited their use. However, further development of technologies, primarily digital signal processing and sensor miniaturization, has significantly improved the accuracy and stability of images, which has led to the gradual introduction of ioUS into elective and oncological brain surgeries [10, 15, 16].

An important stage was the creation of three-dimensional and Doppler visualization systems that provide real-time structural and functional data acquisition. Such solutions, as shown by the research of F. Prada and colleagues [20, 26], allowed surgeons to compensate for the effect of "brain shift" and improve navigation accuracy when removing deep and low-grade gliomas. Russian researchers, including R. S. Talybov and V. V. Mochalova [1], noted that the use of intraoperative ultrasound technologies in combination with fluorescence and MR navigation ensures more complete removal of the tumor and reduces the incidence of complications.

Modern modifications of ioUS are based on the principles of multispectral analysis and contrast enhancement, which makes it possible to detail the vascular architecture of the tumor and the infiltration zone [25, 28]. Studies by Bastos et al. [14] and Yeole et al. [16] have shown that ultrasound navigation is comparable in information content to intraoperative MRI, while it has significantly lower costs and does not require interruption of the surgical process. Additionally, it is noted that the integration of ioUS with neural navigation systems and machine learning forms the basis for the creation of intelligent algorithms capable of automatically correcting tissue displacement and clarifying anatomical landmarks [33].

Thus, the evolution of ultrasound neuronavigation has gone through several key stages: from simple echographic observations to the introduction of hybrid 3D systems with contrast and elastographic modules. This is confirmed by the works of both foreign and domestic authors, from the studies of Konovalov A.N. [2] and Samokhvalov I.M. [6] to multicenter reviews of Prada F., Dixon L. and Gerard I.J. [21, 33]. As a result, ioUS has taken a strong place among modern neurosurgical instruments, while remaining the most accessible, versatile and safe method of intraoperative navigation.

Modern technologies and technical solutions for intraoperative ultrasound

Modern neurosurgery is based on the principles of visual inspection, where intraoperative ultrasound (ioUS) becomes a key tool for accurate guidance and assessment of dynamic changes in the brain during surgery. After cranial trepanation, the unique mechanical properties of the brain tissue provide optimal conditions for the propagation of ultrasonic waves, which allows high-definition images to be obtained in real time. In recent years, there has been a significant technological breakthrough — modern ultrasound systems integrate 3D capabilities, Doppler modes, contrast enhancement and elastosonography, providing the surgeon with not only morphological but also functional information about the structure and perfusion of tissues [8, 9, 21]. These improvements have taken ioUS beyond the auxiliary technology, turning it into a full-fledged navigation platform comparable in diagnostic value to intraoperative MRI and CT systems, but much more accessible and mobile [14, 20]. The main directions of development and varieties of ioUS are shown in Figure 1.

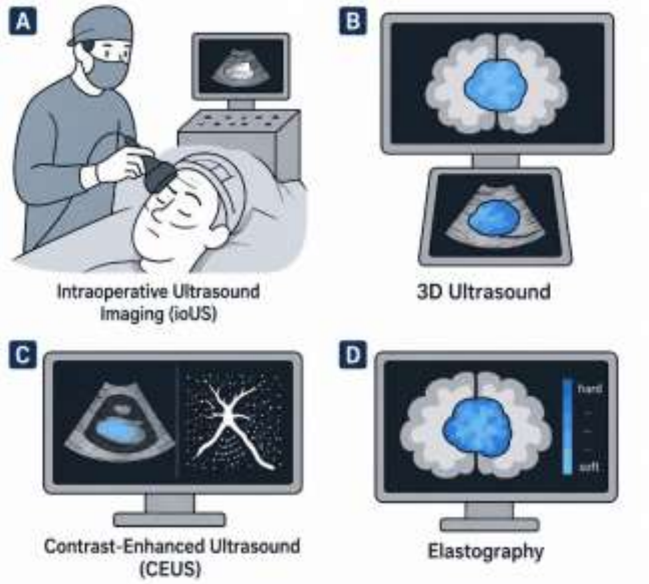

Figure 1: Modern technologies of intraoperative ultrasound (ioUS)

One of the most promising areas has become multiparametric ultrasound imaging (MPUs), which combines B-mode, Dopplerography, contrast ultrasound (CEUS) and elastosonography, which provides a comprehensive view of the structure, vascularization and density of tissues. This approach provides the neurosurgeon with the opportunity to assess the tumor in real time, differentiate between healthy and affected areas, and control the degree of resection, minimizing the risk of damage to functionally significant areas [10, 26]. The use of CEUS proved to be particularly valuable, which, thanks to microbubble contrasts, visualizes the vascular bed and the dynamics of tumor perfusion, allowing the identification of residual neoplastic areas inaccessible to the standard B-mode [25, 28].

An equally significant achievement is the introduction of elastosonography (SE and SWE), which has opened up the possibility of quantifying the mechanical properties of tumor tissue and the surrounding brain. These data make it possible to differentiate the type of tumor, assess its degree of malignancy, and plan safe surgical access trajectories [30, 31]. Due to the combination of high information content, compact equipment and the absence of radiation exposure, ioUS is now considered as a universal navigation tool capable of significantly improving the accuracy and safety of neurosurgical interventions, especially in conditions of limited resources. [8, 13, 19, 46].

Despite significant progress in the development of intraoperative ultrasound, its use is still limited by a number of technical factors, including the dependence of image quality on operator experience, the difficulty of interpreting the data obtained, and artifacts that occur during surgical procedures [8, 9].

To overcome these limitations, advanced imaging modes have been developed - 3D ultrasound, elastosonography, contrast-enhanced ultrasound (CEUS) and hybrid technologies with the integration of MRI data, which can compensate for the effect of brain shift and improve the accuracy of spatial orientation [14, 20, 26]. In addition, the introduction of machine learning and automated image processing systems opens up new opportunities for standardizing the interpretation of ultrasound data, reducing dependence on the human factor and improving the reproducibility of results [19, 31].

Clinical application and results

The expansion of the functionality of intraoperative ultrasound (ioUS) is directly reflected in its clinical effectiveness. Current data confirm that IOUS provides not only high-precision guidance, but also a comprehensive assessment of the condition of brain tissue, allowing the surgeon to adapt an intervention strategy in real time [8, 9]. The use of multilevel ultrasound modes - from the standard B-mode to contrast and elastographic - makes it possible to visually distinguish between the tumor and unaffected parenchyma, assess vascularization and determine the residual volume of the tumor (RTV), which is directly related to survival rates and a reduced risk of recurrence [19, 30].

In practical neuro-oncology, ioUS is used primarily in the removal of glial tumors, meningiomas, and metastatic lesions, where navigation accuracy plays a crucial role in preserving functional areas of the brain. According to the research results of Simfukwe et al. (2022) [8], the use of ioUS increases the probability of achieving complete resection (GTR) by more than 25% compared with traditional microsurgery. At the same time, the integration of the method with fluorescent navigation (5-ALA) and CEUS provides maximum information content, combining morphological and functional monitoring of the state of the tumor bed [48-50].

Russian neurosurgeons have also made a significant contribution to the development of the clinical application of ioUS. So, Talibov R.S. et al. [1] showed that the use of navigation ultrasound in combination with neural navigation systems and fluorescent control allowed to increase the frequency of total glioblastoma resection to 88.2%, while the level of postoperative complications remained minimal. These results confirm that IOUS is able not only to increase the radicality of tumor removal, but also to ensure the functional safety of the patient.

Additional studies by Bastos et al. (2021) and Gerard et al. [14, 33] emphasized that IOUS is an effective means of compensating for brain shift, one of the key limitations of preoperative MR navigation. In conditions of altered anatomy, ultrasound navigation retains spatial accuracy, providing the surgeon with up-to-date visual data and reducing intervention time.

Special attention is paid to the capabilities of ioUS in multidisciplinary neurosurgical complexes. Samokhvalov I.M. et al. (2019) [6] consider IOUS as a natural extension of stereotactic and optical navigation, where the combination of various visual technologies forms an integrated intraoperative control system. This approach makes it possible to reduce the proportion of residual tumor tissue and increase the safety of intervention even when working in functionally significant areas of the brain.

In general, the accumulated data of domestic and foreign authors convincingly demonstrate that the clinical use of ioUS increases the accuracy and safety of neurosurgical operations, increases the duration of the disease-free period and improves the quality of life of patients. The technological evolution of ultrasound navigation has transformed it from an auxiliary tool into a strategically important element of personalized neurosurgery, providing a real advantage in complex intracranial operations. [8, 9, 14, 19, 33].

At the same time, the rapid development of technologies exposes new challenges related to the need to standardize approaches to using ioUS and ensure high reproducibility of the results obtained. Modern practice shows that the effectiveness of the method is largely determined by the qualifications of the surgeon and the uniformity of the protocols used.

Further research and development directions

Of course, the further development of intraoperative ultrasound in neurosurgery requires not only technical improvement, but also unification of approaches to its clinical application. The lack of uniform standards for interpreting ultrasound data and the significant dependence of imaging quality on operator experience remain key limiting factors [52, 53]. In this regard, the development of national and international protocols for the use of ioUS, including standardized methods, training systems and accreditation of specialists, becomes an urgent task [40-45].

In this context, the creation of interdisciplinary training programs that bring together neurosurgeons, radiologists, and medical engineers to improve their skills in interpreting ultrasound data and working with hybrid navigation systems plays a special role. The development of specialized competence centers will allow the formation of expert databases and algorithms for machine image analysis, which will increase the objectivity and reproducibility of the results [47, 49]. In the future, the widespread introduction of artificial intelligence and automated systems for recognizing brain structures will become the basis for personalized ultrasound navigation in real time. Thus, the standardization of techniques and the development of human resources are key conditions for integrating ioUS into modern neurosurgical protocols and improving the effectiveness of surgical treatment of brain tumors [41-43].

CONCLUSION

The analysis of modern research shows that intraoperative ultrasound navigation (ioUS) has become an integral element of modern neurosurgery, providing the surgeon with the opportunity to obtain high-precision images in real time and promptly adjust intervention tactics. The multilevel use of ioUS - from the standard B-mode to contrast and elastographic technologies - has proven effective in increasing the radicality of tumor resection, reducing residual volume and minimizing neurological complications. The data on the high informative value of the method for resection of glial neoplasms are particularly significant, which confirms its value as an alternative to expensive MRI navigation systems and highlights its advantages in conditions of limited resources [8, 19, 29].

Thus, the practical significance of the study lies in the fact that the introduction of standardized protocols for the use of ioUS and the development of specialist training systems can ensure the widespread introduction of the method into clinical practice, improving the quality of neurosurgical care and improving treatment outcomes for patients with brain tumors.

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